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DISSERTATION

IMPROVING THE SENSITIVITY OF RADIONUCLIDE MONITORING STATIONS

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Zusammenfassung

Die Nachweisgrenze von Radionuklid Stationen des Internationalen Messsystemes (IMS) der CTBTO ist hauptsächlich durch den lokalen ^{220}Rn Hintergrund und dessen Tochterprodukte ^{212}Pb, ^{212}Bi und ^{208}Tl beeinflusst, welche die Gammaspektroskopiemessungen dominieren. Obwohl der ^{222}Rn Hintergrund im selben Bereich des ^{220}Rn Hintergrundes liegen kann, haben die Tochterprodukte ^{214}Pb, ^{214}Bi und ^{210}Pb keinen nennenswerten Einfluss auf die Ergebnisse der gammaspektroskopischen Messungen von Aerosolproben und können vernachlässigt werden.

Die Emanation von ^{220}Rn aus dem Boden folgt einem Muster (Taggang) was direkten Einfluss auf die Aktivitätskonzentrationen der Tochterprodukte hat.

In dieser Arbeit wurde gezeigt, dass obwohl ^{212}Pb eine Halbwertszeit hat, die atmosphärischen Transport über mehrere 100 km zulässt, die Änderungen in der gesammelten Aktivität durch den (sehr) lokalen Hintergrund vollständig erklärt werden kann. Mögliche entfernte Hintergrundquellen haben daher nur einen kleinen Einfluss.

Mit dem Wissen des ^{220}Rn Tagganges wurden die Effekte des Startzeitpunktes auf die gesammelte Aktivität untersucht.

Der Unterschied zwischen "bestem" und "schlechtestem" Startzeitpunkt (niedrigste vs. höchste Aktivität am Filter zum Probennahmeende) in Bezug auf die gesammelte Aktivität an der Radionuklid Station RN09 Darwin, Australien, betrug während des Untersuchungszeitraumes 9%. Mit Optimierung des Filterwechselzeitpunktes erreicht man eine Verbesserung der Nachweisgrenze für CTBT relevante Radionuklide von zirka 4%.

Weiters konnte gezeigt werden, dass obwohl in einer Region mit „hohem" ^{220}Rn Hintergrund und der daraus resultierenden Proben mit Aktivitäten von mehreren kBq, die zusätzliche Äquivialentdosis für das Personal vernachlässigbar gegenüber der natürlichen Strahlenbelastung ist.

Abstract

The detection sensitivity of particulate radionuclide monitoring stations of the CTBTO International Monitoring System (IMS) is mainly affected by the local ^{220}Rn background through its progenies ^{212}Pb, ^{212}Bi and ^{208}Tl which dominate the performed gamma spectroscopy measurements. Although the ^{222}Rn background could be in the same range of the ^{220}Rn background, its progenies ^{214}Pb, ^{214}Bi and ^{210}Pb do not have a noteworthy effect on the gamma spectroscopy results of aerosol samples and can be disregarded.

The release of ^{220}Rn from the soil does follow a regular pattern (diurnal variation) and this also affects the activity concentration of its progenies.

This work showed that, although the ^{212}Pb has a half-life allowing atmospheric transport over several 100 km, the variations of the sampled activity can be fully explained by the (very) local background making it the dominating source. Thus possible distant high background sources do have limited effect.

With the knowledge of the ^{220}Rn progenies diurnal variation, the effect of the sampling start time on the sampled radioactivity was assessed.

The effect of the "best" to the "worst" collection start time (ie. maximum versus minimal amount of radioactivity on the filter at the end of sampling) in regard to the sampled radioactivity at the Radionuclide Station RN09 Darwin, Australia, was found to be 9%. By optimizing the filter change time the station sensitivity (capability for the detection of CTBT relevant nuclides) can be improved by app. 4%.

It was also shown that, although being in a "high background" region resulting in samples with activities of several kBq the additional effective dose for the operators is not significant when comparing to the dose from natural sources.

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1.   NUCLEAR TESTING

The first nuclear test was conducted in Alamogordo, New Mexico, on July 16, 1945, during the Manhattan Project, and given the codename "Trinity". The test was originally to confirm that the implosion-type nuclear weapon design was feasible, and to give an idea of what the actual size and effects of a nuclear explosion would be.
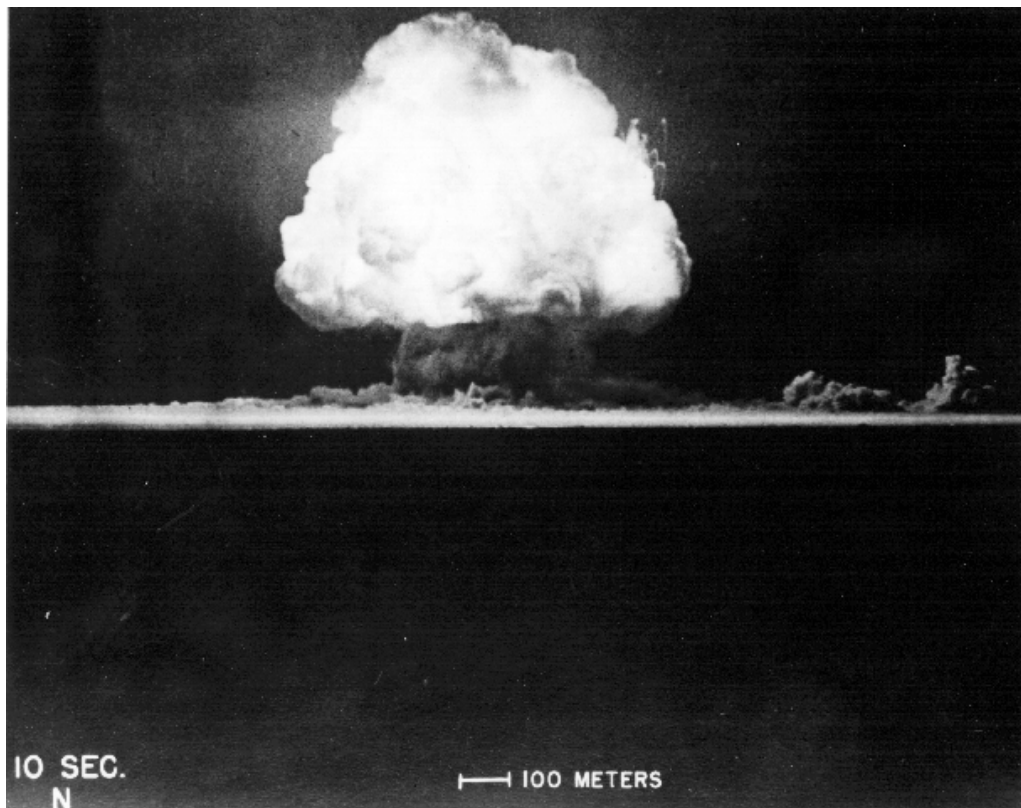
Figure 1 First nuclear explosion on 16 July 1945 in New Mexico, USA

This test was followed by 2081[1] nuclear tests with the last being the test performed by the Democratic People's Republic of Korea on 9 October 2006.

Country	Number	First Test	Last Test
United States of America	1054	16 Jul 1945	23 Sep 1992
Soviet Union	715	29 Aug 1949	24 Oct 1990
United Kingdom	45	3 Oct 1952	26 Nov 1991
France	210	13 Feb 1960	27 Jan 1996
China	45	16 Oct 1964	29 Jul 1996
India	6	18 May 1978	13 May 1998
Pakistan	6	28 May 1998	30 May 1998
North Korea	1	9 Oct 2006	9 Oct 2006
	2082		

Table 1 Nuclear tests performed
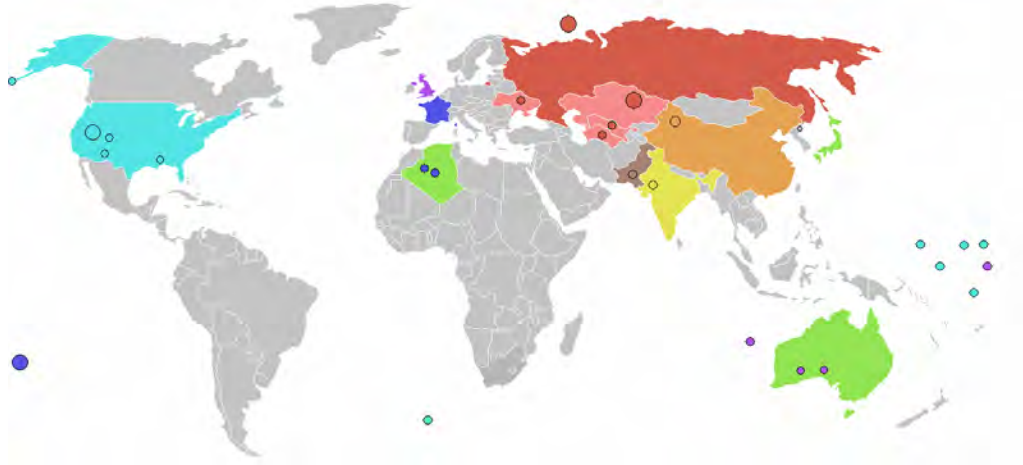
Figure 2 Locations of nuclear tests performed worldwide

1.1 United States of America

The first test of a nuclear weapon was in the atmosphere on July 16, 1945, in a remote part of New Mexico on what was then the Alamogordo Bombing Range, and is now the White Sands Missile Range. The site is 55 miles northwest of Alamogordo, New Mexico. At various times between June 1946 and November 1962, atmospheric and underground tests were conducted by the United States in the Marshall Islands, Christmas Island, Johnston Atoll in the Pacific Ocean, and over the South Atlantic Ocean. Between January 1951 and July 1962, atmospheric and underground nuclear tests were conducted at

the Nevada Test Site [1]. Since July 1962, all nuclear tests conducted in the United States have been underground, and most of them have been at the Nevada Test Site. Some tests were conducted on the Nellis Air Force Range (NAFR); in central and north western Nevada; in Colorado, New Mexico, and Mississippi; and on Amchitka, one of the Aleutian Islands off the coast of Alaska.
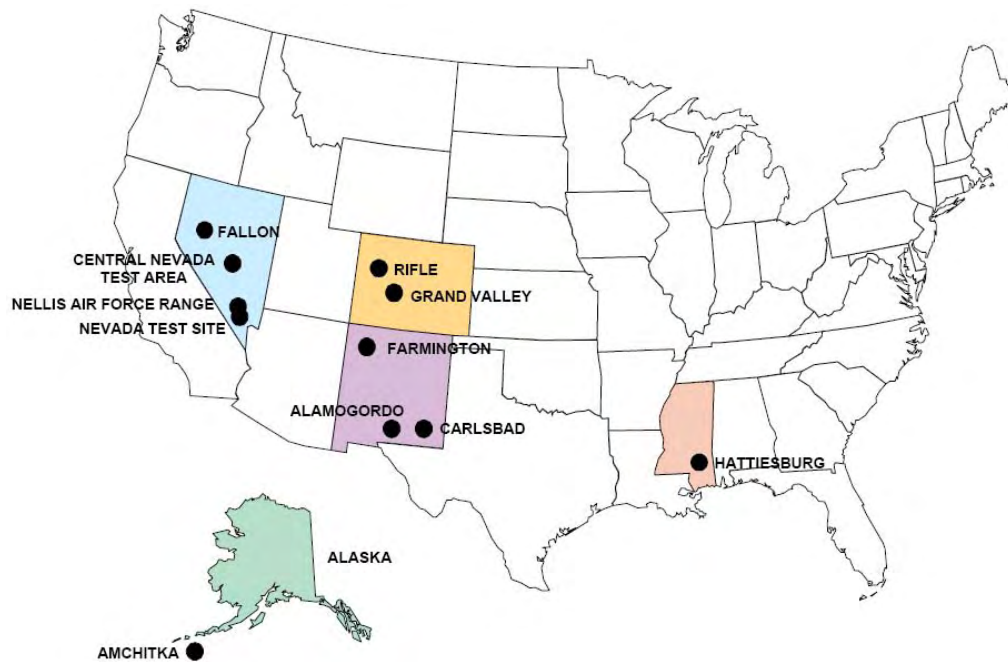
Figure 3 Locations of nuclear tests performed in the USA

Location	Number of Tests	Number of Detonations
Total South Atlantic	3	3
Bikini	23	23
Christmas Island	24	24
Enewetak	43	43
Johnston Island	12	12
Pacific	4	4
Total Pacific	106	106
Alamogordo, New Mexico	1	1
Amchitka, Alaska	3	3

Location	Number of Tests	Number of Detonations
Carlsbad, New Mexico	1	1
Central Nevada	1	1
Fallon, Nevada	1	1
Farmington, New Mexico	1	1
Grand Valley, Colorado	1	1
Hattiesburg, Mississippi	2	2
Nellis Air Force Range	5	5
Rifle, Colorado	1	3
Total Other	17	19
Atmospheric	100	100
Underground	828	921
Total Nevada Test Site (NTS)	928	1,021
TOTAL TESTS	1054	1149

Table 2 Locations and number of nuclear tests

On October 31, 1958, the United States entered into a unilateral testing moratorium announced by President Eisenhower with the understanding that the former Soviet Union also would refrain from conducting tests. The Soviet Union resumed testing in September 1961 with a series of the largest number of tests ever conducted. On September 15, 1961, the United States resumed testing at the Nevada Test Site on a year-round basis. On October 2, 1992, the United States entered into another unilateral moratorium on nuclear weapons testing announced by President Bush. President Clinton extended this moratorium in July 1993, and again in March 1994 until September 1995. On August 11, 1995, President Clinton announced the decision to negotiate a comprehensive nuclear test ban treaty while continuing the cessation of nuclear testing by the United States. On September 24, 1996, President Clinton signed the Comprehensive Nuclear-Test-Ban Treaty.

Calendar Year	US	US - UK	Calendar Year	US	US - UK
1945	1	0	1969	46	0
1946	2	0	1970	39	0
1947	0	0	1971	24	0
1948	3	0	1972	27	0
1949	0	0	1973	24	0
1950	0	0	1974	22	1
1951	16	0	1975	22	0
1952	10	0	1976	20	1
1953	11	0	1977	20	0
1954	6	0	1978	19	2
1955	18	0	1979	15	1
1956	18	0	1980	14	3
1957	32	0	1981	16	1
1958	77	0	1982	18	1
1959	0	0	1983	18	1
1960	0	0	1984	18	2
1961	10	0	1985	17	1
1962	96	2	1986	14	1
1963	47	0	1987	14	1
1964	45	2	1988	15	0
1965	38	1	1989	11	1
1966	48	0	1990	8	1
1967	42	0	1991	7	1
1968	56	0	1992	6	0

Table 3 Number of nuclear tests per calendar year performed by the United States

Tests have been described as being for one of seven purposes [1]: Joint US-UK, Plowshare, Safety Experiment, Storage-Transportation, Vela Uniform, Weapons Effects, and Weapons Related. Weapons related tests were conducted to gather data on nuclear devices; weapons effects tests were conducted, usually by the U.S. Department of Defense (DoD), to determine the effects of nuclear detonations on military offensive and defensive systems; and tests conducted for the United Kingdom (UK) are shown as "Joint US-UK."

Purpose	Detonations
Joint US-UK	24
Plowshare	35
Safety Experiment	88
Storage-Transportation	4

Purpose	Detonations
Vela Uniform	7
Weapons Effect	100
Weapons Related	891
TOTAL DETONATIONS	1,149

Table 4 Purpose and number of detonations

Each series of tests is given a name such as Operation Crossroads. United States nuclear tests were conducted on an intermittent basis from June 1946 to October 1958.On September 15, 1961, when the United States resumed testing at the Nevada Test Site on a year-round basis with Operation Nougat, tests were grouped for fiscal and reporting purposes according to the fiscal year in which they took place. For example, fiscal year 1963 tests—which began July 1, 1962 and extended through June 30, 1963—were in the Operation Storax series. Between April and November of 1962, the United States conducted Operation Dominic, which included the DoD Operation Fishbowl high-altitude tests in the Pacific. The DoD also conducted four weapons effects tests at the Nevada Test Site in July 1962 as Operation Sunbeam. In 1976, the federal government changed the fiscal year to begin on October 1 and end on September 30.Accordingly, the fiscal year 1976 series, Operation Anvil, did not end on June 30, but was extended through September 30, 1976—a period of 15 months.

The type of a nuclear test refers to the method of deployment of the nuclear device at time of detonation such as tower, tunnel, airdrop, etc. In Table 5, the sum of all tests conducted underground (tunnel, shaft, and crater) appears as Total Underground. With the exception of five underwater tests, the remaining tests appear as Total Atmospheric.

Type	US	US-UK
Airburst	1	0
Airdrop	52	0
Balloon	25	0

Type	US	US-UK
Barge	36	0
Rocket	12	0
Surface	28	0
Tower	56	0
Total Atmospheric	210	0
Crater	9	0
Shaft	739	24
Tunnel	67	0
Total Underground	815	24
Total Underwater	5	0
TOTAL TESTS	1,030	24

Table 5 Types of performed nuclear tests

1.2   Union of Soviet Socialist Republics

The Soviet Union equipped two test sites for nuclear tests: the Semipalatinsk Test Site (approximately 150 km to the west from Semipalatinsk) and the North Test Site, on the Novaya Zemlya archipelago.

Within the Semipalatinsk test site, the Soviet Union conducted about 456 nuclear tests at three locations, called 'technical areas' over a period of 40 years for military and peaceful purposes [2]. The earliest tests were above ground (atmospheric and surface) and were carried out in the northern technical area Š. The centre of the first (surface) explosion is historically referred to as 'Ground Zero'. There were 116 explosions between 29 August 1949 and 25 December 1962, including 30 that were carried out on the surface. Five of these surface tests were not successful and resulted in the dispersion of plutonium in the environment.

The other 340 test explosions were conducted underground, in the widely separated technical areas in the south (between 1961 and 1989) and east (from 1968 to 1989) [2]. This total includes four cratering nuclear explosions at Chagan, Sary-Uzen, Tel'kem and Tel'kem-2, where the explosive charge was placed at a shallow depth below ground. Chagan was the first and largest of

these tests and resulted in a lake about 0.5 km in diameter and about 100 m deep with cliffs up to 100 m high, called Lake Balapan or the 'Atomic Lake'. A much smaller lake was also formed by the Tel'kem-2 test. Of the tests carried out deep underground, 13 resulted in the release of radioactive gases to the atmosphere. A summary of the nuclear tests undertaken at Semipalatinsk is presented in Table 6.

Technical site and geographical location	Duration of testing		Number of tests
Technical area Š Ground Zero N 50° 26' E 77° 50'	First nuclear test Last	1949-08-29 1962-12-24	Surface: 26 Air: 87
Technical area G Degelen Mountain N 49° 46' E 77° 59'	First nuclear test Last	1961-10-11 1989-10-04	In mine galleries: 215
Technical area G Degelen Mountain N 49° 59' E 77° 38'	First nuclear test Last	1965-10-14 1980-04-04	In boreholes: 24 (including one as part of the programme on peaceful nuclear explosions in borehole Sary-Uzen)
Technical area B Balapan N 49°43' E 78° 29'	First nuclear test Last	1968-10-21 1968-11-12	In boreholes: 2 (excavation explosions as part of the programme on peaceful nuclear explosions in boreholes Tel'kem and Tel'kem-2)
Technical area B	First nuclear test	1965-01-15	In boreholes: 107

Technical site and geographical location	Duration of testing		Number of tests
Balapan N 49° 56' E 78° 29'	Last	1989-10-19	(including the peaceful nuclear explosion which produced Lake Balapan)

Table 6 Nuclear Tests performed at the Semipalatinsk Test Site
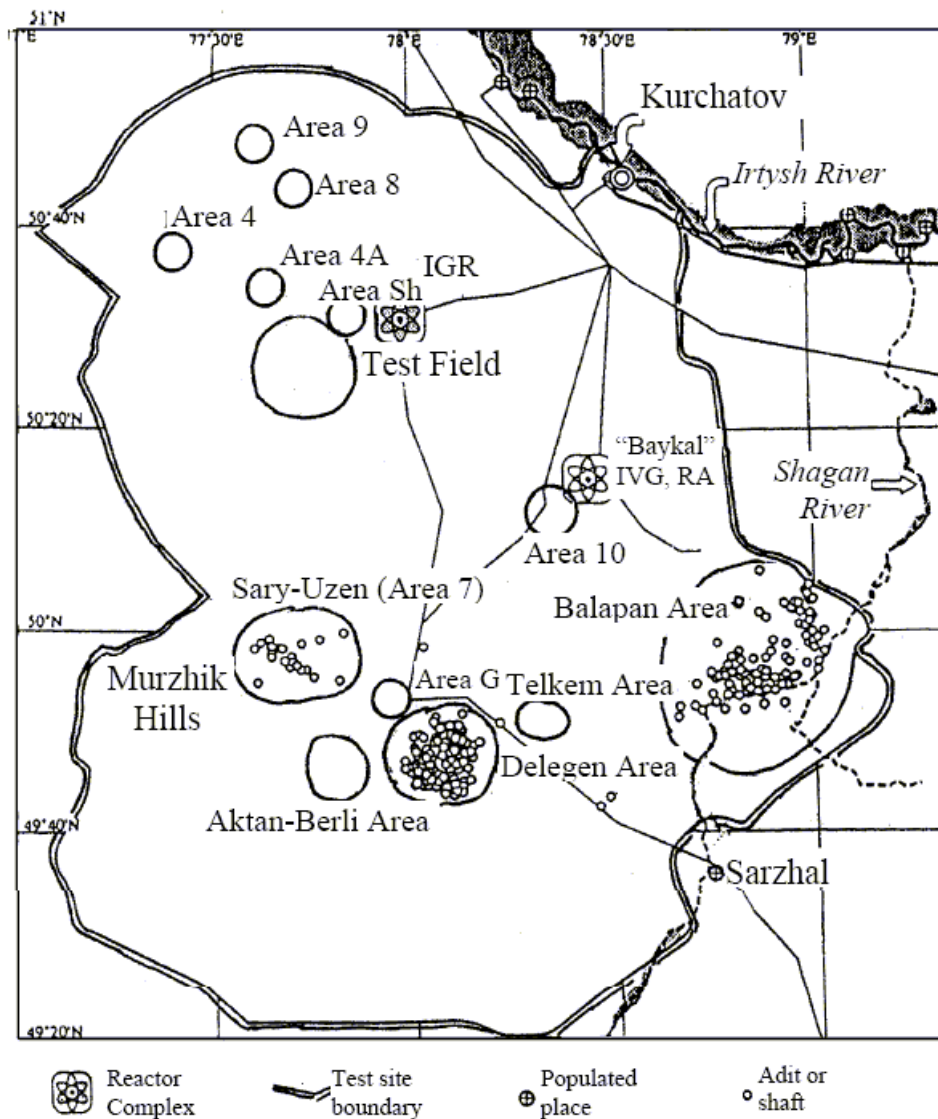
Figure 4 Overview map of the Semipalatinsk test site (STS)

The North Test Site was the most favourable with regard to geographical, geological and economic parameters, and radiation and seismic safety. The test site is removed from inhabited localities by several hundred kilometres. Alienation of land for the test site did not have any noticeable negative impact on the economic activity in the region and tests could be conducted in various media (on the ground surface and underground, above the water surface and underwater, high in the atmosphere) in order to examine the effect of various nuclear blast factors on all types of weapons and military equipment.

The tests were performed at three technological sites [3]: Chernaya Bay (zone A – a series of atmospheric nuclear explosions (bursts), three underwater nuclear explosions and five underground nuclear tests in boreholes); Matochkin Shar Strait (zone B – 34 underground nuclear tests in tunnels); south end of the Severny Island between Mityushikha Bay and Sulmeneva Bay, Sukhoy Nos Peninsula (zone C – series of aerial nuclear tests). Figure 5 shows the location of the test sites.

