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A Review of Nuclear Testing by the Soviet Union at Novaya Zemlya, 1955–1990

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The Novaya Zemlya Test Site was used by the Soviet Union for many different types of nuclear weapons tests and nuclear effects tests. Taking our information principally from numerous books and papers in Russian published from 1988 to 2003, we describe the test site history and facilities, the early underwater tests, the many atmospheric tests from 1957 to 1962, and the underground tests in adits and shafts from 1964 to 1990. Each test often entailed several nuclear explosions fired simultaneously. We describe the largest group underground test (about 4.2 mt on 12 September 1973), which was conducted in a unique combination of horizontal adit and vertical shaft; and comment briefly on radioactive releases, which were substantial for some tests. In many but not all cases, the Soviet Union's nuclear tests at Novaya Zemlya followed similar tests conducted by the United States.

INTRODUCTION

With the end of the Cold War, extensive new information has become available in the Russian Federation on the conduct of nuclear weapons testing by the Soviet Union over more than three decades. At Novaya Zemlya (Russian for "New Land"), a total of 130 tests were carried out high in the atmosphere, at low levels above water, at the water/air interface, below water, and underground. These 130 tests entailed 224 separate explosive devices, including by far the largest atmospheric and underground tests of the Soviet Union, and that country's only tests above and below water. About 265 megatons of nuclear explosive energy was released at Novaya Zemlya from 1955 to 1990, in some of the

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most extreme environments to be found anywhere on Earth. Contamination by radionuclides is apparent at some locations there today.

Here we review the available information on nuclear testing at Novaya Zemlya, paying particular attention to new information on the largest tests (atmospheric and underground), and the Soviet Union's only tests above and below water. Separate papers are in preparation on details of the 39 underground nuclear tests, giving best estimates of locations and yields.[1]

Following World War II, the Soviet Union's major programs of nuclear weapon development resulted in that county's first nuclear device, named RDS-1 (standing for Rossia Delaet Sama, meaning "Russia does it itself"). It was first tested in Kazakhstan on 29 August 1949, at what became known as the Semipalatinsk Test Site (STS). Until the mid-1950s, all Soviet nuclear tests were conducted above ground at STS. But in 1954 the first Soviet nuclear torpedo (the antiship weapon T-5) was under development and shortly became ready for testing. The Soviet military was eager to test it in a more realistic situation, requiring a site near a seacoast, and Novaya Zemlya was selected at that time for what became the first test in that region, an underwater test on 21 September 1955.

Extensive nuclear testing continued in Kazakhstan, including an atmospheric test with yield around 1.6 megatons on 22 November 1955, which resulted in significant radioactive fallout in Eastern Kazakhstan and West Siberia, and detection of significant radioactive debris as far east as Japan. Many physicians and biologists, now able to observe the long-term medical effects of the Hiroshima and Nagasaki bombings, charged that atmospheric tests would carry radioactive material worldwide, causing a genetic hazard that would be particularly damaging if cumulative doses occurred from fallout. In 1954, fallout from the US 15 megaton test "BRAVO" had contaminated a Japanese fishing boat, causing the death of one man and the serious illness of several others. It thus became clear to Soviet leaders that the Semipalatinsk Test Site was unsuited to large-scale atmospheric testing. After evaluating alternative locations in summer 1957, Novaya Zemlya was selected as the site for multimegaton atmospheric tests as well as for tests underwater—despite the harsh environment far above the Arctic Circle, and proximity to the Russian mainland and Europe. Eighty-five atmospheric nuclear tests (ANTs) are officially listed as having taken place at Novaya Zemlya from the first on 24 September 1957 to the last on 25 December 1962. Eventually this site was also used, following the Limited Test Ban Treaty of 1963, for the Soviet Union's largest underground nuclear tests (UNTs), which peaked in the early 1970s prior to limitations imposed in March 1976 by the Threshold Test Ban Treaty.