A – the zone for underwater and on-water nuclear tests (1955–1962), an surface nuclear explosion (7 September 1959) and five underground nuclear tests in six vertical boreholes (shafts) (1972–1975);

B – the zone for 34 underground nuclear tests in horizontal tunnels (1964–1990);

C – the zone for aerial nuclear tests (1957–1962).
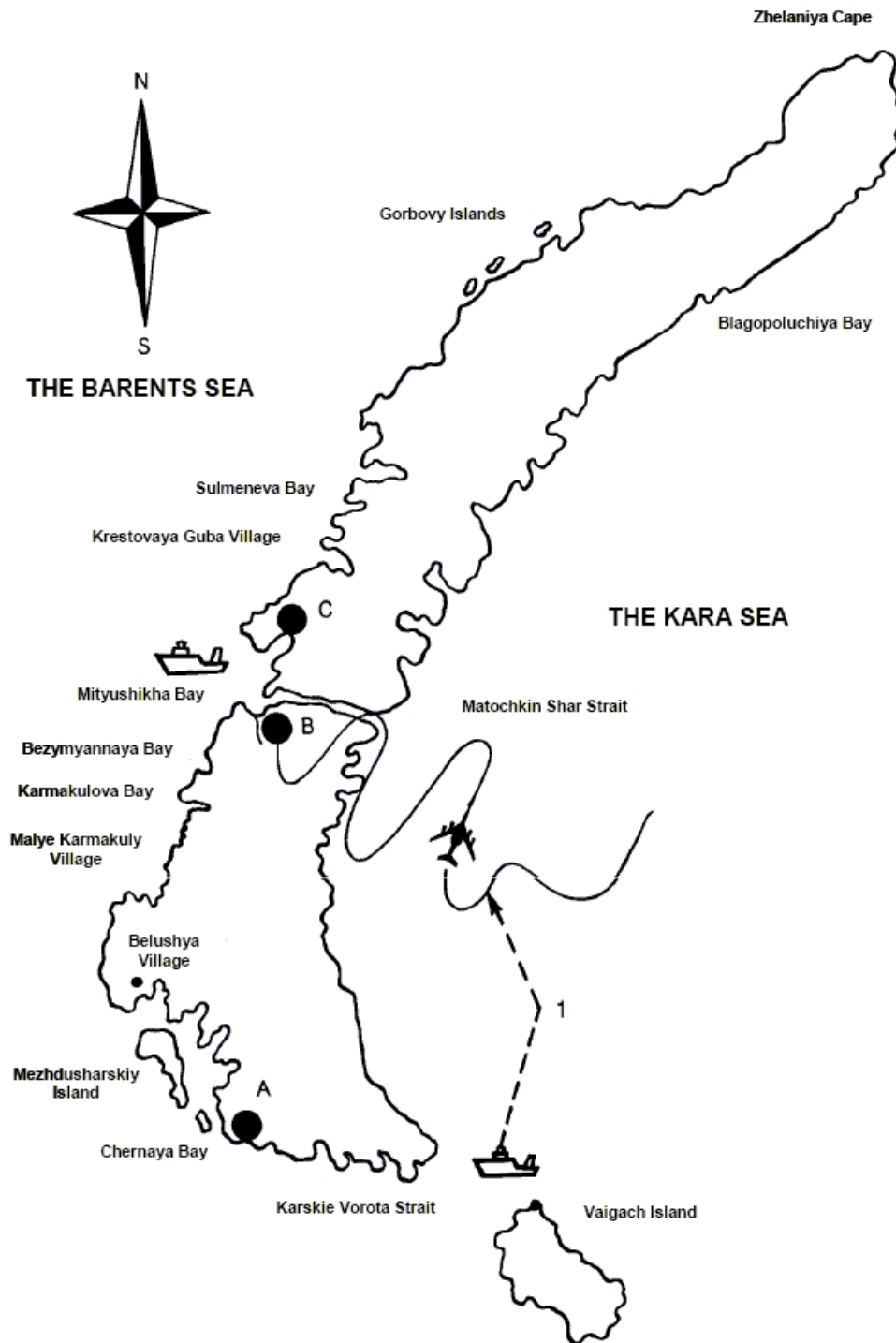
Figure 5 Overview map of the North Test Site (NTS) at Novaya Zemlya

In all, 130 nuclear tests were performed from 21 September 1955 until 24 October 1990, including [3]:

88 atmospheric nuclear tests (one surface test –7 September 1957, 85 aerial ones, which were performed at the altitudes of 0.7–10 km depending on the yield, i.e. on the "bombing" mode, whereby the expanding fireball did not touch the earth`s surface and caused no local contamination on the test site, but contributed, along with nuclear tests of other countries, to the total global contamination of the environment; two on-water tests: 16 kt – 27 October 1961 and 6 kt – 22 August 1962); three underwater nuclear explosions (3.5 kt – 21 September 55, 10 kt – 10 October 1957 and 4.8 kt – 23 October 1961); 39 underground nuclear tests.

The first nuclear explosion at the test site was detonated underwater on 21 September 1955.

A super high-yield hydrogen bomb with a TNT equivalent of about 50 Mt was tested on 30 October 1961, above the Novaya Zemlya archipelago (zone C), at an altitude of about 3.5 km. It is important to note that the energy release due to the fission reaction in this test was less than 10%.

At the North Test Site, the last burst in the atmosphere was performed on 25 December 1962, and underground on 24 October 1990

Like the United States, the Soviet Union performed a program of Peaceful Nuclear Explosions (PNE) for various applications. Since its inception in 1965, the Soviet Union PNE program carried out 122 explosions involving approximately 128 explosives to study some 13 potential uses [4]. Five applications were put into industrial use (e.g., cavities for storing gas condensate and deep seismic sounding of the Earth's mantle). Table 7 summarizes these explosions in terms of their general purpose. In all, PNE explosions were carried out at 115 sites located throughout the Soviet Union. The Soviet program came to an end with the adoption by the Soviet Union of a unilateral moratorium on the testing of nuclear weapons at Soviet Test Sites in 1989.

Purpose	Number
Cratering Application	
Water Reservoir Construction	5
Kama-Pechora Canal Project	3
Dam Construction	2
Total Cratering Applications	10
Contained Applications	
Oil Stimulation	12
Cavity Technology Development	3
Elimination of Gas Well Fires	5
Cavities for Underground Storage	25
Gas Stimulation	9
Deep Seismic Sounding	39
Ore Breakage	2
Toxic Oil Field Waste Disposal	2
Heavy Element Production	13
Decoupling Experiment	1
Prevention of Coal Gas Explosion	1
Total Contained Applications	112
Total Peaceful Nuclear Explosions	122

Table 7 Purpose and number of Peaceful Nuclear Explosions
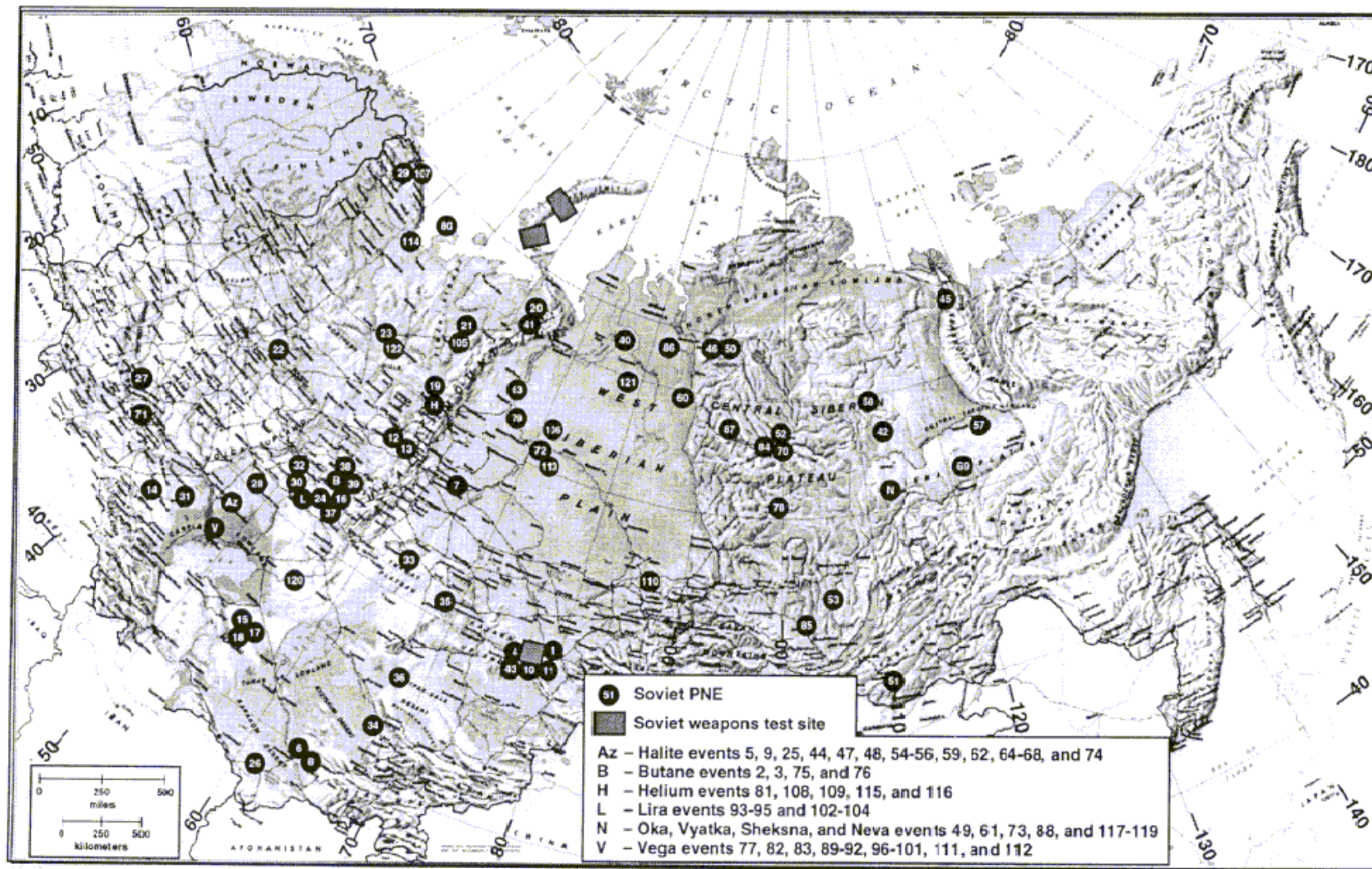
Figure 6 Overview map of Peaceful Nuclear Explosions performed by the Soviet Union

The legend reads:

- **51** Soviet PNE
- Soviet weapons test site

- **Az** – Halite events 5, 9, 25, 44, 47, 48, 54-56, 59, 62, 64-68, and 74
- **B** – Butane events 2, 3, 75, and 76
- **H** – Helium events 81, 108, 109, 115, and 116
- **L** – Lira events 93-95 and 102-104
- **N** – Oka, Vyatka, Sheksna, and Neva events 49, 61, 73, 88, and 117-119
- **V** – Vega events 77, 82, 83, 89-92, 96-101, 111, and 112

1.3   United Kingdom of Great Britain and Northern Ireland

In January 1947 the British Government authorized the development of nuclear weapons. In July 1947 the Government announced that it had chosen a site for plutonium production: Windscale on the coast of Cumberland. Work began almost at once and by June 1951 both piles had gone critical. Design of the first weapon (a plutonium bomb) began in June 1947 at Fort Halstead in Kent.

In mid-1951, the Australian Prime Minister accepted a British proposal to conduct nuclear weapons testing in Australia. The UK had experienced problems with determining a site for testing its newly developed devices. It wanted to carry out a test in 1952 but would have preferred to use the already developed sites in the US, since both equipment and infrastructure would have been available. However, the US remained evasive in providing a final answer and the British were forced to seek an alternative in Australia. The first test, supported by British naval resources, was conducted at the Monte Bello Islands in 1952 but subsequent tests were transferred, mainly for logistical reasons, initially to Emu on the mainland, then briefly back to the Monte Bello Islands, and finally to Maralinga [5].

Britain's first nuclear test was performed in the Monte Bello Islands off the north west coast of Australia in on 3 October 1952.

Between 1953 and 1957, the British conducted a program of nine nuclear weapon tests involving atomic explosions at Maralinga and Emu. In 1953, the first two tests (Totems 1 and 2) were carried out at Emu. The next series of trials took place at Maralinga in 1956, when four major trials, code named One Tree, Marcoo, Kite and Breakaway, were carried out in Operation Buffalo.

Figure 7 Overview map of the Maralinga and Emu test sites

In 1957, the final three major tests at Maralinga, code named Tadje, Biak and Taranaki, were carried out in Operation Antler. The smallest of the trials were

Tadje and Marcoo (each of approximately 1 kT yield), and the largest of the trials was Taranaki (approximately 27 kT yield).

The culmination of Britain's atmospheric test programme was the Grapple series of trials at Malden Island and Christmas Island in the Pacific which took Britain into the thermonuclear era [6]. The first two-stage design to be tested was Short Granite; on 15 May 1957, it was air-dropped. The Grapple-X device was a great success. Fired on 8 November 1957 off the southwest coast of Christmas Island, it yielded 1.8 megatons. Grapple-Y was dropped on 28 April 1958 giving 3 megatons. Even though the relative closeness of ground zero to the installations on Christmas Island meant deliberately limiting the yield, it was the largest ever British test. Four months later, the final Christmas Island trial began. Code-named Grapple-Z, it tested a number of experimental designs, two of which were suspended from balloons, whilst the others in the series were freefall air drops. Grapple-Z culminated with a hollow gas-boosted device which was fired on 23 September with a yield in the kiloton range. It was the United Kingdom's final atmospheric test.

Code name of major trial series	Site of test	Date	Yield (kt TNT)	Position
Hurricane	Monte Bello:	03-Oct-1952	25	Barge
Totem	Emu: Totem 1 Totem 2	14-Oct-1953 26-Oct-1953	10 8	30 m steel tower 30 m steel tower
Mosaic	Monte Bello:	16-May-1956 19-Jun-1956	15 60	30 m aluminium tower 30 m aluminium tower
Buffalo	Maralinga: One Tree Marcoo Kite	27-Sep-1956 04-Oct-1956 11-Oct-1956	15 1.5 3	30 m aluminium tower ground level 150 m air burst (free fall)

	Breakaway	21-Oct-1956	10	30 m aluminium tower
Antler	Maralinga:			
	Tadje	14-Sep-1957	1	30 m aluminium tower
	Biak	25-Sep-1957	6	30 m aluminium tower
	Taranaki	09-Oct-1957	27	300 m airburst (balloon)
Grapple	Malden Island: Short Granite	15-May-1957	300	air drop 2400 m
	Orange Herald	31-May-1957	720	air drop
	Purple Granite	19-Jun-1957	200	air drop
Grapple X	Christmas Island:	08-Nov-1957	1800	air drop 2250 m
Grapple Y	Christmas Island:	28-Apr-1958	3000	air drop 2350 m
Grapple Z	Christmas Island:			
	Pennant	22-Aug-1958	24	balloon – burst over land
	Flagpole	02-Sep-1958	1000	air drop 2850 m
	Halliard 1	11-Sep-1958	0.8	air drop 2650 m
	Burgee	23-Sep-1958	25	balloon – burst over land

Table 8 List of nuclear tests performed by the UK (not included the joint US-UK tests)

On 2 July 1958, President Eisenhower signed amendments to the 1954 US Atomic Energy Act which opened the way to a bilateral agreement between Britain and America on nuclear weapon design information. Only one day after the signing of this amendment, the Agreement for Co-operation on the Uses of Atomic Energy for Mutual Defence Purposes was signed. The Agreement permitted an exchange of classified information which effectively would allow British delivery systems to be fitted with warheads based on American designs, as well as to improve the technical capability of both parties to the agreement in the field of nuclear weapons. Britain's first underground nuclear test (UGT) took place on 1 March 1962; a further four tests had been mounted in Nevada

when, at the end of 1965, the British Government decided to suspend nuclear testing. A total of twenty tests were carried out between May 1974 and 26 November 1991, when the final test - codenamed Bristol - took place.

1.4   French Republic

The French Government began testing nuclear weapons in 1960 at a site in the Sahara Desert in Algeria.

17 nuclear tests were performed in the Sahara Desert between 1960 and 1966; the first four tests were atmospheric and the following 13 were underground [7]. 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. The 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.
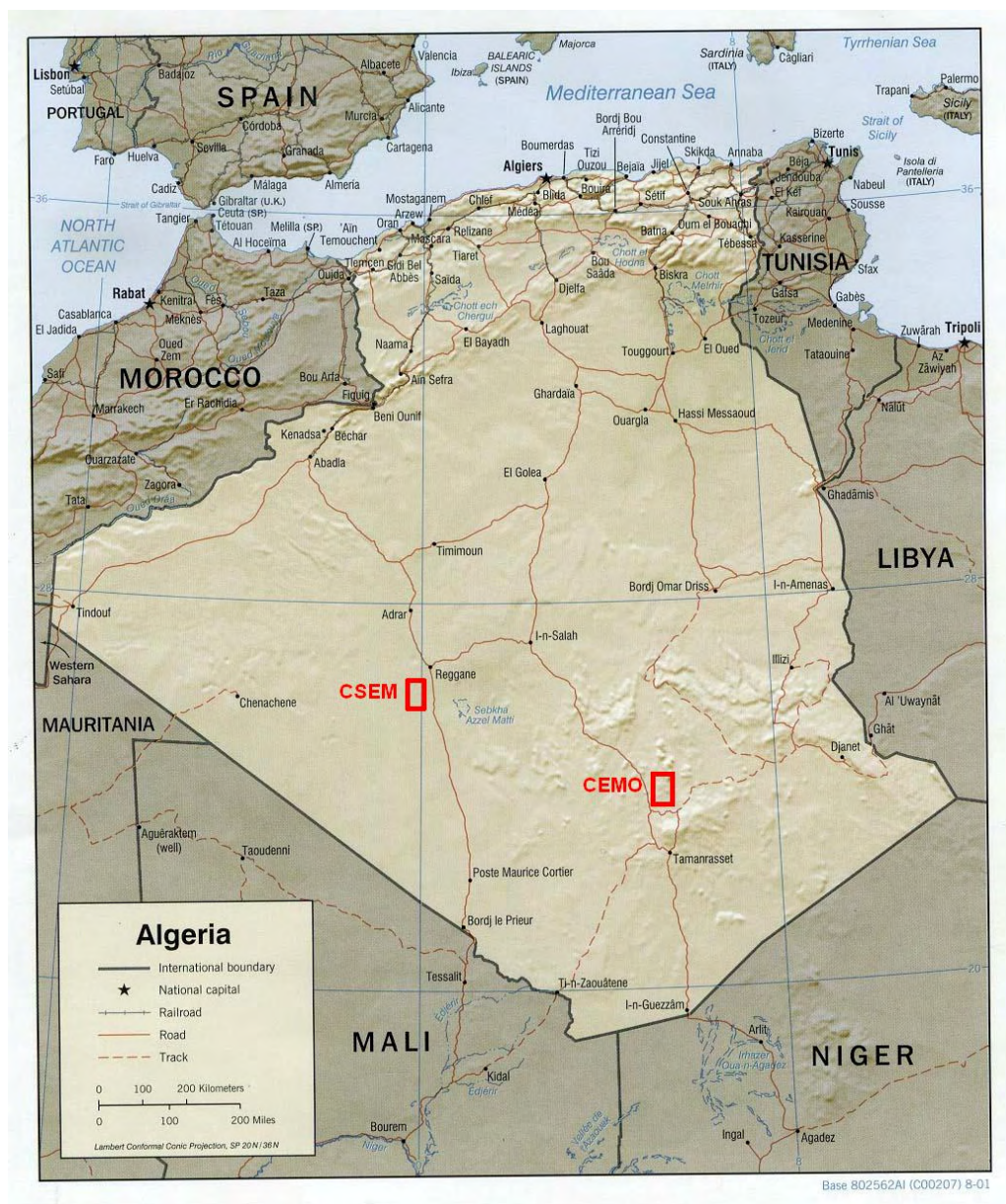
Figure 8 Overview map of the French nuclear test sites in Algeria

Test	Date	Type	Estimated Yield (kt)
Gerboise Bleue	1960-02-13	Tower, 100m	between 40 and 80
Gerboise Blanche	1960-04-01	Surface	<10
Gerboise Rouge	1960-12-27	Tower, 50m	<10
Gerboise Verte	1961-04-25	Tower, 50m	<10

Table 9 Athmospheric nuclear tests performed by France in Algeria

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

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. 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.

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

Table 10 Underground nuclear tests performed by France in Algeria

In July 1962, the decision was made to establish a new test site in the South Pacific—the Centre d'experimentations du Pacifique (CEP)—in the French sovereign territory of French Polynesia [8]. The site chosen for the CEP was the uninhabited atoll of Mururoa, 460 km to the south of the major airbase at Hao, and with reasonable access to the main logistic base of Tahiti, 1200 km to the northwest. From the point of view of the French authorities, Mururoa had the advantage of lying within a sparsely populated area, with the good

meteorological conditions needed to conduct high yield atmospheric tests. Fangataufa, 40 km south of Mururoa, was originally envisaged as an observation post, but was also used for some testing. The first troops arrived in May 1963 and the first civilian workers, from Anaa Atoll in the northeastern region of the Tuamotu Archipelago, were engaged on 7 September 1964. Management of the CEP was the joint responsibility of the Ministry of Defence and the Commissariat a 1'energie atomique (CEA, the French Atomic Energy Commission). A managing body, the Direction des Centres d'experimentations nucleaires (DIRCEN), was established in January 1964 and comprised a military general, responsible directly to the Defence Minister, and two deputies, one from the Ministry of Defence and the other from the CEA. The CEA was responsible for the scientific planning and execution of the tests, while the Ministry of Defence was in charge of operational and logistic support for the testing programme. France conducted 193 'experiences nucleaires' (nuclear experiments) above and beneath Mururoa and Fangataufa Atolls between July 1966 and January 1996 [8]. The experiences nucleaires were of two types: 178 were nuclear tests ('essais nucleaires'), in which nuclear devices were exploded with large releases of fission energy, and 15 were safety trials ('experiences de secunte'), in which more or less fully developed nuclear devices were subjected to simulated accident conditions and the nuclear weapon cores were destroyed by means of conventional explosives, with no or—on a few occasions—very small releases of fission energy.

Figure 9 Overview map of the Mururoa and Fangataufa atolls

The first nuclear test at the CEP, performed on 2 July 1966, was of a 28 kt device mounted on a barge in the lagoon of Mururoa Atoll. Three more barge mounted tests were earned out, two at Mururoa and one in the lagoon of Fangataufa Atoll. Over the next eight years, a further 34 devices were exploded in the atmosphere, suspended from balloons tethered above the atolls (31 at Mururoa and 3 at Fangataufa), and a further 3 were dropped from aircraft in the vicinity of Mururoa. The largest test was of a 2.6 megaton (Mt) thermonuclear device, Canopus, which was detonated 520 m above Fangataufa lagoon on 24 August 1968. The last atmospheric test, Verseau, carried out on 14 September 1974, was a 0.3 Mt device exploded 433 m above Mururoa.

Of the 46 nuclear experiments listed, 41 were nuclear tests—37 at Mururoa and 4 at Fangataufa—and 5 were safety trials. The safety trials were conducted between 1966 and 1974 on the northern tip of Mururoa Atoll west of Denise. A summary of the atmospheric testing programme at the CEP is given in Table 11.

Type	Mururoa	Fangataufa	Total
Barge	3	1	4
Balloon	31	3	34
Air drop	3	0	3

Type	Mururoa	Fangataufa	Total
Total tests	37	4	41
Safety trials	5	0	5
Total (tests and trials)			46
Approximate total yield			10 Mt

Table 11 Atmospheric nuclear tests performed in Mururoa and Fangataufa

Underground testing was introduced in 1975 and continued until January 1996. Altogether there were 137 underground nuclear tests—127 at Mururoa and 10 at Fangataufa—and 10 underground safety trials, all of which were conducted at Mururoa [8]. Until 1981, all of the testing was carried out in shafts drilled vertically deep into the volcanic rock beneath the coral rim. Thereafter, the limited space available on the Mururoa rim, and developments in drilling techniques, led to the nuclear tests being carried out under the lagoons, with the first of them at Mururoa on 10 April 1981. All tests from 1987 onwards were conducted under the lagoons, though one further underground safety trial was carried out under the Mururoa rim in November 1989.

No very high yield devices were exploded underground—none exceeded 150 kt—and the total energy release associated with all underground testing was reported by the French Government to be 32 Mt. The final test was detonated under Fangataufa lagoon on 27 January 1996, after which all nuclear testing at the CEP ceased. The total yield of all underground tests was 2.4 Mt at Mururoa and 0.8 Mt at Fangataufa A summary of this information is provided in Table 12.

Type	Mururoa	Fangataufa	Total
Rim	73	2	75
Lagoon	54	8	62
Total tests	127	10	137
Safety trials	10	0	10
Total (tests and trials)	137	10	147
Approximate total yield			32 Mt

Table 12 Underground nuclear tests performed in Mururoa and Fangataufa

The ten underground safety trials were all carried out in shafts drilled vertically from the rim in the north-eastern region of Mururoa. The French Liaison Office reported that all the safety trial shafts were located 300-500 m inwards from the external edge of the rim (measured from the face of the coral cliff at a depth of 150 m) Seven of the shafts ended in the carbonate zone, though none was less than 280 m deep, and three entered the volcanics. The three trials that involved some fission energy release were in the carbonate zone The preparation for a trial was similar to that for a test, i e the device was lowered in a steel container to the bottom of the shaft, basaltic sand and cuttings were packed around it and the shaft was sealed with cement.

1.5   People's Republic of China

Beginning with its first test on 16 October 1964, China conducted a total of 45 nuclear weapon tests—23 atmospheric and 22 underground—ranging in yield from about 1 kiloton to about 4 megatons. China first tested underground on 23 September 1969. China's largest atmospheric test was 4 MT, conducted on 17 November 1976; its largest underground test was 660 kT, conducted on 21 May 1992 [9].

China has conducted all of its nuclear weapons testing at Lop Nur, typically in the late spring and early fall. The test site is the world's largest, occupying an area of over 100,000 km^2, with over 2,000 km of highways. Out of this, about 20,000 km^2 have been used for testing. The headquarters of the test base is in Malan, about 125 km northwest of Qinggir. Lop Nur contains four testing zones, three for underground testing and one for atmospheric. Only two of the zones are currently used, which occupy an area of about 200 km^2.