Nuclear testing on the Novaya Zemlya archipelago has been conducted in two separate areas, as indicated in Figure 1. The northern test site (NZNTS) is much larger, as can be seen from Table 1, and includes the location of the largest atmospheric tests, conducted in 1961 and 1962, although testing since 1963

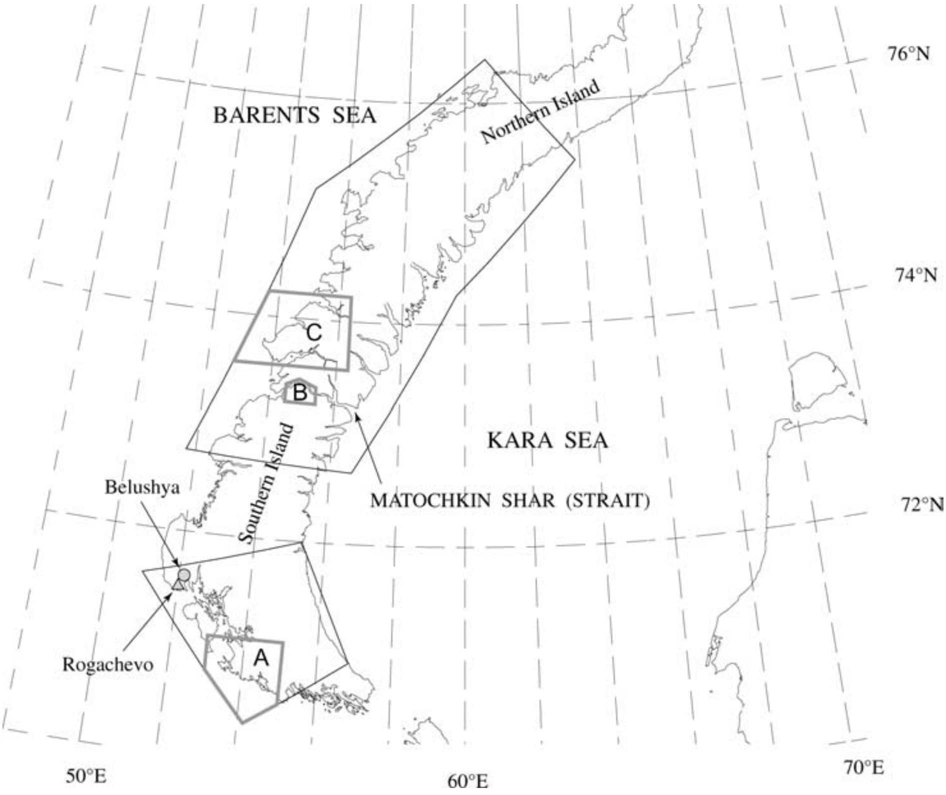

Figure 1: Boundaries of the testing subareas of the Novaya Zemlya Test Site (NZTS). A, B, and C denote three main areas (zones) of military activity: A = Guba (Bay) Chernaya. Six nuclear explosions (underwater, above water, and at the ground surface) were conducted in this area during 1955–1962. Six underground nuclear tests were carried out in shafts during 1972–1975. Further details are shown in Figure 2. B = Guba Mityushikha, south bank of Matochkin Shar. This was the area for underground nuclear tests conducted in adits (tunnels). A total of 33 UNTs were exploded in this area in 36 tunnels. Further details are shown in Figure 4. C = Sukhoy Nos Cape and its vicinity. A special zone, chosen for very large atmospheric nuclear explosions, including the most powerful test (58 mt, 30 October 1961). **Military settlements**: Belushya (open circle)—administrative and scientific center and NZTS headquarters. Rogachevo (open triangle)—settlement and airport, equipped with a long runway for any type of military or civilian planes.

has taken place only underground in a relatively small region (approximately 22 km by 18 km) just to the south of the strait called Matochkin Shar between the main northern and southern Novaya Zemlya islands. The southern test site (NZSTS) includes the locations of underwater and above water tests, some

Table 1: Areas of the Northern and Southern parts of NZTS (km^2).

Subareas	Land	Water	Total
Northern	40400	29800	70200
Southern	14800	6200	21000
Total	55200	36000	91200

relatively small yield atmospheric tests (in the range 1 to 100 kilotons), and six underground tests (the last, in 1975) in deep shafts.

In sections below, we describe: our principal sources of information; the physical environment of nuclear testing at Novaya Zemlya; some basic properties of seismic wave propagation in this region; the test site history and its basic infrastructure; the underwater, above water, and surface nuclear tests of the period 1955 to 1962; the atmospheric tests from 1957 to 1962; underground nuclear testing from 1964 to 1990, with some details on the largest underground test (approximately 4.2 megatons on 12 September 1973); and brief commentary on accidents, radioactive contamination, and hydronuclear and hydrodynamic experiments.

The history of nuclear testing is a remarkable component of power struggles between East and West in the 20th century. Today in Russia, Novaya Zemlya plays a role similar to that played for the United States by the Nevada Test Site. Thus, parts of Novaya Zemlya are currently in active use for nuclear experiments conducted by the Russian Federation since signing the Comprehensive Nuclear-Test-Ban Treaty in 1996. The current continuation of nuclear experiments on the archipelago increases the relevance of documenting and understanding its nuclear testing history.

PRINCIPAL SOURCES OF INFORMATION

Almost all technical information about Soviet nuclear tests was classified during the Soviet era until 1987. In that year, when testing resumed following a unilateral testing moratorium declared by President Gorbachev in 1985 and in effect from late 1985 through all of 1986, announcements about underground nuclear tests (UNTs) began to be published in newspapers (the day after the test was done). Information derived from seismograms such as coordinates of the explosion source, origin time, and magnitude, began to be published in seismological bulletins, and eventually seismograms themselves became available.[2] The great relaxation of censorship started in 1988–1989. During 1988–1992, extensive information and technical analysis concerning the Soviet nuclear test program and its consequences were published. This process began at a time of intense interest in Soviet compliance with the Threshold Test Ban Treaty (which, beginning on 31 March 1976, banned the Soviet Union and the United States from conducting underground nuclear explosions larger than 150 kilotons). Papers by Bocharov and his colleagues from the Special Monitoring Service of the Soviet Ministry of Defense gave detailed information on the location, origin time, and yields of 96 Soviet UNTs at the Semipalatinsk Test Site conducted up to the end of 1972.[3] Several publications devoted to the Novaya Zemlya Test Site date from this period.[4] Hundreds of articles about UNTs at Novaya Zemlya appeared in newspapers and journals. For example, a book by Dubasov et al., published in 1999, references 182 articles written for the general public and 29 technical reports.[5] Almost all of them were published during 1989–1992. Censorial restrictions were reestablished little by little during 1996–1998.

Academician M. A. Sadovsky and his colleagues, starting from 1947 in what was known as the Special Sector of the Institute of Chemical Physics, studied all seismological aspects of chemical and nuclear explosions, as well as the physical effects of explosions upon their immediate environment. Their work was based on observations in the near-field zone, starting from the explosion cavity itself, out to a few km. Sadovsky became Director of the Institute of the Physics of the Earth (IPE) in 1960, and the Special Sector (a large organization of about 500 people) came to IPE with him. The seismic effect of nuclear explosions was a principal topic of their studies from the very beginning of the nuclear program of the USSR. The Special Sector activity was classified: this group did not publish results of their nuclear explosion studies and did not take part in any international scientific communication or meetings. In 1990 the Special Sector was formally restructured as the Institute of Dynamics of Geospheres (IDG) under the directorship of V. V. Adushkin, and almost immediately began to participate in joint programs of research with scientists (many of them seismologists) from western countries.

IDG scientists began intensive publication of studies of various geophysical and ecological consequences of high-yield chemical and nuclear explosions. During 1994–2002 they issued 10 volumes of collected papers.[6] More than two hundred papers covering some aspect of nuclear testing were published in Russian journals.

Several important and informative papers devoted to the NZTS and parameters of underground nuclear tests were published in western journals during this period. W. Leith and his colleagues analyzed the geology using aerial photos and satellite images of the northern testing area (NZNTS).[7] J. Matzko summarized data scattered in Russian publications in geography, geology, meteorology, and reported on yields, scaled depth and radioactive contamination of Novaya Zemlya underground nuclear tests.[8] Skorve and Skogan analyzed satellite images of Novaya Zemlya.[9] Comparing them with German photos taken from the air in 1942, they identified rockfalls caused by megaton-level underground nuclear explosions. Marshall et al. used the "joint determination of epicenters" method to estimate relative locations of underground tests using seismic data.[10] They obtained absolute locations by fixing the location of the underground tests of 2 November 1974 (NZSTS) and 29 September 1976 (NZNTS). Their paper is currently the most widely cited source of origin time, locations, and magnitude information for almost all underground tests at Novaya Zemlya. A slight revision of the locations given by Marshall et al. was reported by Richards,[11] who used the constraint that the seismic epicenters be close to peaks, ridges, or other high terrain of the rugged NZNTS topography, as documented in a stereo image of topography, registered to a