	Date	Yield	Type	Comments
1	16-Oct-1964	20-22 kT	Atmospheric	Fission (U235); China's first nuclear explosion, named "Device 596"
2	14-May-1965	20-40 kT	Atmospheric	Fission (U235); China's first air-drop explosion by aircraft

	Date	Yield	Type	Comments
3	09-May-1966	200-300 kT	Atmospheric	Boosted fission (U235)
4	27-Oct-1966	12-30 kT	Atmospheric	Fission (U235)
5	28-Dec-1966	122 kT	Atmospheric	Boosted fission (U235)
6	17-Jun-1967	3-3.3 MT	Atmospheric	China's first full-yield multi-stage thermonuclear test (U235)
7	24-Dec-1967	15-25 kT	Atmospheric	Fission (U235, U238, and Li-6)
8	27-Dec-1968	3 MT	Atmospheric	Thermonuclear device; China's first test using plutonium (U235, with some Pu)
9	23-Sep-1969	20-25 kT (19.2 kT)	Underground	Fission; China's first underground test
10	29-Sep-1969	About 3 MT	Atmospheric	Thermonuclear
11	14-Oct-1970	3-3.4 MT	Atmospheric	Thermonuclear
12	18-Nov-1971	15-20 kT	Atmospheric	Fission
13	07-Jan-1972	8-20 kT	Atmospheric	Fission
14	18-Mar-1972	100-200 kT	Atmospheric	Possibly trigger device, containing Pu, for thermonuclear warhead
15	27-Jun-1973	2-3 MT	Atmospheric	Thermonuclear
16	17-Jun-1974	200 kT-1 MT	Atmospheric	Thermonuclear
17	27-Oct-1975	Below 10 kT (2.5 kT)	Underground	Fission
18	23-Jan-1976	Below 20 kT	Atmospheric	Fission
19	26-Sep-1976	200 kT	Atmospheric	Fission; Partial failure of fusion; "special weapon"
20	17-Oct-1976	10-20 kT (2.6 kT)	Underground	Fission
21	17-Nov-1976	About 4 MT	Atmospheric	Thermonuclear; Largest Chinese test
22	17-Sep-1977	Below 20 kT	Atmospheric	Fission
23	15-Mar-1978	6-20 kT	Atmospheric	Fission
24	14-Oct-1978	Below 20 kT (3.4 kT)	Underground	China's first shaft explosion
25	14-Dec-1978	Below 20 kT	Atmospheric	Fission
26	13-Sep-1979	Unknown yield	Underground	
27	16-Oct-1980	200 kT-1 MT	Atmospheric	The last atmospheric nuclear explosion by China or any country
28	05-Oct-1982	3-15 kT	Underground	
29	04-May-1983	Unknown yield (About 1 kT)	Underground	
30	06-Oct-1983	20-100 kT (14.9 kT)	Underground	
31	03-Oct-1984	15-70 kT (9.1 kT)	Underground	
32	19-Dec-1984	5-50 kT (1.3 kT)	Underground	
33	05-Jun-1987	Unknown yield (250 kT)	Underground	
34	29-Sep-1988	1-20 kT (2.5 kT)	Underground	Reported to be a 1-5 kT enhanced radiation weapon ("neutron bomb") test
35	26-May-1990	15-65 kT (11.5 kT)	Underground	

	Date	Yield	Type	Comments
36	16-Aug-1990	50-200 kT (189 kT)	Underground	
37	21-May-1992	660 kT-1 MT (650 kT)	Underground	China's largest underground test
38	25-Sep-1992	1-20 kT (About 8 kT)	Underground	
39	05-Oct-1993	40-80 kT	Underground	
40	10-Jun-1994	40-50 kT	Underground	
41	07-Oct-1994	40-50 kT	Underground	
42	15-May-1995	95 kT	Underground	
43	17-Aug-1995	60-80 kT	Underground	
44	08-Jun-1996	20-80 kT	Underground	Reported detonation of two warheads
45	29-Jul-1996	1-5 kT	Underground	China's 45th and most recent test

Table 13 List of nuclear tests performed by China

Although China has not signed the Partial Test Ban Treaty (PTBT), it has been in de facto compliance with the treaty since its last atmospheric nuclear test on 16 October 1980. On 21 March 1986, China stated that it had not conducted atmospheric testing for years and announced a permanent end to its above-ground testing. After conducting an underground nuclear test on 29 July 1996, China began a self-imposed moratorium on testing, effective 30 July 1996.

1.6   Republic of India

India's nuclear program was conceived in the pre-independence era by a small group of influential scientists who grasped the significance of nuclear energy and persuaded political leaders from the Indian National Congress to invest resources in the nuclear sector. In the aftermath of independence in August 1947, the Congress government launched an ambitious dual-use, three-stage nuclear program to exploit India's abundant natural thorium reserves. The primary focus of the program was the production of inexpensive electricity. However, the decision to develop the complete nuclear fuel cycle—from ore mining, processing and fuel fabrication facilities, research and power reactors, spent-fuel reprocessing plants, heavy water production plants, and waste treatment and disposal facilities—also led to India's acquiring the technical capability to build nuclear weapons.

India's defeat in the 1962 war with China and the latter's nuclear test in 1964 triggered an internal debate within and outside the Indian government on whether India should follow suit. Ultimately, in November 1964 the theoretical work on the Subterranean Nuclear Explosion for Peaceful Purposes (SNEPP) was authorized. The SNEPP project culminated in the test of a fission device on 18 May 1974 [10]. India described the test as a peaceful nuclear explosion (PNE). However, India did not follow the 1974 test with subsequent tests, nor did it immediately weaponize the device that was tested. It was claimed that the device tested had a yield of about 12kt. However, that figure has been disputed by independent analysts who estimate that the yield was far lower, probably between 2-6 kt.

Plans for testing were renewed in 1996 and finally authorized two rounds of nuclear tests in May 1998, after which it formally declared India's nuclear status. After the first of round of tests on May 11, India's Department of Atomic Energy (DAE) announced that it had tested three nuclear devices [10]: a fission device with a yield of 15 kt; a thermonuclear device with a yield of 45 kt; and a sub-kiloton device with a yield of 0.2 kt. Based on independent analysis of seismic data, claimed that the cumulative yield of the Indian tests was more likely between 20-30 kt, the implications being the thermonuclear test was likely to have been a failure.

Following the May 11 tests, India carried out two tests of sub-kiloton devices on May 13 "to generate additional data for improved computer simulation of designs and for attaining the capability to carry out sub-critical experiments, if considered necessary." However, observers doubt whether such a small number of tests are sufficient for Indian scientists to have collected all the necessary data to conduct "sub-critical" experiments successfully.

1.7 Islamic Republic of Pakistan

Pakistan's nuclear weapons program was established in 1972 by the Minister for Fuel, Power and Natural Resources. Shortly after the loss of East Pakistan in the 1971 war with India, the program was initiated with a meeting of physicists and engineers at Multan in January 1972.

India's 1974 testing of a nuclear "device" gave Pakistan's nuclear program new momentum. Through the late 1970s, Pakistan's program acquired sensitive uranium enrichment technology and expertise. The 1975 arrival of Dr. Abdul Qadeer Khan considerably advanced these efforts. Under Khan's direction, Pakistan employed an extensive clandestine network in order to obtain the necessary materials and technology for its developing uranium enrichment capabilities.

In 1985, Pakistan crossed the threshold of weapons-grade uranium production, and by 1986 it is thought to have produced enough fissile material for a nuclear weapon [11]. Pakistan continued advancing its uranium enrichment program, and according to Pakistani sources, the nation acquired the ability to carry out a nuclear explosion in 1987.

On May 28, 1998 Pakistan announced that it had successfully conducted five nuclear tests. The Pakistani Atomic Energy Commission reported that the five nuclear tests conducted on May 28 generated a seismic signal of 5.0 on the Richter scale, with a total yield of up to 40 Kt [11].

On May 30, 1998 Pakistan tested one more nuclear warhead with a reported yield of 12 kilotons. The tests were conducted at Balochistan, bringing the total number of claimed tests to six. It has also been claimed that at least one additional device, initially planned for detonation on 30 May 1998, remained emplaced underground ready for detonation.

Pakistani claims concerning the number and yields of their underground tests cannot be independently confirmed by seismic means, and several sources have reported lower yields than those claimed by Pakistan. However, seismic data showed at least two and possibly a third, much smaller, test in the initial round

of tests at the Ras Koh range. The single test on 30 May provided a clear seismic signal.

These tests came slightly more than two weeks after India carried out five nuclear tests of its own on May 11 and 13 and after many warnings by Pakistani officials that they would respond to India.

1.8 Democratic People's Republic of Korea

Rumours of an impending nuclear test circulated already during 2005 and early 2006, though none came to immediate fruition. On October 3, 2006, however, North Korea claimed that it would soon conduct a nuclear test, and on October 9, 2006, the state announced to have successfully conducted a test.

The test was confirmed by various seismological stations with an origin time of the event of 01:35:28 UTC. The coordinates of the event location are latitude - 41.31ºN, longitude - 129.02ºE with a magnitude of 4.1, which corresponds to an equivalent of <1 kt.

The nuclear nature of this test has been confirmed by detections of radioactive xenon (^{133}Xe) by the US Air Force, the Swedish Defence Research Agency (FOI) and the noble gas station installed in Yellowknife, Canada for the International Noble Gas Experiment (INGE).

2. NUCLEAR TESTING TREATIES

Arms control advocates had campaigned for the adoption of a treaty banning all nuclear explosions since the early 1950s, when public concern was aroused as a result of radioactive fall-out from atmospheric nuclear tests and the escalating arms race.

Over 50 nuclear explosions were registered between the first nuclear test on 16 July 1945 and 31 December 1953.

Prime Minister Nehru of India voiced the heightened international concern in 1954, when he proposed the elimination of all nuclear test explosions worldwide.

However, within the context of the cold war, scepticism in the capability to verify compliance with a comprehensive nuclear-test ban-treaty posed a major obstacle to any agreement.

2.1 Limited Test Ban Treaty (LTBT)

An agreement between the United States of America, the Soviet Union and the United Kingdom which prevented nuclear testing above ground, underwater, and in outer space entered into force on 10 October 1963 [12]. Its primary purpose is to "*put an end to the contamination of mans environment by radioactive substances*".

Under Article 1 of the Limited Test Ban Treaty the Parties agree to:

"*… prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control:*

> *(a) in the atmosphere; beyond its limits, including outer space; or under water, including territorial waters or high seas; or*

(b) in any other environment if such explosion causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted. It is understood in this connection that the provisions of this subparagraph are without prejudice to the conclusion of a Treaty resulting in the permanent banning of all nuclear test explosions, including all such explosions underground, the conclusion of which, as the Parties have stated in the Preamble to this Treaty, they seek to achieve. "

It does, however, allow testing to occur underground as long as the radioactive fallout is not widespread. A total of 116 countries have signed this treaty, missing the nuclear weapon states France and China.

2.2 Threshold Test Ban Treaty (TTBT)

The Treaty on the Limitation of Underground Nuclear Weapon Tests (Threshold Test Ban Treaty (TTBT)) was signed 3 July 1974 [13].

It establishes a nuclear "threshold," by prohibiting tests having a yield exceeding 150 kilotons of TNT.

Ratification of this Treaty did not take place until 11 December 1990 following negotiations in 1987 on additional verification provisions. A Joint Verification Experiment was conducted in 1988 by the United States and the Soviet Union as a prelude to the signing of the protocols to the treaty. Proposed treaty verification techniques and measurements were employed on the United States test conducted on 17 August 1988 at the Nevada Test Site and on the test by the Soviet Union, conducted on 14 September 1988 at the Semipalatinsk Test Site.

The Treaty includes extensive verification measures like advanced notifications on tests planned, defined test areas and on-site inspections.

2.3 Peaceful Nuclear Explosion Treaty (PNET)

The Treaty between the United States and the Soviet Union on Underground Nuclear Explosions for Peaceful Purposes was signed 28 May 1976 and entered into force together with the TTPT on 11 December 1990 [14].

In preparing the Threshold Test Ban Treaty (TTBT) in July 1974, the United States and the Soviet Union recognized the need to establish an appropriate agreement to govern underground nuclear explosions for peaceful purposes (PNEs). There is no essential distinction between the technology of a nuclear explosive device which would be used as a weapon and the technology of a nuclear explosive device used for a peaceful purpose.

The agreed statement that accompanies the Treaty specifies that a "peaceful application" of an underground nuclear explosion would not include the developmental testing of any nuclear explosive. Such testing must be carried out at the nuclear weapon test sites specified by the terms of the TTBT, and therefore, is treated as the testing of a nuclear weapon.

The PNET applies to all nuclear explosions carried out by the Parties at locations outside the weapons test sites specified under the TTBT. The PNET limits nuclear explosions to 150 kilotons, prohibits group explosions having an aggregate yield of 1,500 kilotons and prohibits group explosions with an aggregate yield exceeding 150 kilotons unless each explosion can be identified and measured by the agreed verification procedures of the TTBT Protocols. Both the United States and the former Soviet Union once supported peaceful nuclear explosion (PNE) programs.

2.4 Comprehensive Nuclear-Test-Ban Treaty (CTBT)

The Comprehensive Nuclear-Test-Ban Treaty (CTBT) was opened for signature on 24 September 1996 [15] and, as of May 2008, has been signed by 178 countries and ratified by 144.

The CTBT prohibits all nuclear test explosions in all environments for military or civil purposes. It also constrains the development of new and more advanced

nuclear weapons and limits the ability of Non-Nuclear-Weapon-States to acquire nuclear weapons. The CTBT establishes an international body called the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) to achieve its object and purpose and ensure implementation of its provisions. To ensure compliance, the Treaty establishes an extensive verification regime that includes an International Monitoring System (IMS), Consultation and Clarification measures, On-Site Inspection, and Confidence-Building Measures.

3.   COMPREHENSIVE NUCLEAR-TEST-BAN TREATY (CTBT)

The core of the CTBT verification system is the International Monitoring System (IMS), a network of 321 monitoring stations using four technologies: 170 seismic, 60 infrasound, 11 hydroacoustic, and 80 air-monitoring radionuclide stations, 40 of which are to be equipped with noble-gas-detection capability. The network is supported by 16 Radionuclide Laboratories. Data from the IMS are transmitted over a satellite-based communications system to the International Data Center (IDC) in Vienna, where they are processed, and data and products are made available to the States Signatories.

The establishment of the IMS network is governed by the Preparatory Commission (PrepCom) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and executed by the Provisional Technical Secretariat (PTS).

3.1   CTBTO/IMS Radionuclide Network

The verification system of the CTBT is based on four technologies that should detect, locate and identify nuclear weapon tests at least down to 1 kt TNT equivalent.

The four detection technologies are seismic for underground tests, hydroacoustic for underwater tests, infrasound for atmospheric tests and radioactivity measurement to detect radionuclides from all environments. Radionuclides are emitted during an atmospheric test, but they may also bubble out of the water, or leak out of the ground.

The radionuclides are detected after atmospheric transport from the source to the CTBT radionuclide station. The criterion used for designing the network was a 90% detection probability within approx. 14 days for a 1-kt explosion in

the atmosphere or from venting by an underground or underwater explosion assuming a detection limit of 10 µBq/m^3 for ^{140}Ba. The network comprises 80 stations equipped with aerosol detection systems [16].
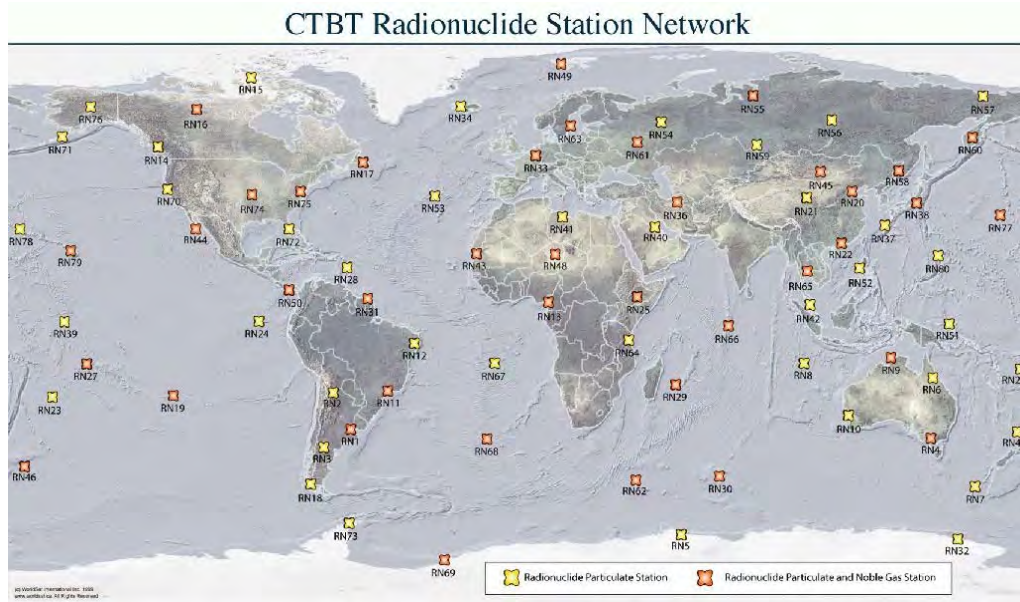
Figure 10 IMS RN Station Network

Of these, 40 will have xenon detection systems when set up. The network includes 16 certified radionuclide laboratories which may evaluate filter samples further if requested. The PrepCom specifications for the radionuclide particulate stations are listed in Table 14.

A simplified model of a radionuclide particulate station consists of a high-volume air sampler and an HPGe detector system. The entire measurement cycle for one sample consists of three steps, sampling, decay and gamma spectrum acquisition. Each of these steps lasts 24 hours, making the overall duration of a measurement 72 hours. At the end, the final gamma spectrum is sent to the IDC of the PTS for analysis and categorisation.

Figure 11 Typical Radionuclide Station Layout. Sampling system on the left, satellite communication system in the center and detector room on the right

Figure 12 High Volume Airsampler

Figure 13 HPGe Detector System

Figure 14 Sample being measured on HPGe detector

Characteristics	Minimum requirements
System	Manual or automated
Air flow	500 m^3 h^{-1}
Collection time [1]	24 h
Decay time [2]	$\leq$ 24 h
Measurement time [3]	$\geq$ 20 h
Time before reporting	$\leq$ 72 h
Reporting frequency	Daily
Filter	Adequate composition for compaction, dissolution and analysis
Particulate collection efficiency	For filter : $\geq$ 80 % at $\varnothing$ = 0.2 µm Global [4]: $\geq$ 60 % at $\varnothing$ = 10 µm
Measurement mode	HPGe High resolution gamma spectrometry
HPGe relative efficiency	$\geq$ 40 %
HPGe resolution	< 2.5 keV at 1332 keV
Base line sensitivity [5] [6]	10 to 30 µBq m^{-3} for ^{140}Ba
Calibration range	88 to 1836 keV
Data format for gamma spectra and auxiliary data	RMS (Radionuclide Monitoring System) format [7]
State of health	Status data transmitted to IDC
Communication	Two-way
Auxiliary data	Meteorological data Flow rate measurement every 10 minutes
Data availability	$\geq$ 95 %
Down time [8]	$\leq$ 7 consecutive days $\leq$ 15 days annually

Table 14 Minimum requirements for an IMS particulate radionuclide station as setup by the PrepCom (CTBT/PC/II/1/Add.2, p. 48)

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[1] Time specifications allow for an uncertainty of 10 %, except for the reporting time parameter.

[2] This value can be reduced, down to a minimum of 6 hours, if a suspicious event is detected by other stations or techniques.

[3] This value allows for authentication measurements for manual systems.

[4] This global value includes the 80% filter efficiency and the collection efficiency of the incoming air circuitry.

[5] The upper limit is intended for high background areas.

[6] Certification procedures to be defined for baseline sensitivities (a posteriori MDCs) as well as the efficiency. Sample preparation losses should not affect base line sensitivities.

[7] This format should make provision for auxiliary data, authentication data and state of health data.

[8] Provision should be made for spare parts in particular areas where periodicity of transportation facilities is more than 7 days.

As of 1 December 2007, 51 particulate stations, 49 of which are certified, have been installed and are sending data to the International Data Center in Vienna, Austria.

Two metrics for particulate station performance were defined at the outset of the IMS provisional operations: data availability, based on the number of transmitted spectra per month, and monitoring metric, which takes into account data quality parameters (e.g., time requirements for collection, decay and acquisition and spectral quality) and is based on the number of spectra of sufficient quality to be categorized [17]. Figure 15 shows the daily data availability of the IMS RN network from 1 January 2004 to 30 November 2007.
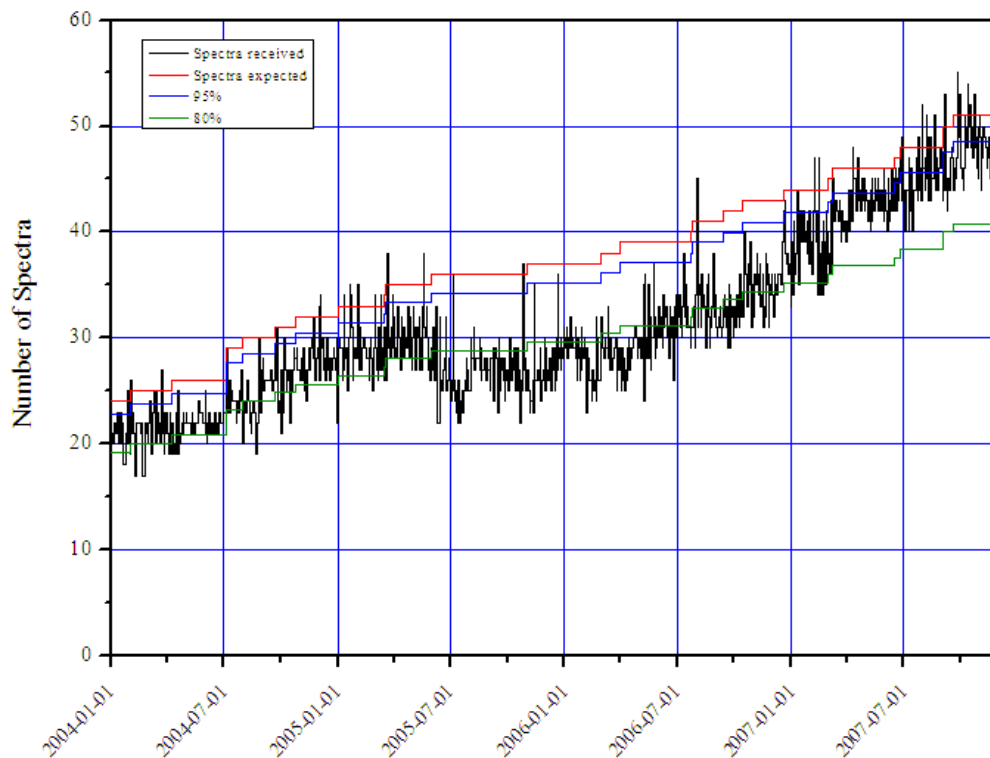
Figure 15 Daily performance of the IMS Radionuclide network 1 Jan 2004 to 30 Nov 2007

The low availability in 2005 and 2006 was mainly caused by outages of the HPGe electrical detector cooling systems which had not performed as expected

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and desired. No spare-part requirement policy could be established for these systems, because the first-generation systems were integrated with the detector. In addition, to the operational problems of this system, maintenance has been difficult due to the nature of the cooling medium (highly flammable compressed gas). Shipment of this has been a major problem which also a reason to change to the next generation of detector cooling system.

Of the 49 certified stations, 35 (71%) have an average data availability of more than 80%, compared to a requirement of 95% for IMS stations. Taking the 2007 data only, this figure becomes then 88% (43 of 49 stations).
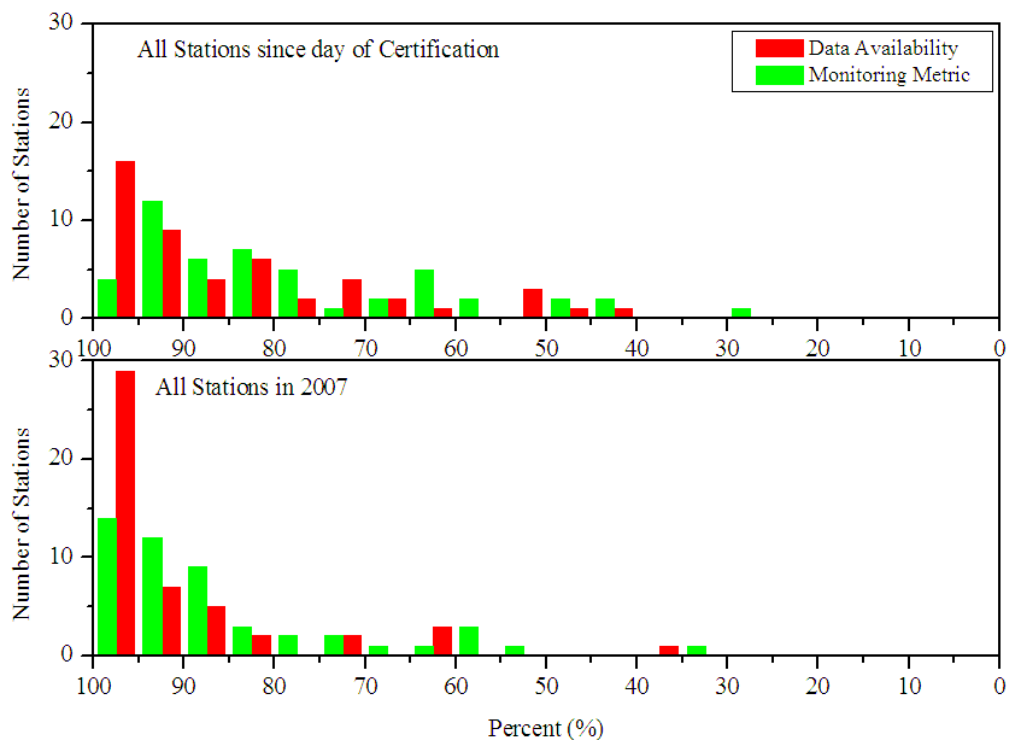
Figure 16 Data availability distribution for all RN stations since certification and 2007

The Treaty relevant Monitoring Metric (i.e. only spectra of sufficient quality are taken into account), the network performance becomes 59% for all stations since the day of certification and 78% analyzing 2007 data only.

3.2 CTBT Verification Relevant Radionuclides

There are more than 3800 different radioactive ground and meta-stable states known to man [18]. A few tens of these are normally present in the atmosphere, either because they are products of very long-lived radionuclides or because they are continuously produced in activation processes caused by cosmic radiation.

Only a subset of the radionuclides can be produced in a nuclear explosion and/or survive the period of the time between the creation at the point of explosion and being counted on a detector at the IMS radionuclide stations. These nuclides should therefore be defined as CTBT relevant.

To illustrate some concepts and terms a schematic picture of a thermonuclear device is given in Figure 17.

PRIMARY   SECONDARY
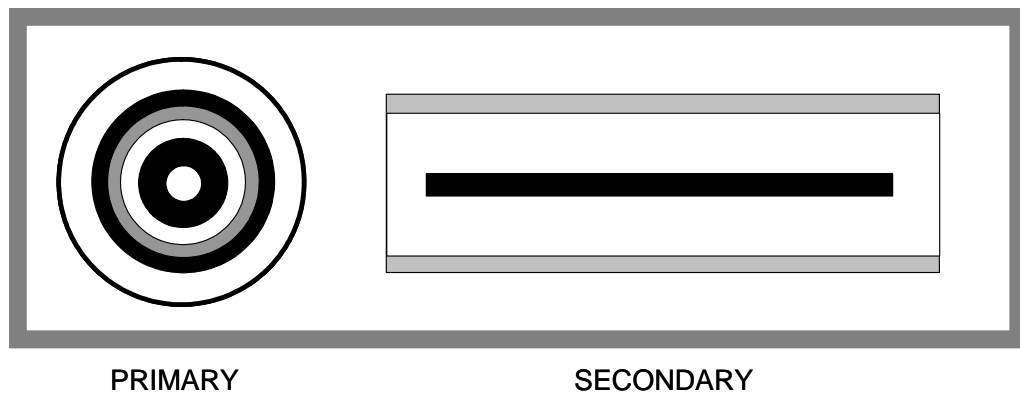
Figure 17 Schematic view of a thermonuclear device

To the left is the primary (a "normal" fission device) with concentric spheres consisting of (from inside out) a mixture of heavy hydrogen isotopes for boosting, fissile fuel for fission, a void, a neutron reflecting material, a tamper and high explosives. To the right is the secondary with concentric cylinders consisting of (from inside out) a fissile material, thermonuclear fuel and a pusher. The pusher absorbs X-rays from the primary and squeezes the secondary to the extreme density needed fro fusion.

In a nuclear explosion radioactive debris can be formed in a number of ways, from the most obvious one, fission, to more esoteric reactions, e.g. used for diagnostics. Ten different categories are distinguished [20]:

1. residues of fission fuel,
2. non-fission reaction products in fuel materials,
3. fission products,
4. activation products in non-fuel materials,
5. activation products in materials surrounding an underground explosion,
6. activation products in the ground below a near surface atmospheric explosion,
7. activation products in sea water around an underwater on a near sea surface explosion,
8. activation products in air around an atmospheric explosion,
9. activation products deriving from neutron fluence detectors and
10. added tracers.

To screen all possible radionuclides the following criteria were applied [20]:

1. The half-life is between 6 hours and 1000 years
2. A primary gamma ray in the energy range of 50-2700 keV and an absolute gamma emission probability larger than 0.1% exists.
3. The relevant production cross sections in non-fuel bomb materials and fluence detectors are larger than 0.1 barn.
4. For target elements in the environment at least one of the abundances in the Earth's crust and Sea is larger that 0.1%. In the case of radiative capture in ground materials the product of the abundance in the Earth's crust or Sea, the isotopic abundance (in ppm) and the cross section (in barn) should be larger than 100.
5. No gases, except xenon are considered.
6. No $(n,2n)^2$, two step high-energy neutron fluence detector products are included.

3.2.1. *Residues of fuel materials*

The fuel of a nuclear weapon is composed of isotopes of uranium, plutonium, lithium and hydrogen, together with decay products of these isotopes.

Assuming normal weapons characteristics, the following compounds and isotopes are considered:

Tritium	^{3}H
Lithium deuteride	^{6}LiD, ^{7}LiD
Weapons grade uranium	^{234}U [<1%], ^{235}U [>90%] and ^{238}U
Depleted uranium	^{235}U [<0.3%] and ^{238}U [>99.7%]
Weapons grade plutonium	^{239}Pu [>93%], ^{240}Pu [<7%], ^{241}Pu, ^{241}Am
Uranium-233	^{232}U, ^{233}U

Table 15 Fuel materials

Tritium is used for boosting a fission device by giving a small thermonuclear flame in the centre of an imploding fission assembly. The resulting neutrons substantially increase the burn-up of the fissile fuel. Some tritium may also be used in the main thermonuclear stage of a fusion device.

Lithium deuteride is the main fuel of the thermonuclear stage. It is the source of tritium and deuterium during the explosion.

Weapons grade uranium and/or plutonium makes the active core of fission fuel. Depleted uranium may form the tamper in a fission, or the pusher in a thermonuclear device and is obtained from the tailings of the enrichment process.

In weapons grade plutonium a small amount of ^{240}Pu is desired to minimise stray neutrons from spontaneous fission.

^{233}U is a fissile isotope made in reactors by irradiating ^{232}Th. This inevitably also produces the by-product ^{232}U which through alpha decay feeds into the natural thorium decay chain. Therefore special attention should be paid to sudden increases in the ^{224}Ra/^{228}Ac ratio.

Applying the relevant screening criteria (shown in Table 16) leaves ^{241}Am as the only nuclide on a final list of relevant nuclides.

Name	Half-Life	Pγ (keV)	Eγ (%)
H-3	13.32 Y	-	-
Li-6D, Li-7D	stable	-	-
U-232	68.9 Y	57.8	0.20
U-233	1.59E+05 Y	42.4	0.09

U-234	2.46E+05 Y	53.2	0.12
U-235	7.04E+08 Y	185.7	57.20
U-238	4.47E+09 Y	1001.0D[1]	0.84
Pu-239	24110 Y	51.6	0.03
Pu-240	6561 Y	45.2	0.05
Pu-241	14.29 Y	148.6	1.86E-04
Am-241	432.6 Y	59.5	35.90

Table 16 Screening data of fuel material

3.2.2. Non-fission reaction products of fuel materials

In the secondary stage of a thermonuclear explosion extremely intense neutron fluences are produced, which, in addition to fission, will induce multiple neutron capture in the pusher (natural or depleted uranium). The resulting high mass uranium isotopes (^{239}U, ^{240}U and ^{241}U) are very short-lived and decay to the corresponding neptunium isotopes further to ^{239}Pu, ^{240}Pu and ^{241}Pu respectively. Applying the screening criteria to this process leaves ^{239}Np with a half-life of 2.356 days and a primary gamma line at 106.1 keV ($P_\gamma = 27.2\%$).

Materials very close to the thermonuclear burn region are exposed to very high energy neutrons (up to 14.1 MeV) and can thus be subject to (n,2n) reactions. These occur mostly in the ^{238}U pusher material creating ^{237}U. ^{237}U has a half-live of 6.75 days and the primary gamma line is at 59.5 keV ($P_\gamma = 34.5\%$) thus surviving the screening criteria.

3.2.3. Fission products

Fission produces hundreds of short-lived, neutron rich nuclides that normally decay by beta emission through the isobaric chains to higher Z, longer lived and finally stable nuclides. The detailed mass distribution of the products, the production probabilities or the yield function, depends on the nucleus split, and on the energy of the initiation neutron [19]. In a pure fission weapon, the effect of fission-spectrum neutrons on ^{235}U and ^{239}Pu must be considered. In a

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[1] D denotes the primary gamma line of a short-lived daughter nuclide

boosted device, where there is a small thermonuclear flame in the centre of the exploding fission device, only a minor part of the fission events are induced by high-energy neutrons, and therefore the high energy yield curves for fissile material can be disregarded.

In full thermonuclear weapons the effect of high energy neutrons on pusher ^{238}U must be considered as well as on ^{235}U and ^{239}Pu used in the primary and secondary stage.

Fission yield data are available for various targets and neutron energies [19]. Analyzing them for the screening criteria including only nuclides with cumulative fission yields of >0.1% in at least one of the fission mechanism of interest leaves 47 nuclides on a final list of CTBT relevant nuclides. These nuclides are shown in Table 17.

Figure 18 to Figure 20 show the cumulative fission yields for ^{235}U, ^{238}U and ^{239}Pu for fission and high energy neutrons as well as the yields of the nuclides surviving the screening criteria in at least one of the yield curves.
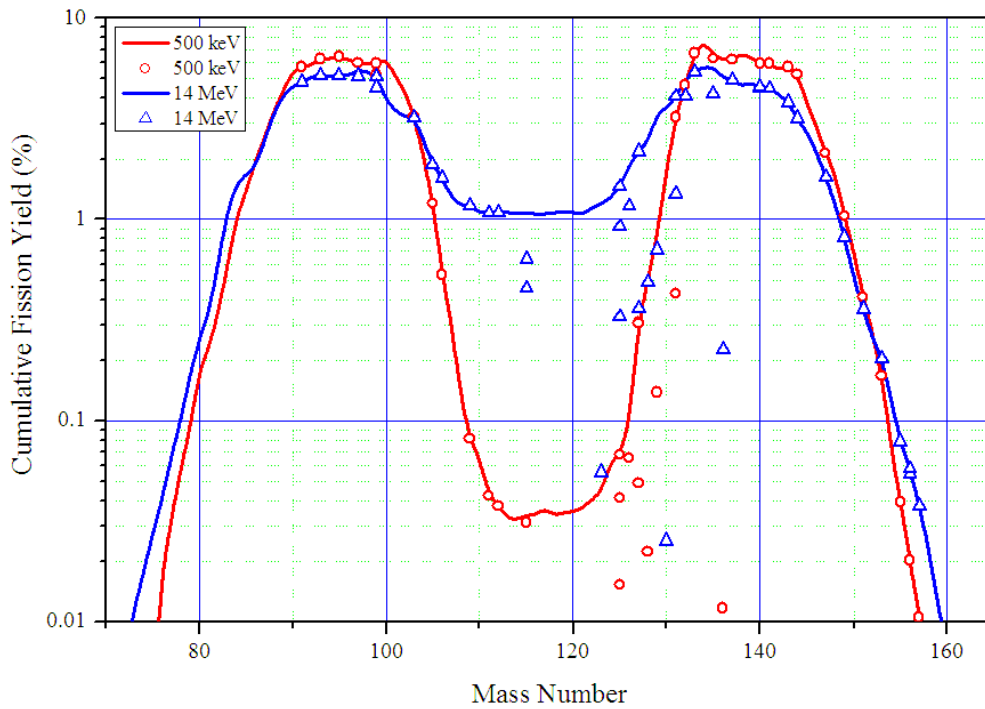
Figure 18 Fission Yields of ^{235}U for fission and high energy neutron
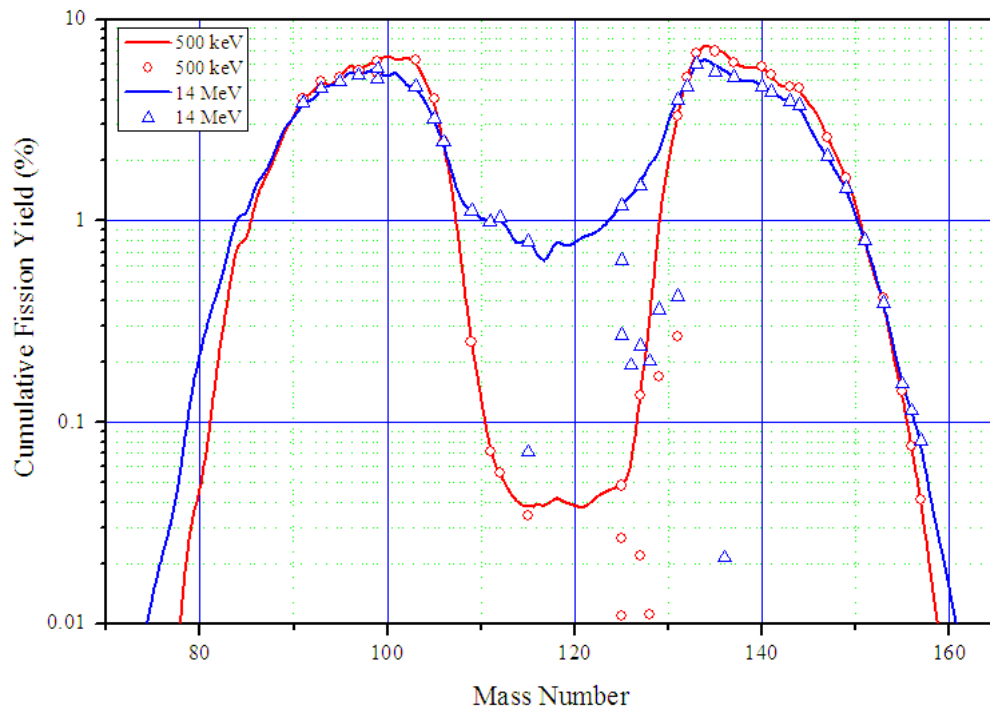
Figure 19 Fission Yields of ^{238}U for fission and high energy neutron
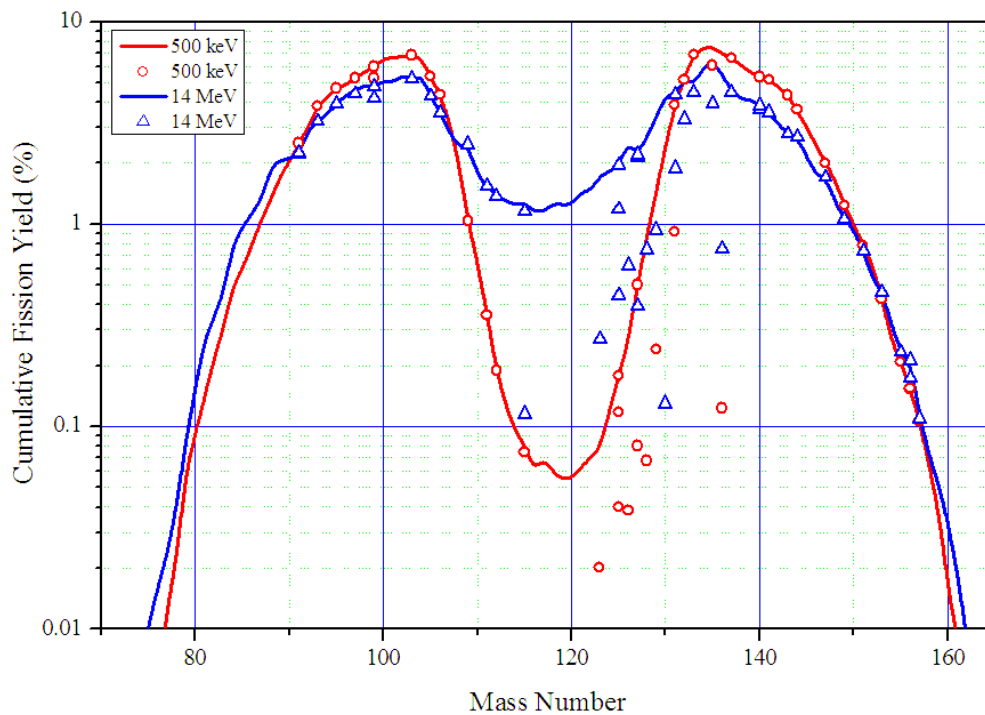
Figure 20 Fission Yields of ^{239}Pu for fission and high energy neutron

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Name	Half-Life	Pγ (keV)	Eγ (%)	²³⁵U		²³⁸U		²³⁹Pu	
				Fission	HE	Fission	HE	Fission	HE
Sr-91	9.6 H	1024.3	33.0	5.73	4.81	4.04	3.87	2.51	2.22
Y-91	58.5 D	1204.8	0.3	5.73	4.82	4.04	3.87	2.52	2.24
Y-93	10.2 H	266.9	7.3	6.25	5.19	4.91	4.53	3.82	3.22
Nb-95	35 D	765.8	100.0	6.43	5.17	5.14	4.89	4.67	3.93
Zr-95	64 D	724.2	44.2	6.43	5.17	5.14	4.89	4.67	3.92
Zr-97	16.7 H	743.4	93.0	6.00	5.14	5.56	5.28	5.27	4.40
Mo-99	65.9 H	739.5	12.1	5.94	5.14	6.17	5.71	5.98	4.75
Tc-99m	6 H	140.5	89.0	5.23	4.52	5.43	5.02	5.26	4.18
Ru-103	39.3 D	497.1	90.9	3.24	3.20	6.28	4.62	6.83	5.21
Rh-105	35.4 H	319.1	19.0	1.20	1.87	4.05	3.22	5.36	4.27
Ru-106	373.6 D	621.9D[1]	9.9	0.53	1.61	2.49	2.45	4.36	3.54
Pd-109	13.7 H	88.0	3.6	0.08	1.17	0.25	1.12	1.04	2.48
Ag-111	7.5 D	342.1	7.0	0.04	1.08	0.07	0.99	0.36	1.54
Pd-112	21 H	617.5D	43.0	0.04	1.08	0.06	1.03	0.19	1.38
Cd-115	53.5 H	336.2	45.9	0.03	0.64	0.03	0.79	0.07	1.16
Cd-115m	44.6 D	933.8	2.0	0.00	0.46	0.00	0.07	0.01	0.12
Sn-123	129.2 D	1088.6	0.6	0.00	0.06	0.00	0.00	0.02	0.27
Sb-125	2.8 Y	427.9	30.0	0.07	1.46	0.05	1.20	0.18	1.95
Sn-125	9.6 D	1067.1	10.0	0.04	0.92	0.03	0.64	0.12	1.18
Te-125m	57.4 D	109.3	0.3	0.02	0.33	0.01	0.27	0.04	0.44
Sb-126	12.4 D	666.3	100.0	0.07	1.17	0.01	0.19	0.04	0.62
Sb-127	3.9 D	685.7	37.0	0.31	2.16	0.14	1.49	0.50	2.14
Te-127	9.4 H	360.3	0.1	0.31	2.17	0.14	1.49	0.50	2.19
Te-127m	109 D	57.6	0.5	0.05	0.36	0.02	0.24	0.08	0.39
Sb-128	9 H	743.2	100.0	0.02	0.48	0.01	0.20	0.07	0.75
Te-129m	33.6 D	695.9	3.1	0.14	0.71	0.17	0.36	0.24	0.93
I-130	12.4 H	536.1	99.0	0.00	0.03	0.00	0.00	0.00	0.13
I-131	8 D	364.5	81.7	3.22	4.10	3.29	3.99	3.88	4.35
Te-131m	30 H	773.7	49.9	0.43	1.34	0.26	0.42	0.92	1.88
Te-132	3.2 D	228.2	88.0	4.66	4.09	5.13	4.65	5.15	3.30
I-133	20.8 H	529.9	87.0	6.72	5.36	6.76	6.00	6.91	4.48
I-135	6.6 H	1260.4	28.9	6.30	4.22	6.94	5.50	6.08	3.96
Cs-136	13.2 D	818.5	100.0	0.01	0.23	0.00	0.02	0.12	0.75

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[1] D denotes the primary gamma line of a short lived daughter nuclide

Name	Half-Life	Pγ (keV)	Eγ (%)	²³⁵U		²³⁸U		²³⁹Pu	
				Fission	HE	Fission	HE	Fission	HE
Cs-137	30.1 Y	661.7	85.1	6.22	4.93	6.05	5.15	6.58	4.45
Ba-140	12.8 D	537.3	24.4	5.98	4.49	5.82	4.61	5.32	3.70
La-140	1.7 D	1596.2	95.4	5.98	4.53	5.82	4.61	5.33	3.84
Ce-141	32.5 D	145.4	48.2	5.95	4.49	5.34	4.38	5.15	3.56
Ce-143	33 H	293.3	42.8	5.73	3.81	4.62	3.91	4.34	2.80
Ce-144	284.9 D	133.5	11.1	5.27	3.17	4.55	3.72	3.67	2.68
Nd-147	11 D	91.1	28.0	2.14	1.62	2.59	2.09	1.99	1.71
Pm-149	53.1 H	286.0	3.1	1.04	0.81	1.63	1.46	1.24	1.06
Pm-151	28.4 H	340.1	23.0	0.41	0.36	0.80	0.80	0.78	0.73
Sm-153	46.3 H	103.2	30.0	0.17	0.20	0.41	0.39	0.43	0.46
Eu-155	4.8 Y	86.5	30.7	0.04	0.08	0.14	0.16	0.21	0.23
Eu-156	15.2 D	811.8	9.7	0.02	0.06	0.08	0.11	0.15	0.21
Sm-156	9.4 H	203.8	20.6	0.02	0.05	0.08	0.11	0.15	0.17
Eu-157	15.2 H	63.9	23.0	0.01	0.04	0.04	0.08	0.11	0.11

Table 17 47 particulate fission products relevant for CTBT verification

In addition to the particulate fission products four xenon isotopes are CTBT relevant. Table 18 shows their properties.

Name	Half-Life	Pγ (keV)	Eγ (%)	²³⁵U		²³⁸U		²³⁹Pu	
				Fission	HE	Fission	HE	Fission	HE
Xe-131m	11.84 D	163.9	1.9	0.05	0.06	0.05	0.06	0.05	0.07
Xe-133	5.243 D	81.0	38.0	6.72	5.53	6.76	6.02	6.97	4.86
Xe-133m	2.19 D	233.2	10.0	0.20	0.30	0.20	0.19	0.25	0.42
Xe-135	9.14 H	249.8	90.0	6.60	5.67	6.97	5.84	7.54	6.18

Table 18 Four xenon isotopes relevant for CTBT verification

3.2.4. *Activation products*

The non-radioactive materials used to construct a nuclear test device cannot be known exactly. Steel, aluminum, brass, plastics, beryllium and high explosives are, however, obvious components [20]. From these constitutes, the following elements are there to be activated: hydrogen, beryllium, carbon, nitrogen,

oxygen, aluminum, chlorine, titanium, chromium, manganese, iron, cobalt, nickel, copper and zinc. Alternative tamper and pusher materials like lead and tungsten might be used to reduce the residual activity. Gallium as a phase stabilizing component of plutonium would also be an activation target. Minor target elements are gold, silver and cesium used to cover surfaces and/or as part of electronic components. Antimony used to increase the strength of lead can be expected as activation target as well [20].

Most activation will occur by slowing down neutrons causing radiative capture. For this type of reaction the resonance integral (indicating the average cross section during slowing down) is used for classification. Higher neutron energies, typically in the MeV range, will also be capable of inducing (n,p), (n,α) and (n,2n) reactions.

Underground nuclear tests will cause activation of nuclides in the surrounding ground (Earth's crust or Sea). These activations depend on the composition of the ground at the site for the test. The selection of target nuclides is based on the average abundances in the Earth's crust and Sea [22]. Applying a cut-off limit of 0.1% (1000 ppm) results in the elements as displayed in Table 19.

Z	Element	ppm in the Earth's crust (by weight)	ppm in the Earth's Sea (by weight)
1	H	1400	108000
8	O	461000	857000
11	Na	23600	10800
12	Mg	23300	1290
13	Al	82300	0.002
14	Si	282000	2.2
15	P	1050	0.06
17	Cl	145	19400
19	K	20900	399
20	Ca	41500	412
22	Ti	5650	0.001
26	Fe	56300	0.002

Table 19 Elemental abundances in the Earth's crust and Sea

As the neutron spectrum in the surrounding of the exploding device is much softer than within the device, the thermal cross section instead of the resonance integral is used for the classification of the radiative capture. Because of this softer neutron spectrum there is no need to include (n,p)-, (n,α)- and (n,2n)-activation reactions. Many trace elements in the 1-1000 ppm (by weight) range are contained in the ground as well. Some elements do exhibit high neutron capture cross sections (several thousands of barns) and must be considered as well. The most prominent element in this category is europium. The relevant properties for (n,γ) processes for europium are shown in Table 20. Due to the much higher thermal cross section of ^{151}Eu (almost a factor of 30) than ^{153}Eu, ^{152}Eu will be the dominant (n,γ) product.

Europium

Target	Abundances		Thermal cross section (barn)	n-γ product	Half-Life	Pγ (keV)	Eγ (%)
	Crustal in ppm	Isotopic in %					
151	2	47.81	9185.3	152	13.537 Y	344.3	26.5
				152m	9.3116 H	841.6	14.2
153	2	52.19	312.5	154	8.593 Y	123.1	40.8

Table 20 Properties of europium for n-γ processes

There is, in principle, no difference in what target nuclides in the ground are available for activation by an atmospheric nuclear explosion or an underground on [20]. Depending on the altitude of the explosion, the neutron spectrum will be more or less soft. The only difference is that for an atmospheric explosion rather the biospheres abundances than the crust abundances are to be used. This however should not result in a difference in the choice of target nuclides.

No CTBT relevant nuclides are expected to be produced by activation of the air constituents[1].

In many atmospheric tests, materials were included in vital parts of the device which allowed the fluence of high energy neutrons to be deduced, by

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[1] CTBT relevance is here in contrast to dose relevance as ^{14}C, a long-lived beta only emitter, is the major contributor to the world wide dose commitment from all past nuclear tests [21].

measuring single and multiple (n,2n)-products. Stable nuclides suitable for this purpose have produced radionuclides with long enough half life to allow for analysis in global fallout. Analyzing the Chart of Nuclides for stable nuclides that will produce (n,2n) and $(n,2n)^2$ products that are fairly easily detected. If a reasonable gamma ray activity is assumed for the products, the possible detectors are: [75]As, [85]Rb, [89]Y, [90]Zr, [103]Rh, [107]Ag, [169]Tm, [191]Ir and [197]Au. These nuclides have a maximum cross section for (n,2n) reactions are in the range of 0.3 - 2 barn for neutron energies below 14 MeV. Materials put into the device as detectors will of course also be subject to (n,γ), (n,p) and (n,α) reactions.

In nuclear weapons tests added traces might prove useful for the diagnostics. They provide a convenient way to calculate the absolute production of isotopes of the same element, and will that way give information on the fluences and production rates in different parts of the device. A tracer should, in contrast to the high energy neutron fluence detectors, be chosen and added in such a way that it is not itself produced or altered by some reaction induced by the experiment, i.e. the explosion.

Nuclides like: [233]U, [237]Np, [238]Pu, [242]Pu, [241]Am, [243]Am and [244]Cm could be added to better understand the reactions in the high Z materials [20]. Based on the specific activity as well as on gamma ray energies and emission probabilities, only [241]Am has a realistic possibility to be detected. Other nuclides that have been suggested to have been added as tracers in past tests were [57]Co and [133]Ba [20].