SPOT photograph and published by the Defense Advanced Research Projects Agency.[12]

A general description of the Soviet nuclear weapons program is given in the official 1997 publication "USSR Nuclear Tests" edited by a team of people led by V. N. Mikhailov,[13] which incorporates much of the information available in several Russian publications mentioned above. For each underground nuclear test, the following data are provided: (1) official number of the test; (2) test date; (3) code of the borehole or adit; (4) number of subexplosions in each test; and (5) the yield or yield range (whether 0.001–20, 20–150, 150–1,500 or 1,500–10,000 kt). The Table of Contents of this book is reproduced in translation in Appendix 1 of this article.

Mikhailov's book also contains summaries of the history of Soviet atomic and nuclear weapon development programs and the history of the Semipalatinsk and Novaya Zemlya Test Sites. Three separate chapters are devoted to tests of the first Soviet atomic bomb (29 August 1949, 22 kt; tower, height = 30 m), the first thermonuclear bomb (12 August 1953, 400 kt; tower, height = 30 m), and to evaluations of nuclear weapons effects, as they were observed during military maneuvers in the Orenburg region (South Urals, 14 September 1954, 40 kt, height of burst = 350 m). This book is the first volume of a six-volume series, which contains a full description of many aspects of the Soviet Nuclear Program. It was published by the Russian Federal Nuclear Center (VNIIEF) in Sarov during 1997–2001. All six volumes were translated into English and published by Begall-Atom in 1999–2001 with the title "USSR Nuclear Tests."

The individual titles are:

Vol. 1. The goals, general characteristics, and organization of nuclear tests. First nuclear tests

Vol. 2. Technology of nuclear tests

Vol. 3. Nuclear weapons. Military-political aspects

Vol. 4. Technology of peaceful nuclear explosions

Vol. 5. Nuclear tests and ecological problems

Vol. 6. The people of the atomic era.

Another key source of information is the 500–page book, "Novaya Zemlya Test Site. Ensuring the general and radiological safety of nuclear tests (facts, testimonies, memories)," published in Moscow in 2000 with Prof. V. Logachev as head of the editorial group.[14] More than 50 nuclear testing experts participated in the compilation. The Table of Contents of this book is reproduced in translation in Appendix 2 of this article. Some technical parameters of the Novaya Zemlya nuclear tests were published in this book for the first time. For example, Logachev's book includes data on the height of burst for atmospheric explosions, and the scaled depth of burst of underground nuclear tests at the Novaya Zemlya Test Site (NZTS). It gives details of three "accidents" (containment failures) that occurred during the Novaya Zemlya underground nuclear testing program. Maps of the locations of underwater, above water, and underground nuclear tests at the Northern and Southern NZ Test Sites are provided, as well as the precise yields of some tests, the history and structure of NZTS, the system used for the observation and remote control of tests, and other information not previously published. Principal items in this book are reviewed below.

A third important Russian publication is "Northern Test Site. Reference Information" published in St. Petersburg.[5] The book is mostly concerned with radioactive contamination (from seepage or venting of underground nuclear tests), the resulting environmental problems and meteorological issues, and other consequences of nuclear testing activities at NZTS. A detailed description of radiological effects after each test was provided for each of the 39 UNTs conducted at NZTS. This listing also contains important information about the scaled depths of burial (SDOB) of each test, making it possible in some cases to estimate the actual depths of underground tests, based on estimated yields. A translation of the Table of Contents of this book is provided in Appendix 3 of this article.

Memoirs of participants of the Soviet Nuclear Weapon Program are also important sources of "informal information." Such memoirs were published in the 1990s during the time of relaxed censorship. Four of these are of particular interest in providing information reported in the present article. The first is a volume of memoirs of participants of nuclear tests on the Novaya Zemlya "Nuclear Archipelago,"[15] the second is a series of memoirs included in a set of 17 volumes published by the Kurchatov Institute from 1994 to 1997,[16] the third is a lengthy description of the Special Monitoring System of the Soviet Ministry of Defense,[17] and finally we note the book "I Am a Hawk" by V. N. Mikhailov and published in Russian and English in 1996.[18] He writes of his experiences as a nuclear weapons designer in Arzamas, as a participant in the underground nuclear test program for several years at Novaya Zemlya, as Russian Ambassador to the 1980s negotiations on a new verification protocol for the Threshold Test Ban Treaty, and as the First Minister in 1992 of the newly formed Ministry of Atomic Energy.