Table 21 shows all 45 CTBT relevant activation products surviving the screening process described above as well as their reasoning to be included.

Name	Half-Life	Pγ (keV)	Eγ (%)	1	2	3	4	5	6
Na-24	14.959 H	1368.6	100.0			●	●		
K-42	12.36 H	1524.7	18.0				●		
Sc-46	83.79 D	1120.5	100.0			●			
Sc-47	3.3492 D	159.4	68.3			●			

Name	Half-Life	Pγ (keV)	Eγ (%)	1	2	3	4	5	6
Cr-51	27.7025 D	320.1	10.0			●			
Mn-54	312.12 D	834.8	100.0			●			
Fe-59	44.495 D	1099.3	56.5			●			
Co-57	271.74 D	122.1	85.6						●
Co-58	70.86 D	810.8	99.0			●			
Co-60	1925.28 D	1332.5	100.0			●			
Cu-64	12.7 H	1345.8	0.5			●			
Zn-65	244.06 D	1115.5	50.6			●			
Zn-69m	13.76 H	438.6	94.8			●			
Ga-72	14.1 H	834.0	96.0			●		●	
As-74	17.77 D	595.8	59.0					●	
As-76	26.24 H	559.1	45.0					●	
Rb-84	32.77 D	881.6	69.0					●	
Rb-86	18.642 D	1076.6	9.0					●	
Y-88	106.626 D	1836.1	99.2					●	
Zr-89	78.41 H	909.0	100.0					●	
Rh-102	207 D	556.4	96.0					●	
Ag-106m	8.28 D	1045.8	29.6			●		●	
Ag-108m	418 Y	722.9	90.8			●		●	
Ag-110m	249.76 D	657.8	94.0			●			
Sb-120m	5.76 D	1023.1	99.4			●			
Sb-122	2.7238 D	564.1	71.0			●			
Sb-124	60.2 D	602.7	98.3			●			
Cs-132	6.48 D	667.7	98.0			●			
Cs-134	2.0652 Y	604.7	97.6			●			
Ba-133	10.51 Y	356.0	62.1						●
Eu-152	13.537 Y	344.3	26.5				●		
Eu-152m	9.3116 H	841.6	14.2				●		
Tm-168	93.1 D	198.2	52.4					●	
Tm-170	128.6 D	84.3	2.5					●	
W-187	23.72 H	685.8	27.3			●			
Ir-190	3.087 H	186.7	52.4					●	
Ir-192	73.827 D	316.5	82.8					●	
Au-196	6.183 D	355.7	87.0			●		●	
Au-196m	9.6 H	147.8	43.0			●			
Au-198	2.69517 D	411.8	96.0			●			
Pb-203	51.92 H	279.2	81.0			●			

Name	Half-Life	Pγ (keV)	Eγ (%)	1	2	3	4	5	6
Ra-224	3.66 D	241.0	4.1	●					
U-237	6.75 D	208.0	21.2		●				
Np-239	2.356 D	277.6	14.4		●				
Am-241	432.6 Y	59.5	35.9	●	●				

Table 21 45 CTBT relevant non-fission products

1	it is a fuel residual
2	it is a non-fission reaction in the fuel
3	it is an activation product in the non-fuel material
4	it is an activation product in the environment
5	it is a high energy neutron fluence detector product
6	it is an added tracer

Table 17 and Table 21 were the basis of discussion for CTBTO Member States who supported the lists with the recommendation to exclude ^{241}Am. The experts also noted that the analysis for five fission products (^{109}Pd, ^{123}Sn, ^{125m}Te, ^{127m}Te and ^{127}Te) and two activation products (^{64}Cu and ^{170}Tm) might require a too long analysis time and recommended their exclusion. With these exceptions the lists were approved by the CTBTO PrepCom in May 2000 [23].

3.3 ^{212}Pb in gamma spectra from aerosol samples

The main component of CTBTO radionuclide particulate station samples are the ^{220}Rn progenies ^{212}Pb, ^{212}Bi and ^{208}Tl. These nuclides are the major contributor to the counts of the gamma spectra measured and hence have a direct effect on the detection capability for CTBT relevant nuclides.

A typical gamma spectrum of an IMS sample is shown Figure 21. As seen in the spectrum and in the peak analysis table (Table 22), 95% of the detected peaks are attributed to ^{212}Pb, ^{212}Bi and ^{208}Tl and these peaks represent app. 97% of the net peak areas.

Figure 21 Typical gamma spectrum

Peak No.	Energy (keV)	FWHM (keV)	NetArea (counts)	Unc. (%)	ID
1	39.9	1.10	8.038E+04	1.4	Bi-212
2	46.6	1.09	2.034E+04	1.2	Pb-210
3	72.8	1.19	4.777E+04	1.1	Pb-X, Tl-X
4	74.9	1.19	7.696E+05	0.3	Pb-X, Bi-X
5	77.1	1.19	1.201E+06	0.3	Bi-X
6	84.8	1.37	2.541E+04	1.8	Pb-X, Tl-X
7	87.2	1.37	4.358E+05	0.6	Pb-X, Bi-X
8	89.9	1.38	1.389E+05	0.6	Bi-X
9	115.2	1.16	3.224E+04	3.0	Pb-212
10	149.6	1.26	8.925E+02	19.9	Pb-212
11	152.0	1.26	3.297E+03	5.5	Pb-212
12	154.2	1.27	3.263E+03	5.6	Pb-212
13	164.4	0.83	9.847E+02	37.3	Pb-212
14	176.7	1.11	2.213E+03	29.3	Pb-212
15	211.5	1.22	1.749E+03	41.2	Tl-208
16	238.6	1.26	1.986E+06	0.1	Pb-212
17	252.6	1.26	7.216E+03	2.2	Tl-208

Peak No.	Energy (keV)	FWHM (keV)	NetArea (counts)	Unc. (%)	ID
18	277.3	1.29	7.018E+04	1.1	Tl-208
19	288.1	1.31	1.418E+04	4.6	Bi-212
20	300.1	1.30	9.449E+04	0.8	Pb-212
21	328.0	1.31	5.097E+03	10.9	Bi-212, Ac-228
22	374.9	1.32	5.754E+03	7.1	Pb-212
23	377.2	1.32	9.689E+03	6.0	Pb-212
24	387.2	1.18	2.295E+03	6.4	Pb-212
25	415.3	1.30	3.694E+03	3.7	Pb-212
26	452.8	1.44	1.053E+04	1.4	Bi-212
27	473.5	1.42	1.219E+03	8.6	Bi-212
28	477.6	1.43	1.112E+05	0.7	Be-7
29	510.7	1.49	1.466E+05	0.6	Tl-208, Annih.
30	583.2	1.49	5.602E+05	0.2	Tl-208
31	656.0	1.57	2.435E+03	4.0	Tl-208
32	658.2	1.58	4.121E+03	2.6	Tl-208
33	668.2	1.70	1.233E+03	7.6	Tl-208
34	670.6	1.71	4.954E+02	16.8	Tl-208
35	722.2	1.58	1.245E+03	6.7	Tl-208
36	727.3	1.58	1.254E+05	0.6	Bi-212
37	763.3	1.58	9.214E+03	5.1	Tl-208
38	785.5	1.63	1.689E+04	2.8	Bi-212
39	835.9	1.50	5.411E+02	14.2	Tl-208
40	860.5	1.67	7.352E+04	0.7	Tl-208
41	893.4	1.65	5.178E+03	6.0	Bi-212
42	911.6	1.96	3.699E+02	19.7	Ac-228
43	927.9	1.44	5.211E+02	13.4	Tl-208
44	952.2	1.70	2.363E+03	3.5	Bi-212
45	982.8	1.80	9.506E+02	27.6	Tl-208
46	1078.8	1.78	6.419E+03	5.0	Bi-212
47	1093.9	1.81	1.465E+04	2.6	Tl-208
48	1346.5	2.03	8.618E+02	7.1	Tl-208
49	1512.9	2.03	4.991E+03	5.0	Bi-212
50	1592.5	2.22	1.129E+04	2.9	Tl-208
51	1620.8	2.11	1.691E+04	1.7	Bi-212
52	1679.5	2.35	8.435E+02	25.8	Bi-212

Peak No.	Energy (keV)	FWHM (keV)	NetArea (counts)	Unc. (%)	ID
53	1806.0	2.29	1.541E+03	4.3	Bi-212
54	2103.5	3.22	2.405E+04	1.9	Tl-208
55	2175.8	2.45	1.052E+03	26.4	Tl-208
56	2614.5	2.69	1.879E+05	0.4	Tl-208, Pb-208
57	2686.9	2.90	2.392E+03	10.2	Tl-208
58	2689.3	2.90	1.764E+03	10.0	Tl-208
59	2699.9	3.34	6.460E+02	7.9	Tl-208

Table 22 Peak analysis results of a typical gamma spectrum. Of the 59 peaks 56 (95%) are attributed to the ^{220}Rn progenies ^{212}Pb, ^{212}Bi and ^{208}Tl.
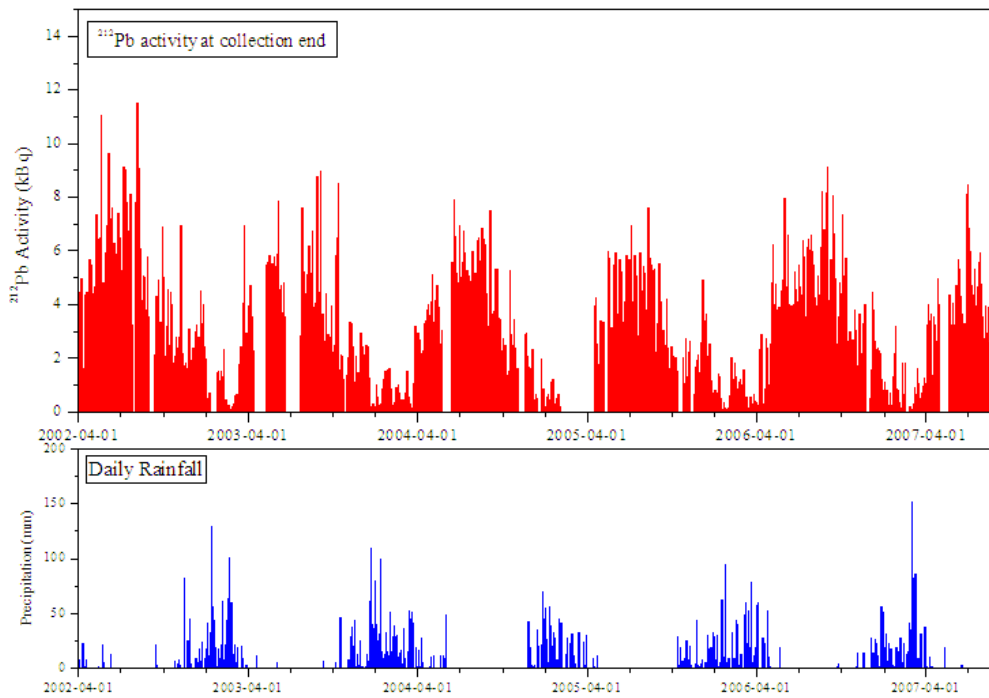
Figure 22 Annual variation of ^{212}Pb activity collected and daily rainfall showing the effect of washout/rainout on the collected ^{212}Pb activity.

3.4   Effects of ^{212}Pb on station sensitivity

One of the major requirements for a particulate monitoring station is the base line sensitivity, or minimum detectable concentration (MDC), which is defined

as 10 to 30 µBq/m³ for ^{140}Ba and interpreted as 10 µBq/m³ for a blank filter, or a filter where all natural nuclides have already decayed, and as 30 µBq/m³ for any other sample.

The ^{212}Pb concentration has proven to be the main contributor to the MDC value. As a fitting function for the MDC, a square root function of the form $MDC = \sqrt{p1 + p2 \cdot Pb212}$, as suggested by Blanchard and Le Petit [24] and Zähringer [25] seems to be adequate to describe the system response.
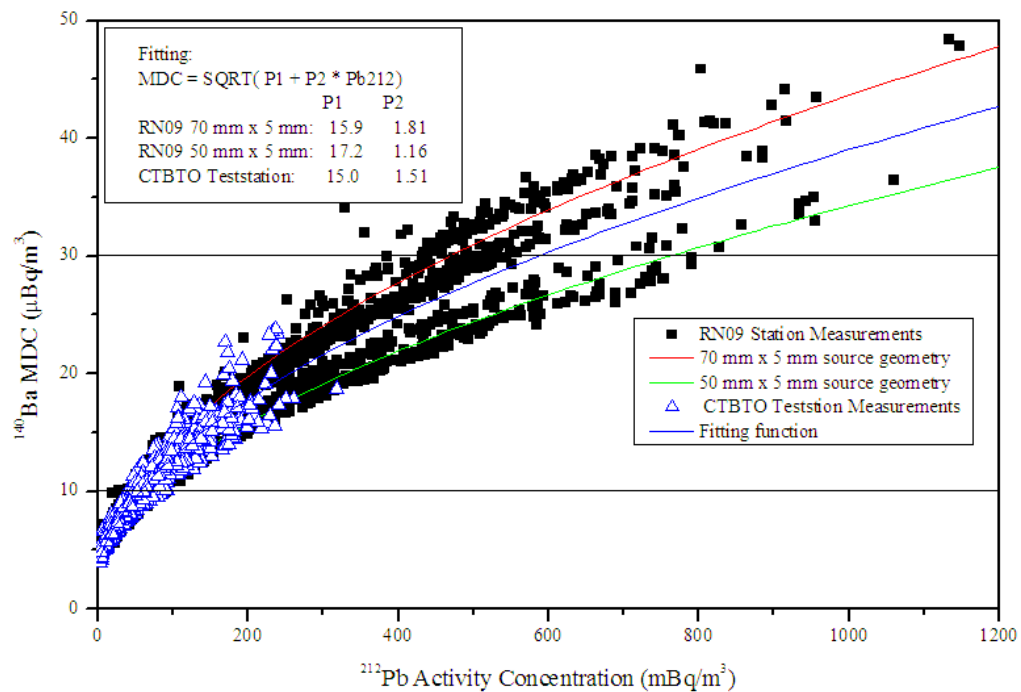
Figure 23 ^{140}Ba MDC in relationship of the ^{212}Pb activity concentration from measurements at RN09 Darwin, Australia and at the CTBTO Test station in Vienna.

Some of the operating stations are in regions with very high ^{212}Pb concentrations, which can exceed 1000 mBq/m³. Results from such stations, and others, show that, regardless of the installed detector systems, the ≤30 µBq/m³ requirement can be met for ^{212}Pb concentrations only up to about 600 to 800 mBq/m³.

The MDC for samples where activity is accumulated assuming a constant concentration in air during a sampling interval is calculated according to:

$$MDC(Bq/m^3) = \frac{L_D}{T \cdot \varepsilon \cdot \gamma_i \cdot V \cdot \xi_i \cdot K_S \cdot K_W \cdot K_C}$$ **Equation 1**

with:

L_D: Lower limit of detection at the 95% confidence level (L. Currie [26])

$$L_D = 2.71 + 4.65 \cdot \sqrt{\mu_B}$$

$\sqrt{\mu_B}$ … Standard deviation of the background at the energy of interest,

$$\mu_B = \sum_i^{ROI} counts_i$$

T: Acquisition life time

ε: Photo peak detection efficiency at the energy of interest

γ_i: Gamma emission intensity of the isotope i

V: Sample volume in m^3 at STP

ξ_i: Sampling system global collection efficiency for the isotope i (for checking the station performance this is set to 1)

K_S: Decay correction during sampling $K_S = \dfrac{1 - e^{-\lambda_i \cdot t_S}}{\lambda_i \cdot t_S}$

K_W: Decay correction between end of sampling and start of acquisition

$$K_W = e^{-\lambda_i \cdot t_W}$$

K_C: Decay correction during acquisition $K_C = \dfrac{1 - e^{-\lambda_i \cdot t_C}}{\lambda_i \cdot t_C}$

λ_i: Decay constant for the isotope i (s^{-1})

t_S: Time between start and end of sampling (s)

t_W: Time between end of sampling and start of acquisition (s)

t_C: Acquisition real time (s)

The background counts in the region of interest (ROI) can be expressed as

$$\mu_B = (a + b \cdot A(T_S) \cdot e^{-\lambda \cdot t_W}) \cdot t_C$$ **Equation 2**

where:

> A(T_S): Activity on the filter at the end of sampling
>
> a and b are detector and system specific constants (a refers to the system background and b to the background contributing from the sample)

For samples from stations in a high [212]Pb background, the detector system background term can be neglected and we get

$$\mu_B \propto A(T_S)$$

As seen in Figure 23 and also in Equation 2, the photo peak detection efficiency (i.e. the detector – sample geometry) does affect positively the MDC when it is increased. The photo peak detection efficiency increased at the Stations when new filter material was introduced which allowed a smaller sample size (i.e. 5 cm disk vs. 7 cm disk). Further improvement of the MDC by increasing the photo peak detection efficiency is not feasible without major detection system changes (e.g. installation of compton suppression systems).

4. SCOPE

The local ^{220}Rn background through its progeny ^{212}Pb is one of the major contributors affecting the detection capability of an environmental radionuclide monitoring station of the IMS network of the CTBTO.

While the IMS monitoring regime requires a 24 hours sampling duration, a 24 hours decay and 20 hours gamma spectrum acquisition for the radionuclide monitoring stations, the start time of the sampling process is freely selectable, though not on a daily basis.

Scope of this work is to assess the potential detection capability improvement by adjusting the start time of the collection process in order to minimize the ^{212}Pb radioactivity at the end of sampling.

For this, a model connecting the local ^{220}Rn background and the ^{212}Pb activity concentration taking into account the much longer half life of ^{212}Pb and the local meteorological conditions should be developed. Based on the model developed, the daily activity concentration variation is to be assessed and its possible impact on the detection capability quantified when adjusting the sampling start time.

As such improvement is primarily of interest for radionuclide monitoring stations in high background regions with considerable higher sample activities a radiological assessment at such radionuclide monitoring station is to be performed. This assessment should evaluate the gamma dose rate and the corresponding equivalent dose for the local operators.

5. PRODCUTION OF [220]RN AND ITS RELEASE TO THE ATMOSPHERE

This section follows to a great extent J. Porstendörfer 1994. While not primarily part of this work, it is deemed necessary to provide the background on the source term for better understanding.

The thorium decay chain is one of three still existing natural decay chains and present in all terrestrial materials. The different nuclides, the decay modes and half lives are displayed in Figure 24. [220]Rn is the gaseous radioactive product in this decay chain and this gas can leave the earth's crust and enter the atmosphere were they are distributed by meteorological process (see Figure 25). The radon decay products are radioactive isotopes of polonium, bismuth, lead and thallium which are easily fixed to existing aerosol particles in the atmosphere.
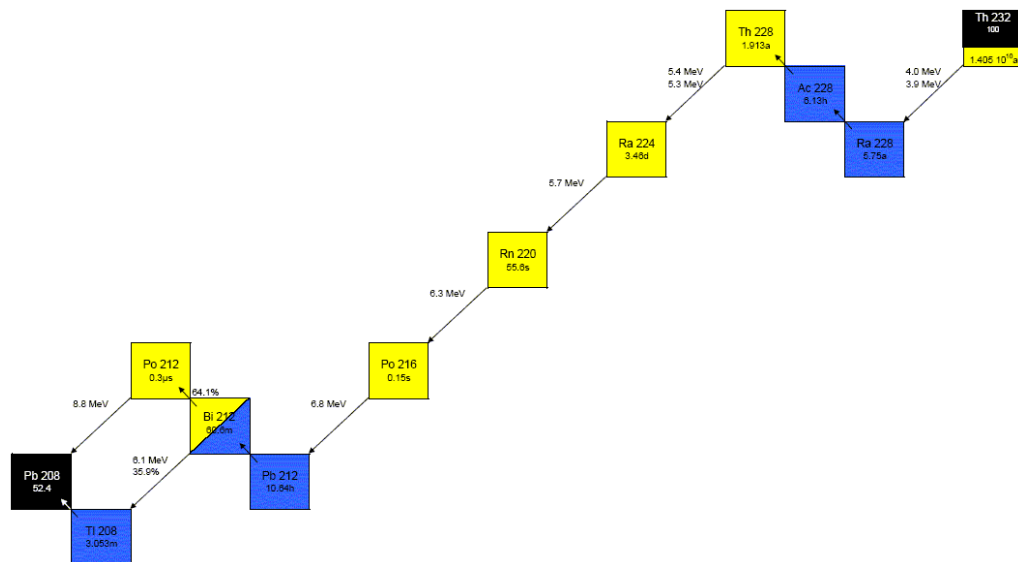
Figure 24 Thorium 232 decay chain

Radon enters the atmosphere mainly by crossing the soil-air interface. The contribution of other sources such as ocean, ground-water and natural gas are relatively small.
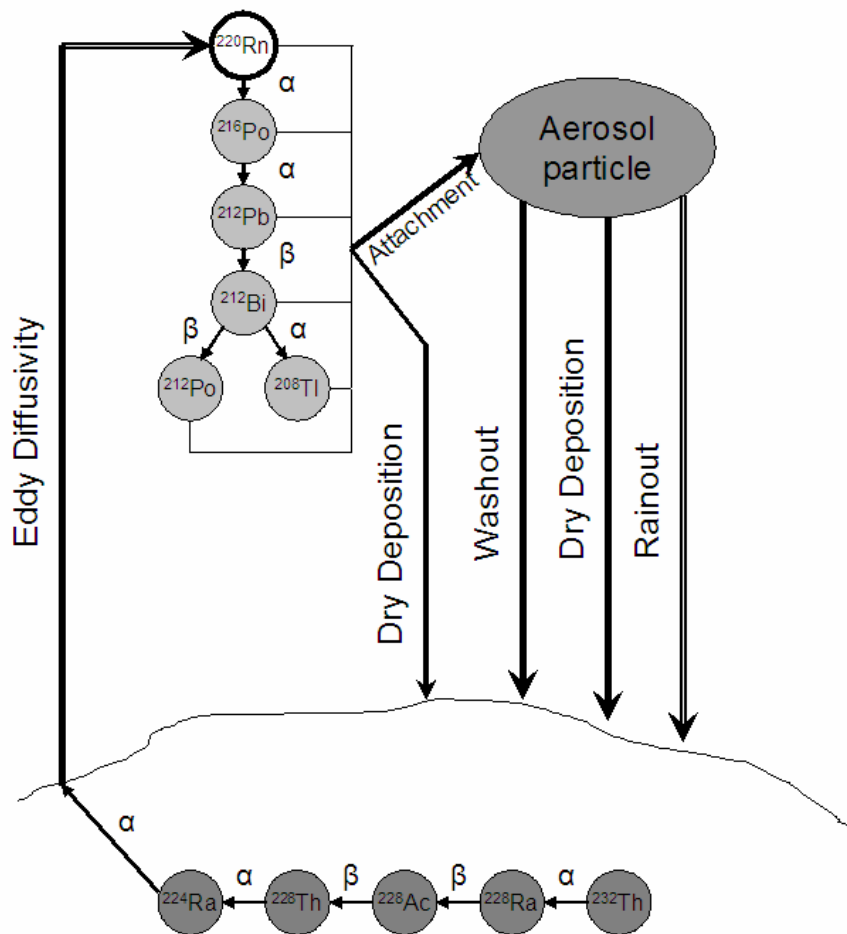
Figure 25 [220]Radon and its decay products in the open atmosphere

Because soil has $10^3 - 10^4$ times higher gas concentrations than the atmosphere, there is a great radon concentration gradient to the open air. The gradient is permanently maintained by the generation of the ^{238}U and ^{232}Th series from long lived mother nuclides and is responsible for a continuous flux of radon isotopes into the atmosphere.

The concentration of radon in the pone atmosphere is governed by the source term, characterized by the exhalation rate, and the atmospheric dilution processes, which are affected by meteorological conditions.

In general, tow steps determine the radon flux from materials (Figure 26):

- Release from the solid mineral grains to the air-filled pores called "emanation"; and

- Subsequent transport through the pores of the material into the atmosphere.
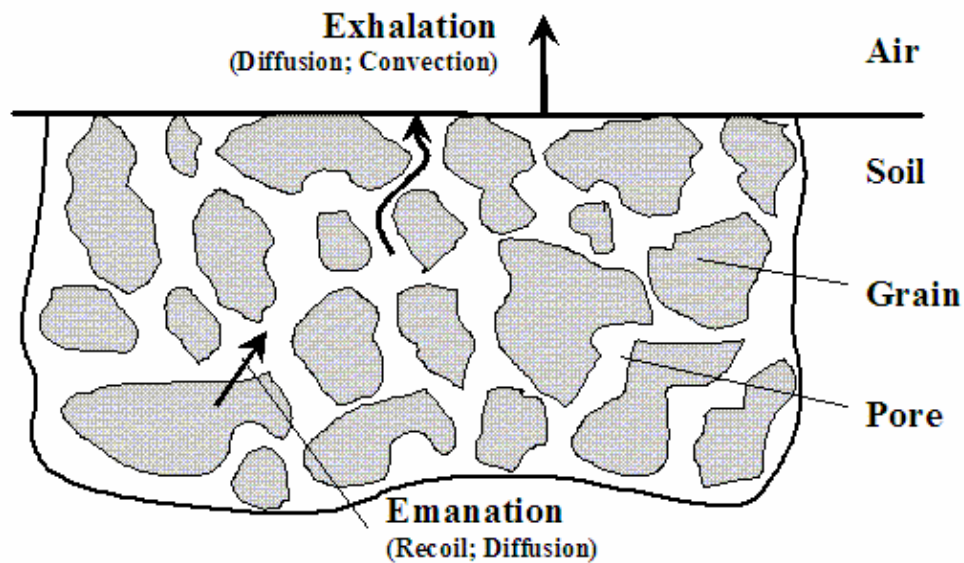
Figure 26 Mechanism of exhalation of radon from soil

When radium decays in soil grains, the resulting atoms of radon isotopes must first escape from the mineral grains to air-filled pores. The fraction of radon

formed in the soil grains that escapes into the pores is known as the emanation power, coefficient, or fraction.

The emanation fraction is considered to have two components, recoil and diffusion. Because of the low diffusion coefficient of gases in the solid grain material, it is assumed that the main fraction of the emanation power is contributed by the recoil process. After the alpha decay of the radium isotopes (^{226}Ra and ^{224}Ra) radon atoms possess kinetic energies of 86 and 123 keV, respectively and travel from the site of generation until their energy is transferred to the material. The travel distance is about $0.04 - 0.06$ µm in grain and about 60 µm in air.

The moisture content has a large impact on the emanation coefficient, which can be explained by the lower recoil stopping distance for radon in water than in air. A radon atom entering a pore that is filled or partially with water has a higher probability being stopped in the pore volume without crossing the pore space and penetration another grain.

In order to enter the atmosphere the radon gas be transported through the pores of the material so that a fraction reaches the surface before decaying. There are two basic mechanism of transport of radon into air – diffusion and convective flow.

Diffusion, described by Ficks's Law ($\vec{j} = D \cdot grad(n)$) results in a flux density in the z-direction that is proportional to the gradient of the gas concentration C_B in the interstitial space and the bulk or effective diffusion coefficient D_B^*.

$$l_d = -D_B^* \frac{dC_B}{dz}$$
<div align="right">**Equation 4**</div>

Convective movements, induced by pressure differences created by meteorological conditions, vary with time and cannot be readily quantified. Pressure-driven convective flow can be characterized by Dacy's Law, which relates the flowrate per unit cross-sectional area v_d to the gradient of the pressure p.

$$v_d = -\frac{K'}{\mu}\frac{dp}{dz}$$ **Equation 5**

with:

K'   permeability of the medium

μ   dynamic viscosity of air

If the fluid density is $l_f = v_d \cdot C_B$, then the total radon flux in the material is

$$l = -D_B^* \frac{dC_B}{dz} + v_d \cdot C_B$$ **Equation 6**

The radon concentration profile in a homogeneous material up to the surface can be expressed by the following steady-state equation

$$\frac{D_B^*}{P_{eff}}\frac{d^2C_B}{dz^2} - \frac{1}{P_{eff}}\frac{d(v_d \cdot C_B)}{dz} - \lambda_0 \cdot C_B + \lambda_0 \cdot C_{BS} = 0$$ **Equation 7**

with:

P_{eff} Effective fractional pore space (effective porosity)

λ_0 Radon decay constant

C_{BS} Maximal radon concentration in material air at large

depth ($z = -\infty$)

For flow by molecular diffusion alone - under the assumption that the gas concentration at the ground surface (z=0) can be neglected (C_B=0) in comparison to C_{BS} – the solution of Equation 7 is:

$$C_B(z) = C_{BS} \cdot \left(1 - e^{-\left(\frac{\lambda_0}{D_B}\right)^{\frac{1}{2}} \cdot z}\right)$$ **Equation 8**

with:

$$D_B = \frac{D_B^*}{P_{eff}}$$

The exhalation rate e (in Bq m^{-2} s^{-1}) from the ground is expressed by:

$$e = D_B^* \frac{dC_B(z=0)}{dz} = \varepsilon \cdot a_B \cdot \rho \cdot \lambda_0 \cdot R_B \qquad \textbf{Equation 9}$$

with:

R_B Diffusion length of radon in soil (typical value 0.02 m for ^{220}Rn and 1.5 m for ^{222}Rn)

$$R_B = \sqrt{\frac{D_B}{\lambda_0}}$$

a_B Mean radium concentration (typical value 40 Bq/kg for ^{224}Ra and ^{226}Ra)

ε Radon emanation power (typical value 0.05 for ^{220}Rn and 0.1 for ^{222}Rn)

ρ Soil density (typical value $2 \cdot 10^3$ kg/m^3)

Using typical values for the factors of Equation 9 an estimate for the ^{220}Rn exhalation rate is 1 Bq m^{-2} s^{-1} and 0.026 Bq m^{-2} s^{-1} for ^{222}Rn.

As mentioned above, many external factors that influence the diffusivity and thereby the exhalation rate: rainfall, snowfall, freezing and increasing atmospheric pressure decrease the exhalation rate, while increasing wind speed and temperature can increase it. In addition, these meteorological parameters can cause a convective flow in the pore space and therefore change the radon flux from the soil.

6.   CREATION OF ^{212}PB

All radon decay products are heavy metals and undergo a series of chemical and physical processes, which are displayed in Figure 27.

During the alpha decay, the alpha particle removes with a high probability two electrons in of the electron shell leaving positive charged clusters which have a high mobility. This mobility, characterized by the diffusion coefficient, chiefly controls the formation of the radioactive aerosol by attachment and the deposition on surfaces.
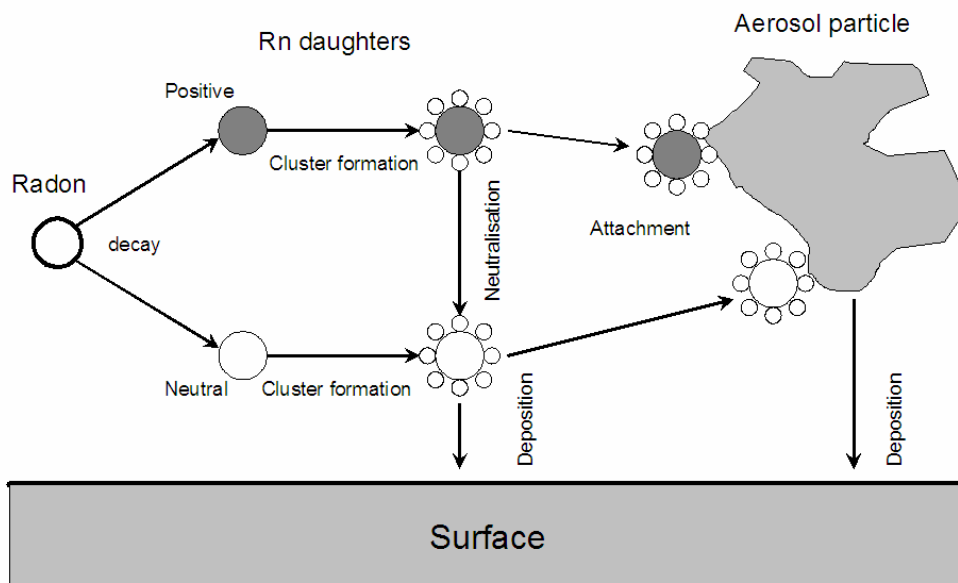
Figure 27 Basic processes of radon decay product behaviour in air

In order to understand the effects of the local radon background on the results of the sampling and measurement of CTBTO samples the ^{220}Rn emanation is linked with the measured ^{212}Pb activity by the following model:

For this model two assumptions are made:

1. The ^{232}Th soil content in the vicinity of the air sampler does not change significantly (e.g. same order of magnitude) and thus a ^{220}Rn point measurement is representative for the local source term.

2. The sampling area/volume is considered closed or any ^{212}Pb activity introduced from "outside" is balanced by the loss of the same amount (i.e. $div\vec{j}(\vec{r}) = 0$).

The ^{212}Pb source term is calculated by

$$C_{Pb} = \frac{\lambda_{Pb}}{\lambda_{Rn} - \lambda_{Pb}} C_{Rn}$$

Equation 10

Using the ^{220}Rn and ^{212}Pb decay constants this results in

$$C_{Pb} = 0.00154 \, C_{Rn}$$

Taking into account the ^{212}Pb half life of 10.64 hours, the maximum (i.e. disregarding any losses not due to radioactive decay) ^{212}Pb concentration at any time t can be calculated by:

$$C_{Pb}(t) = \sum_{k=t-T_0}^{t} c_{Pb}(k) \cdot e^{-\lambda_{Pb} \cdot (t-k)}$$

Equation 11

By starting the calculation with T_0 = 72 (i.e. taking into account the 72 hours prior), the contribution of that nuclides is app. 1% of its original amount.

Assuming that the probability for a ^{212}Pb nucleus be still in the air available for sampling at the sample is proportional to the "age" of the nuclide and the absolute humidity of the air one can define a weighting factor:

$$w_{Pb}(t) = e^{-\frac{k_H \cdot (t-t_0)}{H_{abs}(t_0)}}$$
Equation 12

with

k_H …   normalization factor

$H_{abs}(t_0)$ …   Absolute Humidity in g/kg at the time of ^{212}Pb creation

t_0 …   Time of ^{212}Pb creation

And Equation 11 becomes:

$$C_{Pb}(t) = \sum_{k=t-T_0}^{t} c_{Pb}(k) \cdot e^{-\frac{k_H \cdot (t-k)}{H_{abs}(k)}} \cdot e^{-\lambda_{Pb} \cdot (t-k)}$$
Equation 13

The absolute humidity at the time a ^{212}Pb nucleus is formed is chosen as a probability parameter that this nucleus remains in the air (and as such available for sampling) since particles are attached to water vapor (i.e. droplets).

For the summation intervals (i.e. the minimum difference between t and k) in Equation 13 a value of one hour is deemed appropriate taking into account the variation rate of the ^{220}Rn emanation and the ^{212}Pb half live.

To account for particle losses caused by rain ("wash out") Equation 13 can be re-written to a recursive form including a "precipitation washout factor":

$$C_{Pb}(t) = \frac{1}{1+k_r \cdot r(t-1)} \cdot C_{Pb}(t-1) \cdot e^{-\lambda_{Pb} \cdot (t-1)} + \left(k_0 + k_c \cdot c_{Pb}(t)\right)$$
Equation 14

with:

$r(t)$ …   Precipitation (mm/m^2)

k_r …   precipitation normalization factor

k_0, k_c fitting parameters

The concentration results reported for CTBTO stations assume constant concentration during the sampling process. As this is not true, one needs to compare the activity on the filter at the end of sampling.

The activity at end of sampling can be expressed by:

$$A_{Pb}(T_S) = \sum_{n=t-T_S}^{T_S} F(n) \cdot C_{Pb}(n) \cdot e^{-\lambda_{Pb} \cdot n}$$

Equation 15

with:

F(n) …   sampling flow rate (m^3/h)

7.   MEASUREMENTS PERFORMED

To evaluate the model described in Section 6 the hourly average of the ^{220}Rn concentration was measured in the Atomic Institute of the Austrian Universities (ATI) from 8 March to 8 May 2007. In order to verify it in a high background region as well, measurements were performed at the CTBTO Radionuclide Station RN09 Darwin, Australia from 16 May to 26 June 2007.

The RN09 station is located at the Darwin International Airport next to the Bureau of Meteorology (BOM) weather station. The radionuclide station was designed and built by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). The station was installed in 2001 and data have been used within the IMS network since 1 April 2002. The station was formally certified to comply with all requirements for an IMS Radionuclide station on 19 July 2002. RN09 is also one of the 40 stations defined by the CTBTO PrepCom where equipment for noble gas detection is to be installed.

Figure 28 Overview of RN09 Darwin   **Figure 29 Installed air sampler at RN09**

Figure 30 Detector system

Figure 31 HPGe detector

Figure 32 Sample preparation
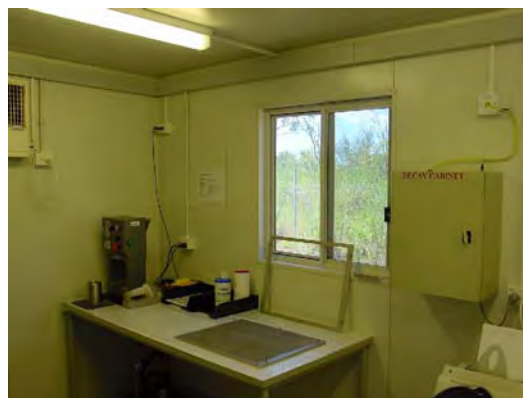
Figure 33 Sample preparation area

Both stations use a Snow White JL-900 high volume air sampler from the company Senya Oy, Finland.

Figure 34 Snow White JL-900 air sampler installed at the Vienna International Centre

The Snow White sampler allows the airflow to be adjusted. In RN09 it has been set to 850 m³/h and at the VIC station to 560 m³/h. The global collection efficiency for the sampling system has been measured [29] to be 92 % and 87 % for 10 µm (AMD) particles at flow rates of 500 m³/h and 700 m³/h respectively. For particles with smaller aerodynamic diameters, the global collection efficiency increases and at AMDs of about 0.3 µm reaches 100 %. The activity size distribution for radon progenies shows that app. 95 % of the activity is attached to particles with AMDs of less than 0.4 µm [30].

The filter material used at both stations is a polypropylene material from 3M (3M 5379) which has a collection efficiency of app. 90 % for 0.2 µm particles at the face velocities used [29].

One can conclude that more than 90 % of the radon progenies particles are sampled by the sampling system if they reach the air sampler.

The gamma detection system used at the CTBTO test station is a BEGE5030 HPGe detector from Canberra, while the RN09 station uses a GMX70 from Ortec. The photo peak detection efficiency at the energy of 238.6 keV (the main gamma emission of ^{212}Pb) is 0.140 ± 0.002 for the CTBTO station and 0.135 ± 0.002 for the RN09 station.

7.1   Experimental setup

To measure the radon concentration a radon detection system RAD7 from the company Durridge was used. This system uses a planar silicon alpha detector which is installed at the centre of a 0.7 liter hemispherical shaped sample cell.

Air is pumped into the sample cell and the alpha particles created by the decay of radon (and progenies) are detected by the Si detector. To exclude any radon progenies of entering the sample cell, the air is filtered by a particle filter.

A voltage of 2200 V is applied between the surface of the sample cell and the Si alpha detector creating an electrical field throughout the volume of the cell. The positively charged radon progenies are driven to the detector surface where they stick to. Any subsequent alpha decay has a 50% efficiency of being detected by the Si detector.

Figure 35 RAD7 Radon Measurement System

The RAD7 produces a 200 channel alpha spectrum with an energy span of 0 to 10 MeV (i.e. 0.05 MeV per channel). The measured spectra are grouped into eight separate energy windows. Four of these windows are used to calculate radon activity levels and available to the user. The four other windows are combined into one and can be used as state-of-health indicator.
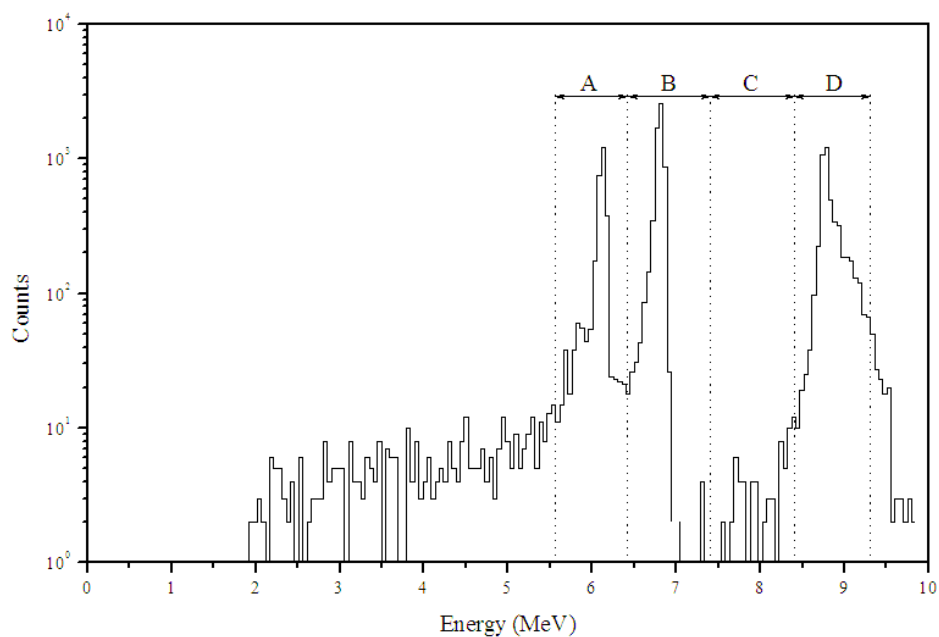
Figure 36 RAD7 alpha spectrum of a ^{220}Rn source

Window	Energy range (MeV)	Nuclides covered
A	5.60 – 6.40	^{218}Po (6.00 MeV) ^{212}Bi (6.05 MeV)
B	6.40 – 7.50	^{216}Po (6.78 MeV)
C	7.50 – 8.40	^{214}Po (7.69 MeV)
D	8.40 – 9.30	^{212}Po (8.78 MeV)

Table 23 RAD7 Energy Windows

Parameter	
Serial Number	1592
^{222}Rn sensitivity, Normal mode	0.013 CPM/(Bq/m^3)
^{222}Rn sensitivity, Sniff mode	0.0063 CPM/(Bq/m^3)
^{222}Rn conversion, Normal mode	76.92 (Bq/m^3)/CPM
^{222}Rn conversion, Sniff mode	158.73 (Bq/m^3)/CPM
Calibration uncertainty	2% (k=1)
Calibration date	30 Sep. – 3 Oct. 2005

Table 24 System information of the RAD7 used

While the RAD7 is not calibrated against an absolute ^{220}Rn standard the manufacturer estimates its ^{220}Rn sensitivity to be 50% of the ^{222}Rn value.

To calculate the ^{220}Rn activity concentration the ^{216}Po alpha counts in Window B were used.

$$C(^{220}Rn)(Bq/m^3) = \frac{cnts(B)}{T} \cdot 2 \cdot conv$$

with:

cnts(B)   Counts in window B (i.e. ^{216}Po decays)

T   Measurement live time (min)

conv ^{222}Rn conversion factor

7.2   Results

Figure 37 shows a comparison of the measured ^{220}Rn concentration at the Atomic Institute of the Austrian Universities (ATI) and the ^{212}Pb activity concentration (assuming constant concentration during sampling) on the CTBTO test station in the Vienna International Centre (VIC).
Figure 38 shows the same comparison with data from the IMS radionuclide monitoring station RN09 Darwin, Australia.

Using the model described in Section 6 one gets a ^{212}Pb activity concentration as displayed in Figure 38 for the CTBTO test station and Figure 42 for the RN09 station.
In both cases the fitting parameters k_r, k_0 and k_c of Equation 14 where retrieved by minimizing the difference of the measured ^{212}Pb activity at the end of the sampling process and the, according to Equation 15, calculated activity.
This fitting process resulted in the following values:

Parameter	CTBTO test station	RN09 Darwin
k_r	0.1	0.04
k_0	0.264	-2.303
k_c	0.201	0.344

Table 25 Fitting parameters for ^{212}Pb calculation

The effect of wash out at the CTBTO test station is shown in Figure 39. It must be noted, however, that only a few samples were affected by rain.

A comparison of the activity at the end of sampling at both stations is shown in Figure 40 for the CTBTO test station and in Figure 43 for the RN09 station.

All results from both stations are displayed in Figure 44 and shown in Annex A in Table 32 and Table 33 for the CTBTO test station and the RN09 station respectively.

As seen in Figure 44, most results from both stations lay very well within a $\pm 20\,\%$ band, which for environmental sampling is to be considered as good agreement. The slightly higher scatter for the CTBTO test station results are most likely due to the lower ^{220}Rn activity concentration and the associated higher measurement uncertainties.
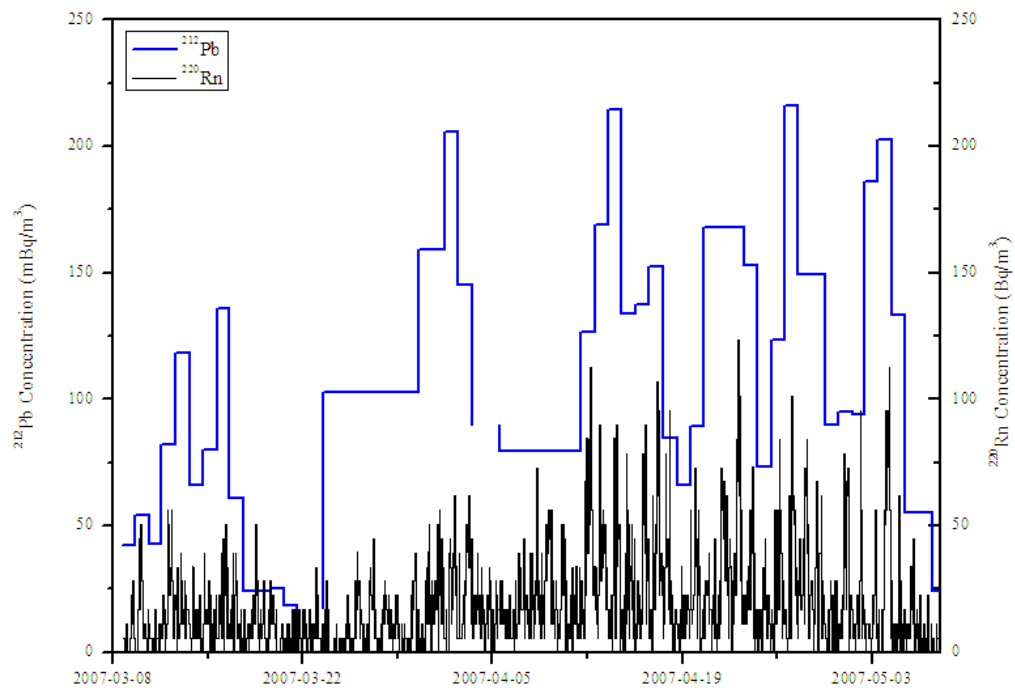
Figure 37 Hourly ^{220}Rn and daily averaged ^{212}Pb activity concentrations at the ATI and the CTBTO test station respectively
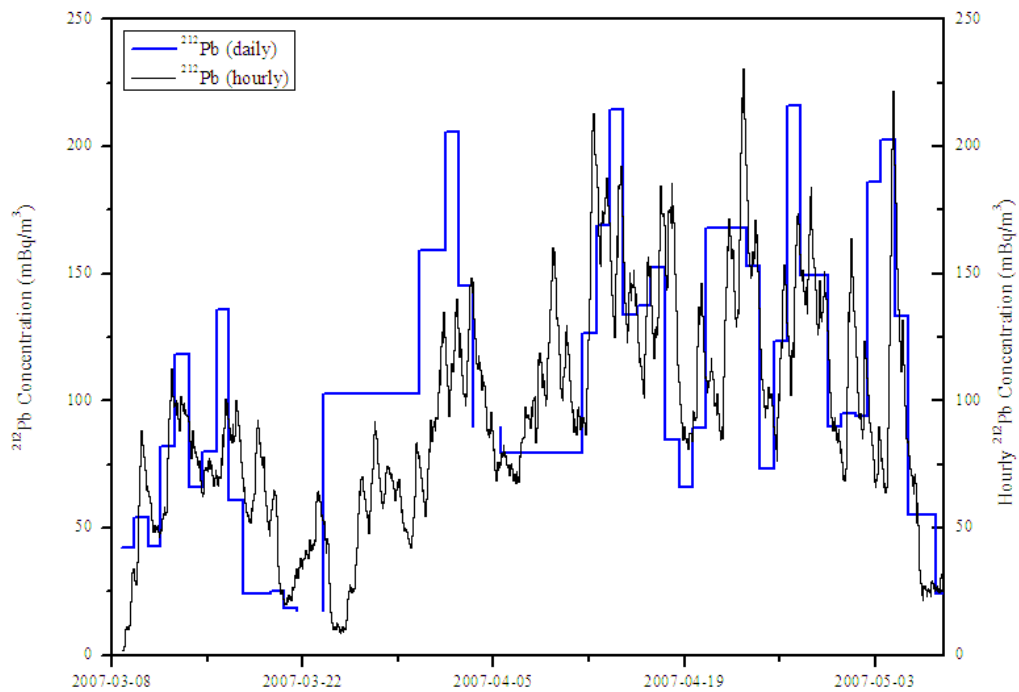
Figure 38 Hourly and daily averaged ^{212}Pb activity concentrations at the ATI and the CTBTO test station respectively
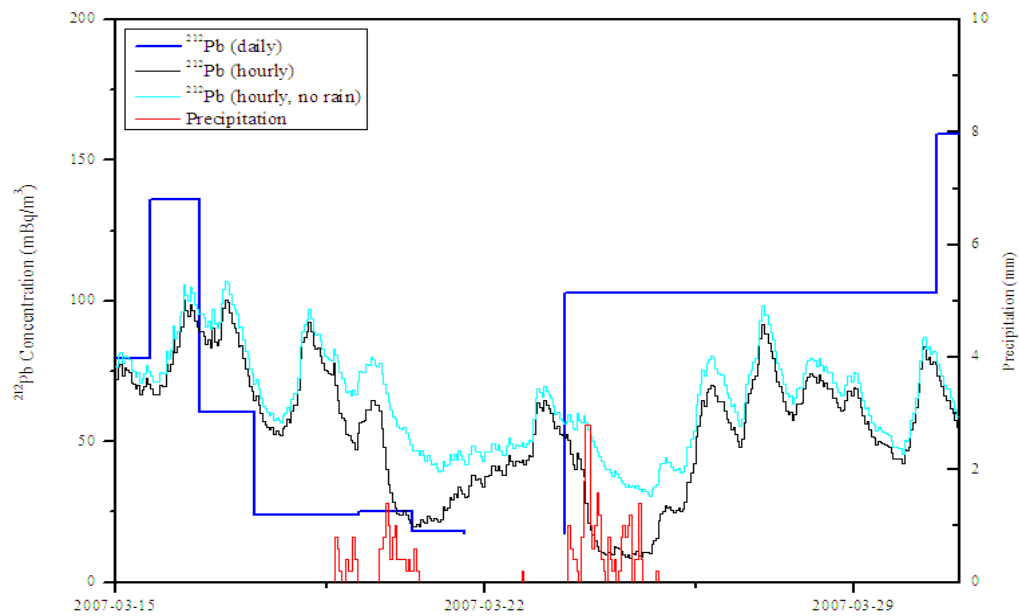
Figure 39 Hourly and daily averaged ^{212}Pb activity concentrations taking precipitation into account at the ATI and the CTBTO test station respectively
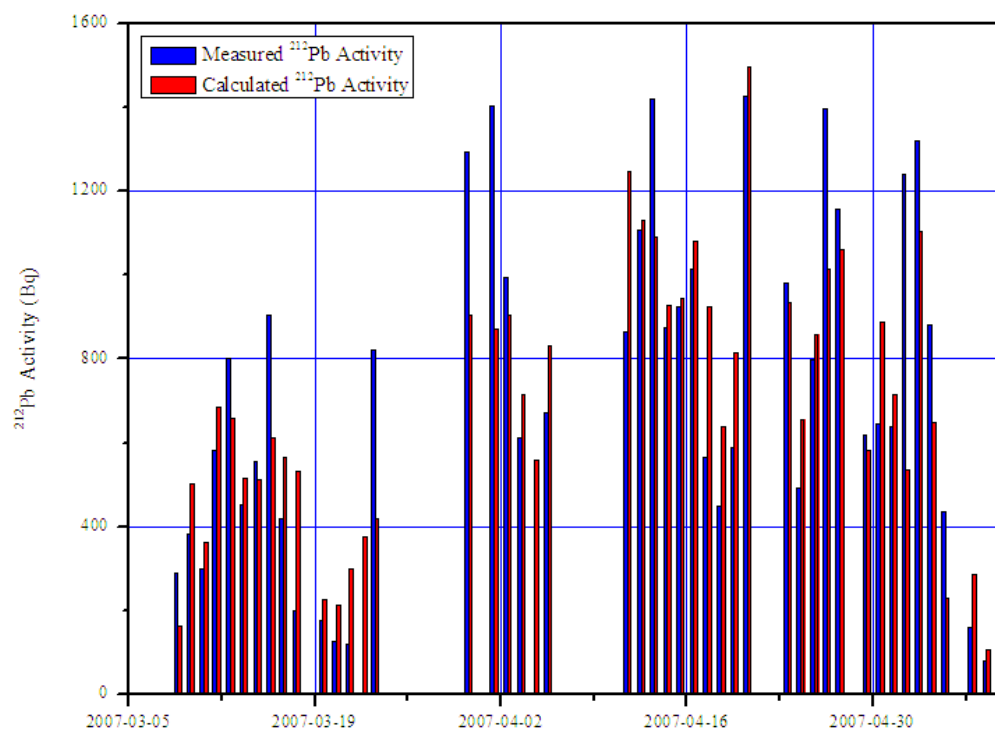
Figure 40 Measured and calculated (expected) ^{212}Pb activity at the end of the sampling process at the CTBTO test station
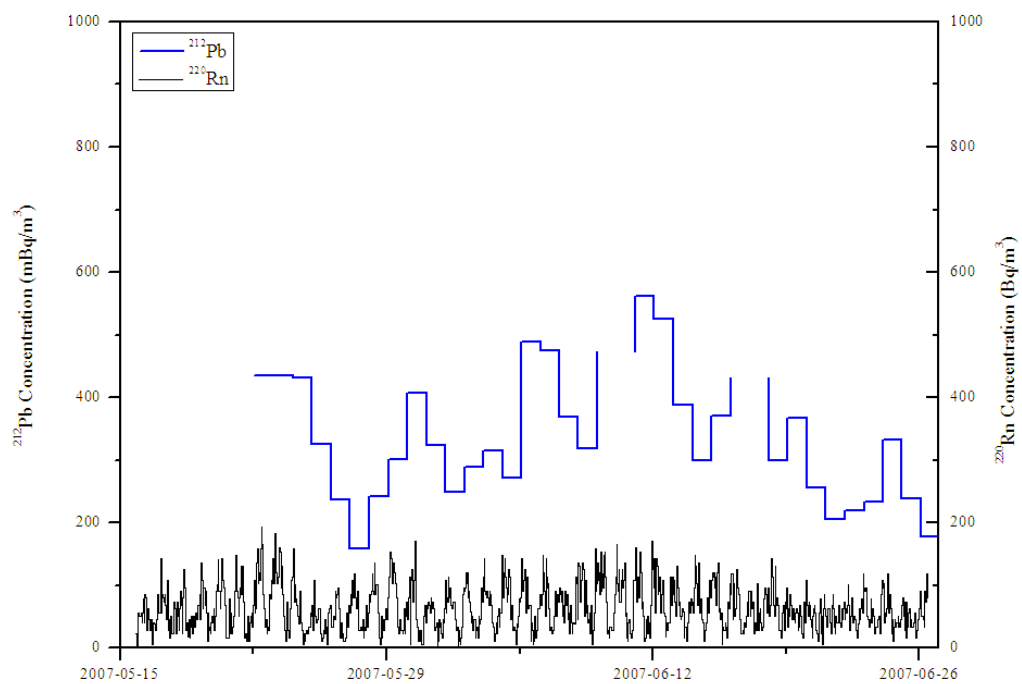
Figure 41 Hourly ^{220}Rn and daily averaged ^{212}Pb activity concentrations at the IMS Station RN09 Darwin, Australia
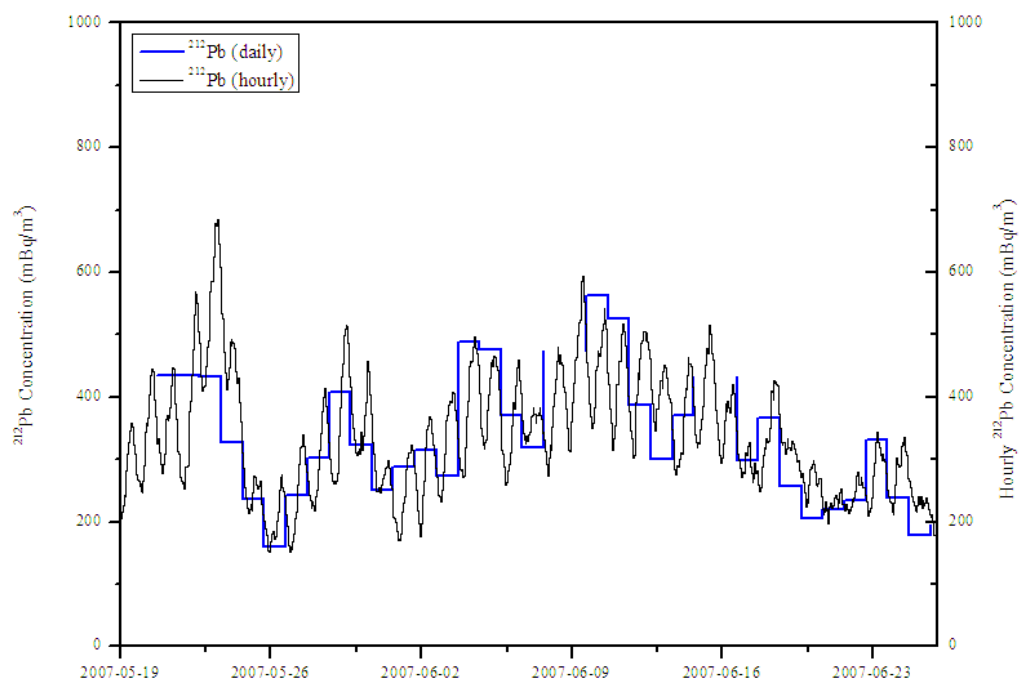
Figure 42 Hourly and daily averaged ^{212}Pb activity concentrations at the IMS Station RN09 Darwin, Australia

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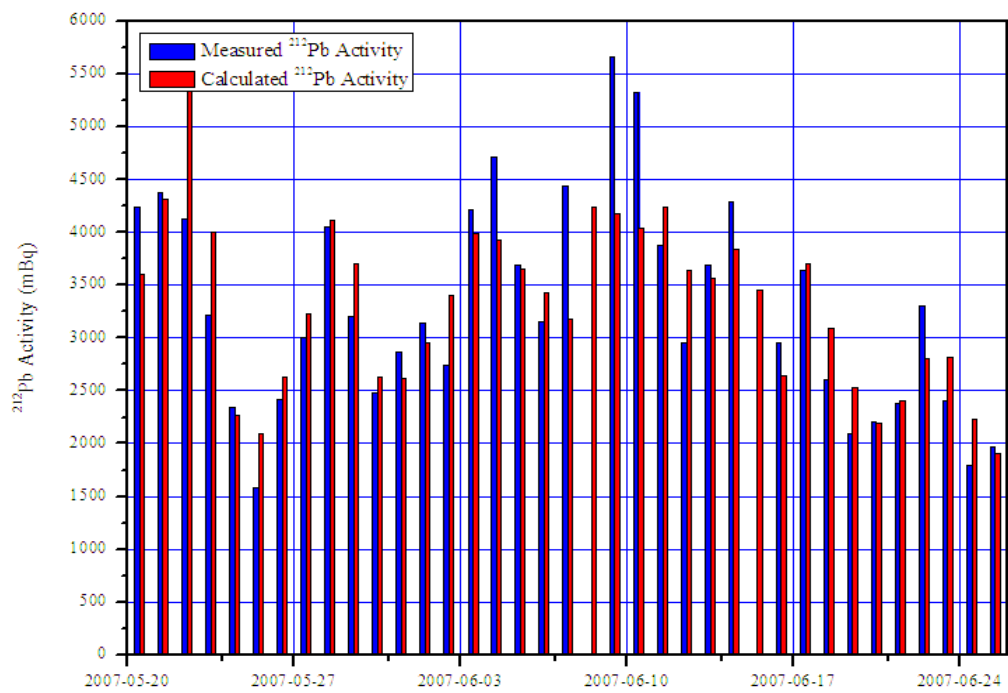
Figure 43 Measured and calculated (expected) ^{212}Pb activity at the end of the sampling process at the IMS Station RN09 Darwin, Australia
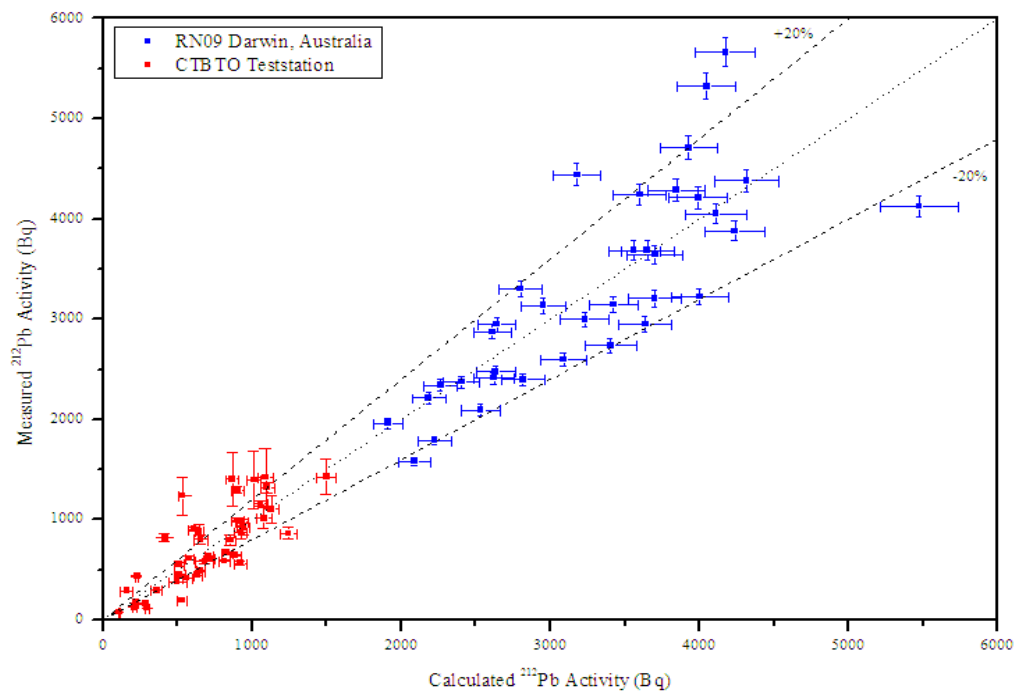
Figure 44 Measured and calculated ^{212}Pb activities at end of sampling, CTBTO test station and the IMS station RN09 Darwin, Australia

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8. EFFECTS OF ^{212}PB DIURNAL VARIATION ON SAMPLED ACTIVITY

Taking into account the diurnal variation of the ^{212}Pb activity concentration, the activity on the filter can be calculated by solving:

$$\frac{dN(t)}{dt} = -\lambda \cdot N(t) + c(t) \cdot F \qquad \textbf{Equation 16}$$

where:

N(t):   Number of nuclides

λ: Decay constant

c(t):   Concentration in air

F: Airflow rate

The time dependent activity concentration can be expressed as

$$c(t) = c_0 + \hat{c} \cdot \cos[\frac{\pi}{12}(t - T_0)] \qquad \textbf{Equation 17}$$

where:

T_0:   Maximum of activity concentration

For IMS radionuclide stations the airflow rate can considered constant since they either deploy flow rate controlled systems or the variations during a 24-hour period are low (< 10%).

Solving Equation 16, using Equation 17 for the time dependent source term c(t) and the boundary condition N(0)=0, results for the sampled activity on the filter at any time during the sampling process:

$$A(t) = \frac{F}{\pi^2 + 12^2 \lambda^2}(c_0 \cdot (1 - e^{\lambda \cdot (-t + T_1)}) \cdot (\pi^2 + 12^2 \cdot \lambda^2) + 12 \cdot \hat{c} \cdot \lambda \cdot (P1 + e^{\lambda \cdot (-t + T_1)} \cdot P2)$$

Equation 18

with:

$$P1 = 12 \cdot \lambda \cdot \cos[\frac{\pi}{12}(t - T_0)] + \sin[\frac{\pi}{12}(t - T_0)]$$

$$P2 = -12 \cdot \lambda \cdot \cos[\frac{\pi}{12}(T_0 - T_1)] + \pi \cdot \sin[\frac{\pi}{12}(T_0 - T_1)]$$

where:

T_1:   Time of sampling start

At the station RN09 the maximum of the ^{212}Pb concentration is seen at about 10:00.
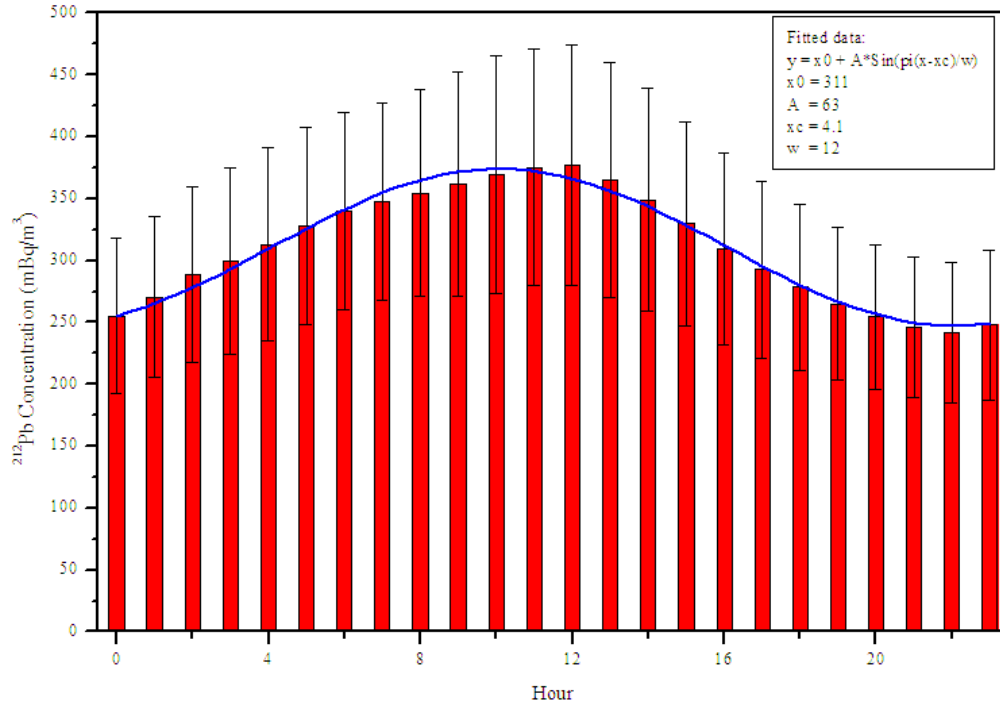
Figure 45 Diurnal variation of ^{212}Pb activity concentrations at RN09 (i.e. average day during the measurement time)

Setting $t = T_1 + 24$ in Equation 18 results in the activity on the filter at the end of a 24-hour sampling period. As can be seen on Figure 46 the minimum ^{212}Pb activity is accumulated when starting the sampling process at about 03:00. There is no analytical solution for the extremes in Equation 18, but numerically one solves the "optimum" time to be 03:02 and the "worst" time at 15:02. The difference in activity between this two starting times is 9.3 %.

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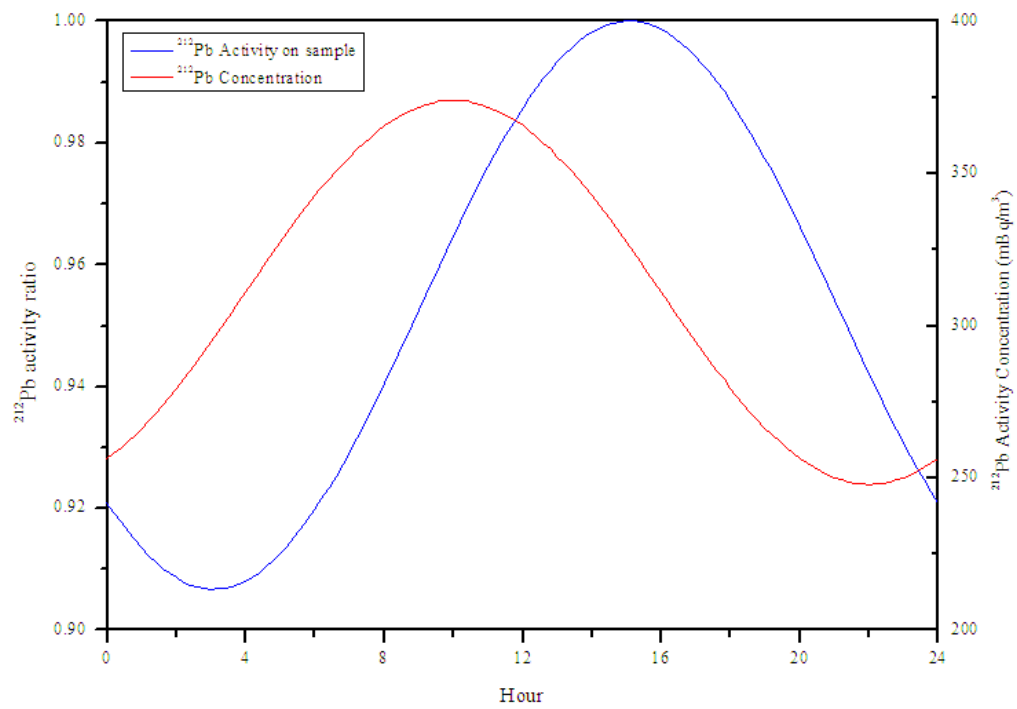
Figure 46 Effect of sampling start time on ^{212}Pb activity on filter at the end of sampling process at RN09

The difference of 9.3% in the ^{212}Pb activity at the end of sampling results in a MDC difference of 4.3%.

9. RADIOLOGICAL ASSESSMENT

When analyzing a radiological situation two points need to be addressed: first the radioactive inventory and, second, the time a person is exposed to the radiation. With this information the effective dose can be calculated.

9.1 Inventory

At an IMS radionuclide station three kind of radioactive sources can be indentified:

Amount	Type	Usage
1	Quality Control	Daily for detector QC measurement
1	Calibration	Detector efficiency calibration
Up to 180	Sample	Samples collected and measured

Table 26 Number and type of radioactive sources at an IMS station

A typical QC source used at an IMS station contains a mixture of ^{60}Co, ^{137}Cs and ^{152}Eu with an activity in the order of 1 kBq for each nuclide. The source has point source geometry, produced by placing the radioactivity inside a sample container and sealing it with an epoxy resin.

Nuclide	Half Live	Activity (kBq)
^{152}Eu	13.537 Y	1.39 ($\pm$ 0.07)
^{137}Cs	30.07 Y	1.18 ($\pm$ 0.06)
^{60}Co	1925.28 D	0.82 ($\pm$ 0.04)

Table 27 Content of a typical QC source

Calibration sources are prepared by drop wise addition of a standardised mixed radionuclide solution containing ^{210}Pb and/or ^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{54}Mn, ^{88}Y, ^{65}Zn and ^{60}Co to a polypropylene filter sheet, as used at

the IMS stations. After drying, the filter is folded and compressed to produce a disk with a diameter of 50 mm and thickness of 4.5 mm to resemble the same sample geometry used. The source is then placed in a sample container which is sealed with epoxy resin. The specific nuclide activities are chosen to keep the overall activity low but still allowing for good counting statistics in a reasonable measurement time (e.g. a few hours).

Nuclide	Half Live	Activity (kBq)
^{210}Pb	22.2 Y	1.09 (± 0.022)
^{241}Am	432.6 Y	0.20 (± 0.002)
^{109}Cd	461.4 D	1.00 (± 0.020)
^{57}Co	271.74 D	0.04 (± 0.001)
^{139}Ce	137.64 D	0.04 (± 0.001)
^{113}Sn	115.09 D	0.13 (± 0.002)
^{85}Sr	64.84 D	0.14 (± 0.002)
^{137}Cs	30.07 Y	0.18 (± 0.002)
^{54}Mn	312.12 D	0.17 (± 0.002)
^{88}Y	106.63 D	0.30 (± 0.004)
^{65}Zn	244.06 D	0.41 (± 0.008)
^{60}Co	1925.28 D	0.20 (± 0.002)

Table 28 Content of a typical calibration source

The QC and calibration sources are stored at the station in small safes made of steel. These are placed away from the detector system to not interfere with the routine measurements.

After being measured, samples are stored up to six months at the station before they are sent to the CTBTO for archiving. During the on-site storage samples are stored in dedicated cupboards.

About five days after end of sampling all ^{212}Pb has decayed and the remaining activity will be from ^{7}Be and ^{210}Pb. The ^{7}Be activity concentration seen

throughout the IMS network is in the range of 2 - 10 mBq/m^3 and the ^{210}Pb activity concentration is about 0.1 – 1 mBq/m^3. With an average sample volume of 19500 m^3 and disregarding radioactive decay during sampling this results in an activity of about 200 Bq for ^{7}Be and 20 Bq for ^{210}Pb at the end of sampling. As seen in Figure 22 and Table 33 the ^{212}Pb activity at the end of sampling is in the range of 1 – 7 kBq. To account for the ^{212}Pb progenies ^{212}Bi and ^{208}Tl assuming equilibrium, this figure needs to be multiplied by 2.503[1].

Using these figures a maximum total activity of the sample storage at an IMS station can be estimated by summing the individual decay corrected activities:

$$A = \sum_{t=0}^{180} \left(A_{Be-7} \cdot e^{-\lambda_{Be-7} \cdot t} + A_{Pb-210} \cdot e^{-\lambda_{Pb-210} \cdot t} \right) + \sum_{t=0}^{5} 2.503 \cdot A_{Pb-212} \cdot e^{-\lambda_{Pb-212} \cdot t} \qquad \textbf{Equation 19}$$

with:

A: Activity of station sample storage

A_{Be-7}: ^{7}Be activity of a sample at the end of sampling; A_{Be-7} = 200 Bq

λ_{Be-7}: ^{7}Be decay constant; λ_{Be-7} = 1.51 · 10^{-7} s^{-1}

A_{Pb-210}:^{210}Pb activity of a sample at the end of sampling; A_{Pb-210} = 20 Bq

λ_{Pb-210}:^{210}Pb decay constant; λ_{Pb-210} = 9.89 · 10^{-10} s^{-1}

A_{Pb-212}:^{212}Pb activity of a sample at the end of sampling; A_{Pb-212} = 7 kBq

λ_{Pb-212}:^{212}Pb decay constant; λ_{Pb-212} = 1.81 · 10^{-5} s^{-1}

t: time in days after end of sampling

When solving Equation 19 one gets a total activity of the station sample storage of 22 kBq.

9.2   Time protocol

The protocols for the daily operation at an IMS station were developed to reduce the time spent at a station. This was primarily done to keep the labour

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[1] The equilibrium factor for ^{212}Bi/^{212}Tl is 1.1049 and for ^{208}Tl/^{212}Pb 0.3986.

costs low but as an additional effect this also minimizes any radiological impact for the operator. The general operations process at an IMS station is shown in Table 29.

Step	Description
1	On entering the station, conduct a visual inspection
2	Go to the station PC and log on
3	Stop the current acquisition
4	Take out the QC source from storage and open the shielding lid
5	Take out the recently measured sample from the detector sample holder and place it in the station sample storage
6	Place the QC source in the sample holder on top of the detector; close the shielding lid
7	Start the QC Acquisition
8	Clean filter cassette elements, take a new filter from the box and place it in the filter cassette
9	Go to the sampler site with the prepared filter cassette and the sampler key
10	Stop the air sampler; change cassettes; turn on the sampler
11	Fold the sample and compress it with the filter press
12	Place the compressed sample in a new sample container
13	Open the decay chamber and take out the sample to be measured
14	Place the recently compressed sample in the decay chamber and close the door
15	When the QC measurement has ended check the QC spectrum for anomalies
16	Open the shielding, take out the QC source and place it in the storage
17	Place the new sample in the sample holder on top of the detector; close the shielding lid
18	Start the sample acquisition
19	If needed, perform any scheduled maintenance actions
20	Verify operational status of all systems and exit the station

Table 29 Standard operations procedure at an IMS station

The overall time spent at the station can be estimated to be one hour. Of this time the operator will handle the QC source for about 5 minutes (steps 4, 6 and 16), the sample that just finished sampling for 10 minutes (steps 10, 11, 12 and 14) and the samples either put on or taken of the detector for 2 minutes (steps 5 and steps 13 and 17).

9.3 Annual effective dose

Assuming point source geometry the effective gamma dose rate can be calculated by $H = \frac{A}{r^2} \cdot \Gamma$ where H is the effective dose rate in mSv/h, A the source activity in Bq, r the distance to the source in m and Γ is the gamma dose rate constant in mSv·m^2/(h·GBq). Calculated effective dose rate for each nuclide and activity from Section 9.1 and tabled values for Γ [33] are shown in Table 30.

Nuclide	Activity (kBq)	Gamma Dose Rate Constant (mSv·m²/(h·GBq))	Effective Dose Rate (nSv/h)				
			10 cm	20 cm	50 cm	1 m	2 m
Be-7	13.79	7.656E-03	10.56	2.64	0.42	0.11	0.03
Pb-210	3.57	4.490E-04	0.16	0.04	0.01	0.00	0.00
Pb-212	1.85	2.069E-02	3.83	0.96	0.15	0.04	0.01
Bi-212	2.05	1.270E-02	2.60	0.65	0.10	0.03	0.01
Tl-208	0.82	3.873E-01	31.76	7.94	1.27	0.32	0.08
Total Sample Storage:			48.9	12.2	2.0	0.5	0.1
Be-7	0.20	7.656E-03	0.15	0.04	0.01	0.00	0.00
Pb-210	0.02	4.490E-04	0.00	0.00	0.00	0.00	0.00
Pb-212	7.00	2.069E-02	14.48	3.62	0.58	0.14	0.04
Bi-212	7.73	1.270E-02	9.82	2.45	0.39	0.10	0.02
Tl-208	3.08	3.873E-01	119.29	29.82	4.77	1.19	0.30
Fresh Sample:			143.7	35.9	5.7	1.4	0.4
Be-7	0.20	7.656E-03	0.15	0.04	0.01	0.00	0.00
Pb-210	0.02	4.490E-04	0.00	0.00	0.00	0.00	0.00
Pb-212	1.47	2.069E-02	3.04	0.76	0.12	0.03	0.01
Bi-212	1.62	1.270E-02	2.06	0.51	0.08	0.02	0.01
Tl-208	0.65	3.873E-01	25.17	6.29	1.01	0.25	0.06

Nuclide	Activity (kBq)	Gamma Dose Rate Constant ($mSv·m^2/(h·GBq)$)	Effective Dose Rate (nSv/h)				
			10 cm	20 cm	50 cm	1 m	2 m
To be measured Sample:			30.4	7.6	1.2	0.3	0.1
Co-60	0.82	3.502E-01	28.72	7.18	1.15	0.29	0.07
Eu-152	1.18	1.353E-01	15.97	3.99	0.64	0.16	0.04
Cs-137	1.39	8.787E-02	12.21	3.05	0.49	0.12	0.03
Total QC Source:			56.9	14.2	2.3	0.6	0.1
Pb-210	1.09	4.490E-04	0.05	0.01	0.00	0.00	0.00
Am-241	0.20	6.784E-03	0.14	0.03	0.01	0.00	0.00
Cd-109	1.00	3.047E-02	3.05	0.76	0.12	0.03	0.01
Co-57	0.04	1.504E-02	0.06	0.02	0.00	0.00	0.00
Ce-139	0.04	3.142E-02	0.13	0.03	0.01	0.00	0.00
Sn-113	0.13	7.821E-02	1.02	0.25	0.04	0.01	0.00
Sr-85	0.14	7.928E-02	1.11	0.28	0.04	0.01	0.00
Cs-137	0.18	8.787E-02	1.58	0.40	0.06	0.02	0.00
Mn-54	0.17	1.253E-01	2.13	0.53	0.09	0.02	0.01
Y-88	0.30	3.579E-01	10.74	2.68	0.43	0.11	0.03
Zn-65	0.41	8.112E-02	3.33	0.83	0.13	0.03	0.01
Co-60	0.20	3.502E-01	7.00	0.07	0.28	0.07	0.02
Total Calibration Source:			30.3	5.9	1.2	0.3	0.1

Table 30 Effective dose rate at various distances

Using the estimates for the time spent at the station from Section 9.2 and assuming that the same person will operate the station each day, the annual effective dose for an operator adds up to 530 nSv for the QC source handling (at a distance of 10 cm), 180 nSv for the sample storage (distance 1 m), 865 nSv for the handling of the fresh sample (distance 20 cm) and 1 nSv for the handling of the measured sample (distance 10 cm). Summing these values results in a maximal additional effective annual effective dose for the operator of 1.6 µSv.

Average radiation dose from natural sources [21] are shown in Table 31.

Source	Worldwide average annual effective dose (mSv)	Typical range (mSv)
External exposure		
Cosmic rays	0.4	0.3 - 1.0 [a]

Source	Worldwide average annual effective dose (mSv)	Typical range (mSv)
Terrestrial gamma rays	0.5	0.3 - 0.6 [b]
Internal exposure		
Inhalation (mainly radon)	1.2	0.2 - 10 [c]
Ingestion	0.3	0.2 - 0.8 [d]
Total	2.4	1 - 10

Table 31 Average radiation dose from natural sources

[a] Range from sea level to high ground elevation
[b] Depending on radionuclide composition of soil and building materials
[c] Depending on indoor accumulation of radon gas
[d] Depending on radionuclide composition of foods and drinking water

Comparing the additional annual 1.6 µSv resulting from the work at the radionuclide station for operator with the average annual effective dose value from 2.4 mSv it can be concluded that the work at an IMS radionuclide station does not contribute significantly to the overall effective dose.

10. CONCLUSIONS

A model allowing the correlation of the local ^{220}Rn background and the sampled radioactivity of its progenies has been established.

Based on the measurement results from two environmental monitoring stations it was shown that the variation of the sampled ^{212}Pb activity can be fully explained by the diurnal variation of the local ^{220}Rn activity concentration.

The analysis of the ^{212}Pb activity concentration over a long time allowed the definition of an average day which was used to estimate the sampled radioactivity in relation to the sampling start time.

Analysis of this data showed that the difference in sampled ^{212}Pb radioactivity between the "best" and "worst" case is around 9%. Such activity difference results in an improvement of 4.3% for the detection capability of CTBT relevant radionuclides. Even an improvement of 4.3% at one station does positively affect the overall network performance, hence improving the detection probability for a nuclear test.

Example:

During a System Wide Performance Test in 2005 a filter sample from the station RN04 in Melbourne, Australia, was spiked with small amounts of radioactivity to test the analysis capabilities of the IDC and IMS laboratories. The spike included 0.053 Bq of ^{60}Co corresponding to an activity concentration of 2.95 µBq/m^3. The automatic analysis of the spectrum did not identify ^{60}Co. Manual review, however, did provide a small peak at 1173.2 keV (see Figure 47) but the second ^{60}Co line at 1332.5 keV was not found (see Figure 48) and also its manual insertion was not justified.
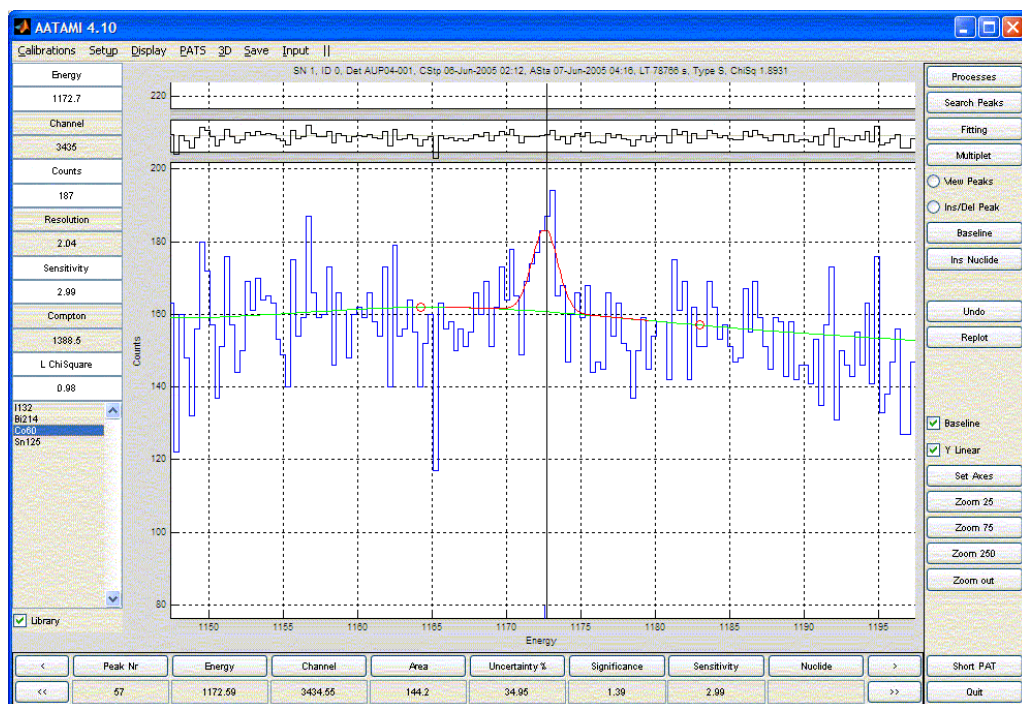
Figure 47 1173.2 keV ^{60}Co peak identified
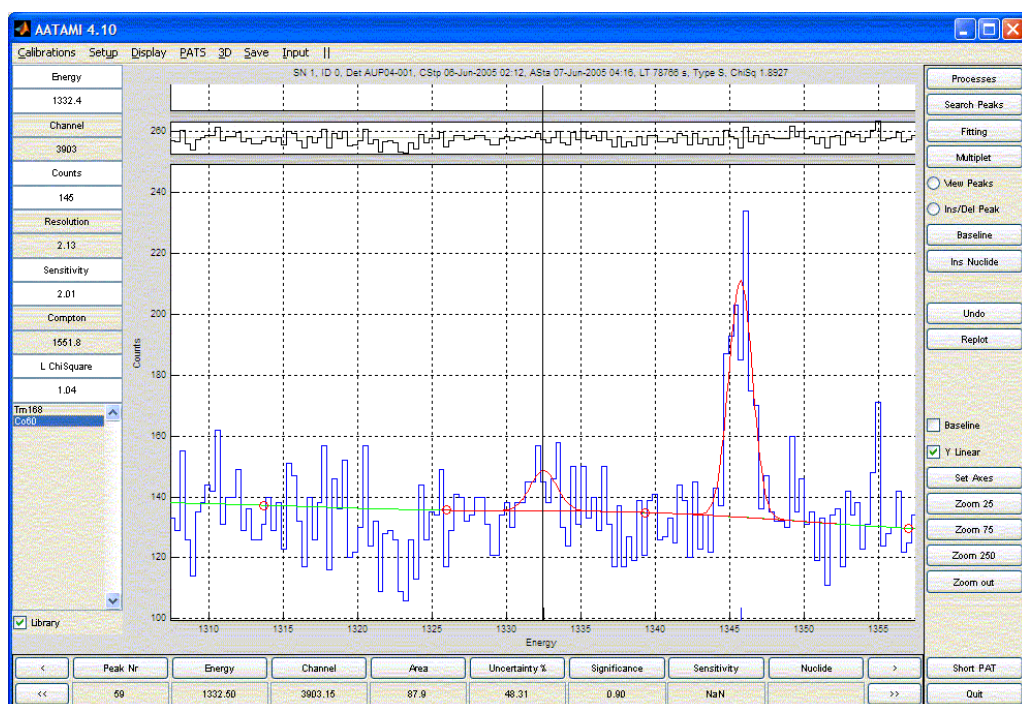
Figure 48 1332.5 keV ^{60}Co Region of Interest (the peak shown was manually inserted)

If the station sensitivity had been improved by 4%, the 1173.2 keV peak would have been identifiable already in automatic processing and, most likely, also the 1332.5 keV peak reducing the risk of missing a nuclide during analysis and also reducing the analysts time, as the review for Level I (false positive) errors require less time than correcting for Level II (false negative) errors.

The radionuclide station RN09 Darwin, Australia is one of the stations having the highest ^{212}Pb background and any improvement possibility must be taken into account. For stations with lower ^{212}Pb background the positive effect, however, would be smaller.

To achieve this positive effect requires the filter change to be performed at around 03:00 local time. This, however, is at manually operated stations not possible or very impractical. At automatic station such sample change time is from routine operations point of view not advisable as any manual interaction or intervention with the system during the sample change process is not possible for the same reasons.

The radiological assessment showed that the work at the radionuclide station does not contribute significantly to the overall annual effective dose for the operators.

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ANNEX A

Collection Start	Sampling Duration	Sample Volume	Decay Duration	Acquisition Start	Acquisition Duration	Activity at Collect Stop	Unc.	Calc. Activity	Unc.
	h	m^3	h		h	Bq	%	Bq	%
2007-03-08 17:11	23.0	13228.7	23.5	2007-03-10 15:41	22.4	288.8	0.8	160.4	26.2
2007-03-09 16:10	24.4	14012.1	21.7	2007-03-11 14:16	23.8	380.7	1.3	499.5	12.2
2007-03-10 16:32	22.6	13227.6	24.4	2007-03-12 15:30	23.4	297.2	0.2	360.6	10.3
2007-03-11 15:08	25.2	14488.4	22.7	2007-03-13 15:04	22.9	581.9	2.9	684.1	8.7
2007-03-12 16:21	23.6	13282.1	24.6	2007-03-14 16:34	22.6	802.2	6.1	657.4	8.4
2007-03-13 15:56	25.5	14014.5	23.0	2007-03-15 16:26	21.8	452.7	1.9	515.5	8.1
2007-03-14 17:25	23.8	13691.5	21.2	2007-03-16 14:25	23.8	554.7	2.8	512.6	8.4
2007-03-15 17:15	22.0	12532.7	24.1	2007-03-17 15:24	23.8	906.2	1.8	611.1	8.6
2007-03-16 15:16	25.0	13971.9	46.6	2007-03-19 14:54	23.8	418.0	0.4	565.4	8.4
2007-03-17 16:16	47.4	26557.3	23.5	2007-03-20 15:10	23.3	197.8	0.0	532.7	8.7
2007-03-19 15:42	24.3	13925.3	22.8	2007-03-21 14:51	23.7	176.1	0.3	225.5	9.3
2007-03-20 16:01	23.5	13556.7	23.4	2007-03-22 14:58	21.8	126.2	0.1	213.0	10.4

Collection Start	Sampling Duration	Sample Volume	Decay Duration	Acquisition Start	Acquisition Duration	Activity at Collect Stop	Unc.	Calc. Activity	Unc.
	h	m^3	h		h	Bq	%	Bq	%
2007-03-21 15:36	24.2	13935.2	21.2	2007-03-23 12:59	23.8	120.5	0.1	298.5	11.8
2007-03-22 15:50	22.0	12619.3	169.0	2007-03-30 14:53	23.8	0.0	0.0	375.4	11.8
2007-03-23 13:51	168.9	87828.2	46.7	2007-04-01 13:28	23.8	819.9	4.7	417.6	10.1
2007-03-30 14:44	46.6	25897.6	24.5	2007-04-02 13:50	23.8	1294.6	2.4	903.2	8.7
2007-04-01 13:18	24.4	13635.5	25.5	2007-04-03 15:13	21.9	1404.1	18.7	870.3	7.4
2007-04-02 13:41	25.4	13990.8	24.6	2007-04-04 15:41	21.8	994.8	2.0	904.9	7.0
2007-04-03 15:05	24.4	13676.7	23.1	2007-04-05 14:39	23.8	613.1	3.6	716.0	7.1
2007-04-04 15:32	23.0	13322.7	143.8	2007-04-11 14:20	23.8	0.0	0.0	559.0	7.5
2007-04-05 14:30	143.7	79216.9	25.5	2007-04-12 15:41	22.9	671.7	0.6	832.3	7.6
2007-04-11 14:14	25.3	13948.0	23.2	2007-04-13 14:44	23.3	864.8	7.1	1247.0	6.9
2007-04-12 15:32	23.0	12639.3	24.3	2007-04-14 14:55	23.5	1106.5	12.7	1129.8	6.6
2007-04-13 14:35	24.2	13162.8	23.8	2007-04-15 14:34	23.8	1420.9	20.4	1091.5	6.3
2007-04-14 14:46	23.6	12815.6	24.9	2007-04-16 15:21	23.3	874.7	7.9	926.5	6.4

Collection Start	Sampling Duration	Sample Volume	Decay Duration	Acquisition Start	Acquisition Duration	Activity at Collect Stop	Unc.	Calc. Activity	Unc.
	h	m^3	h		h	Bq	%	Bq	%
2007-04-15 14:25	24.6	13508.5	24.3	2007-04-17 15:19	22.9	924.8	8.4	944.9	6.6
2007-04-16 15:02	24.1	13185.6	25.4	2007-04-18 16:36	22.3	1013.9	10.4	1081.1	6.6
2007-04-17 15:10	25.3	13661.6	23.3	2007-04-19 15:46	23.2	565.4	3.1	922.8	6.5
2007-04-18 16:27	23.2	13168.4	23.7	2007-04-20 15:21	23.8	447.9	0.4	636.5	6.8
2007-04-19 15:38	23.6	12867.3	73.3	2007-04-23 16:28	22.9	588.5	1.1	813.9	7.0
2007-04-20 15:13	73.1	40859.4	23.2	2007-04-24 15:32	23.8	1428.3	12.4	1498.7	6.9
2007-04-23 16:20	23.1	12396.5	25.2	2007-04-25 16:37	22.8	980.4	2.1	933.5	6.3
2007-04-24 15:23	25.1	13627.6	23.1	2007-04-26 15:36	23.3	490.1	2.3	655.7	6.6
2007-04-25 16:28	23.0	12435.2	23.6	2007-04-27 15:04	23.8	796.3	6.8	857.7	7.0
2007-04-26 15:27	23.5	12632.0	48.1	2007-04-29 14:59	23.8	1397.4	20.7	1014.1	7.1
2007-04-27 14:56	47.9	25387.3	24.8	2007-04-30 15:36	23.3	1158.7	2.1	1060.3	6.6
2007-04-29 14:51	24.6	13814.7	23.7	2007-05-01 15:07	22.3	616.9	3.6	581.4	6.9
2007-04-30 15:27	23.5	13220.0	22.6	2007-05-02 13:34	23.4	643.5	0.9	887.6	7.2

Collection Start	Sampling Duration	Sample Volume	Decay Duration	Acquisition Start	Acquisition Duration	Activity at Collect Stop	Unc.	Calc. Activity	Unc.
	h	m^3	h		h	Bq	%	Bq	%
2007-05-01 15:01	22.4	12901.9	23.8	2007-05-03 13:14	23.3	637.0	0.8	713.5	7.5
2007-05-02 13:27	23.5	13038.0	23.7	2007-05-04 12:44	23.8	1239.6	15.2	536.0	7.5
2007-05-03 13:00	23.6	12756.4	24.9	2007-05-05 13:28	23.4	1319.4	3.8	1104.6	7.2
2007-05-04 12:36	24.7	13335.8	48.8	2007-05-07 14:07	23.8	883.0	7.9	647.4	7.1
2007-05-05 13:20	48.7	26096.4	25.5	2007-05-08 15:32	23.8	435.3	1.3	229.7	7.8
2007-05-07 14:00	25.4	13603.7	25.2	2007-05-09 16:33	21.3	159.0	0.3	285.4	10.9
2007-05-08 15:24	25.0	13732.5	23.2	2007-05-10 15:38	23.6	80.0	0.1	107.2	11.6

Table 32 Sample details, measured and calculated (expected) [212]Pb activity at end of sampling from the CTBTO test station

Collection Start	Sampling Duration	Sample Volume	Decay Duration	Acquisition Start	Acquisition Duration	Activity at Collect Stop	Unc.	Calc. Activity	Unc.
	h	m^3	h		h	Bq	%	Bq	%
2007-05-22 01:09	25.0	20455.0	24.1	2007-05-24 02:17	22.3	4382.2	2.5	4316.2	4.9
2007-05-23 02:12	24.0	18849.0	24.2	2007-05-25 02:20	22.9	4125.9	2.5	5474.7	4.8
2007-05-24 02:11	24.0	19543.0	24.1	2007-05-26 02:19	22.9	3223.3	2.5	4002.1	4.8
2007-05-25 02:12	24.0	19596.0	24.1	2007-05-27 02:17	22.9	2341.9	2.5	2264.8	4.8
2007-05-26 02:12	23.9	19587.0	24.2	2007-05-28 02:23	22.8	1582.2	2.5	2092.3	5.1
2007-05-27 02:09	24.1	19708.0	24.2	2007-05-29 02:25	22.7	2412.8	2.5	2623.8	5.2
2007-05-28 02:15	24.0	19660.0	24.0	2007-05-30 02:19	22.9	2999.8	2.5	3231.9	5.1
2007-05-29 02:18	23.8	19583.0	24.1	2007-05-31 02:16	23.0	4050.2	2.5	4111.0	5.0
2007-05-30 02:10	24.0	19604.0	24.1	2007-06-01 02:17	22.9	3208.1	2.5	3700.8	4.9
2007-05-31 02:09	24.0	19612.0	24.1	2007-06-02 02:17	22.9	2476.9	2.5	2635.1	4.9
2007-06-01 02:09	24.0	19710.0	24.1	2007-06-03 02:18	22.8	2874.1	2.5	2612.9	5.0
2007-06-02 02:10	24.0	19736.0	27.8	2007-06-04 06:00	20.2	3138.4	2.5	2952.6	5.1

Collection Start	Sampling Duration	Sample Volume	Decay Duration	Acquisition Start	Acquisition Duration	Activity at Collect Stop	Unc.	Calc. Activity	Unc.
	h	m^3	h		h	Bq	%	Bq	%
2007-06-03 02:11	24.5	20104.0	23.7	2007-06-05 02:23	22.8	2736.7	2.5	3405.3	5.0
2007-06-04 02:40	23.6	16887.0	24.2	2007-06-06 02:27	18.0	4210.5	2.5	3993.8	4.9
2007-06-05 02:16	23.9	19537.0	24.2	2007-06-07 02:20	22.9	4709.6	2.5	3927.5	4.9
2007-06-06 02:11	24.0	19739.0	24.2	2007-06-08 02:20	22.8	3688.5	2.5	3649.7	4.9
2007-06-07 02:12	24.0	19526.0	24.2	2007-06-09 02:23	22.8	3148.3	2.5	3426.0	4.9
2007-06-08 02:14	24.0	18560.0	24.1	2007-06-10 02:21	22.9	4443.2	2.5	3180.1	4.9
2007-06-09 02:12	24.0	0.0	23.0	2007-06-11 01:14	25.0	0.0	0.0	4240.4	4.8
2007-06-10 02:13	23.9	19893.0	24.1	2007-06-12 02:17	22.9	5663.1	2.5	4175.5	4.8
2007-06-11 02:10	24.0	20062.0	24.1	2007-06-13 02:16	22.9	5322.0	2.5	4046.8	4.8
2007-06-12 02:11	24.0	19759.0	24.2	2007-06-14 02:22	22.8	3879.3	2.5	4236.8	4.8
2007-06-13 02:09	24.1	19467.0	24.0	2007-06-15 02:16	22.9	2951.4	2.5	3637.9	4.8
2007-06-14 02:14	23.9	19632.0	24.2	2007-06-16 02:20	22.9	3689.4	2.5	3561.4	4.9
2007-06-15 02:08	24.0	19655.0	24.1	2007-06-17 02:15	22.9	4287.7	2.5	3845.2	4.9

Collection Start	Sampling Duration	Sample Volume	Decay Duration	Acquisition Start	Acquisition Duration	Activity at Collect Stop	Unc.	Calc. Activity	Unc.
	h	m^3	h		h	Bq	%	Bq	%
2007-06-16 02:11	23.9	3.0	24.3	2007-06-18 02:24	22.8	3.6	3.9	3454.2	4.9
2007-06-17 02:08	24.1	19590.0	24.1	2007-06-19 02:21	22.8	2949.1	2.5	2642.9	4.9
2007-06-18 02:15	23.9	19615.0	24.2	2007-06-20 02:21	22.0	3644.4	2.5	3703.7	5.0
2007-06-19 02:12	24.0	20049.0	24.1	2007-06-21 02:19	22.9	2599.5	2.5	3090.3	5.0
2007-06-20 02:13	24.0	20152.0	24.1	2007-06-22 02:18	22.9	2097.5	2.5	2534.1	5.0
2007-06-21 02:12	24.0	19956.0	24.6	2007-06-23 02:49	22.0	2213.3	2.5	2187.3	5.1
2007-06-22 02:12	24.5	20389.0	23.6	2007-06-24 02:17	22.9	2376.0	2.5	2406.8	5.1
2007-06-23 02:42	23.5	19448.0	24.2	2007-06-25 02:21	23.3	3304.3	2.5	2802.2	5.1
2007-06-24 02:10	24.0	19894.0	24.1	2007-06-26 02:18	22.9	2399.6	2.5	2817.8	5.1
2007-06-25 02:14	23.9	19824.0	24.1	2007-06-27 02:15	23.0	1787.3	2.5	2226.7	5.1
2007-06-26 02:11	23.9	19828.0	24.2	2007-06-28 02:16	22.9	1962.1	2.5	1911.5	5.1

Table 33 Sample details, measured and calculated (expected) [212]Pb activity at end of sampling from the IMS Station RN09 Darwin, Australia

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                               Wien
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