Accurate values for the yields of Soviet nuclear tests are of particular interest. There were 496 underground nuclear tests (UNTs) conducted on USSR territory from 1949 to 1990. Among them were 340 tests at the Semipalatinsk Test Site (STS) in Kazakhstan, 117 so called Peaceful Nuclear Explosions (PNEs) at many different places on USSR territory other than at test sites, and 39 tests at the Novaya Zemlya Test Site. Soviet yields have been officially published for all 124 PNEs (including seven conducted at STS), and for 22 UNTs at STS.[19] They have also been published for 81 atmospheric nuclear tests, and for six underwater, above water and surface nuclear tests.[13] But specific information on the origin times, coordinates, Soviet seismic network magnitudes, and yields of most nuclear tests are still classified today in Russia. Such data could be used to calibrate monitoring systems and thus to improve nuclear explosion monitoring. In a separate article we obtain estimates of NZ yields for each UNT, and coordinates, using information derived from seismograms and other sources.[20]

PHYSICAL ENVIRONMENT

The Novaya Zemlya Islands (archipelago) are located between the Barents and Kara polar seas (Figure 1). They consist principally of two large islands, northern and southern, separated by a narrow strait, Matochkin Shar. The northern island comprises an area of about 49,000 sq. km, and the southern island about 33,200 sq. km. The total extent of the archipelago is about 750 km from north to south, and its width ranges from 100 to 140 km. The Novaya Zemlya Test Site boundaries were specified in an exchange of documents when the Threshold Test Ban Treaty (signed in 1974) was formally ratified and entered into force, which did not happen until 1990. Details of the test site areas and location of the test site boundaries are given in Table 1 and Figure 1.

The northern ("Matochkin Shar") and southern ("Krasino") subareas provide significantly different environments. In the northern subarea there are higher mountains, thicker permafrost, and harder rocks with higher strength.[5,14] Most underground tests at Novaya Zemlya were conducted in frozen rock, unlike any other tests worldwide.

The Novaya Zemlya Northern Test Site (NZNTS) is mountainous, with average elevations ranging from 600 to 800 m. Tests there were conducted in adits. (Adits are commonly called tunnels, though a tunnel is technically different in having two ends that allow passage through the tunnel from one entrance to an exit at a different place. An adit has just one opening.) The area of testing activity is concentrated within a region about 22 km × 18 km, along the south bank of Matochkin Shar (see Figure 1). The settlement Severny is included in this region. The rocks consist generally of Devonian age metasediments (e.g., shales, sandstones), probably greenschist facies, with an average density of 2700 kg/m^3 and compressional wave velocities (Vp) of 5.0–5.3 km/s.[5,8] Glaciers cover more than a half of the Northern Island, their thickness reaching more than 300 m.[21]

The southern area of underground nuclear testing activity was chosen in 1970. It is located in the southern part of the southern island, about 280 km from the northern test site, in an area ~20 km × 25 km of low relief (about 150 m elevation) near the Barents Sea coast, between the bays called Guba Chernaya and Guba Bashmachnaya. Its center of human activities was the settlement of Bashmachkino. Tests in this area were conducted in boreholes with depth up to about 1600 m. The rocks throughout NZSTS are sedimentary, of Permian age (argillite, sandstone, siltstone and carbonates), with a thickness from 2 to 5 km, and a density of 2500 to 2700 kg/m^3. The compressional wave velocity, Vp, is 4.5–6.0 km/s for the sandstones and 2.2–5.6 km/s in siltstones. In NZNTS the thickness of the permafrost reaches about 400–500 m in the mountainous regions and about 250–350 m in the flat-lying regions.[22] Wells extending beneath the bottom of permafrost in NZSTS find little water.[5] Water content of the rocks is low, only 1–1.5%. A water table in the usual sense does not exist over much of the archipelago. Several wells were drilled in NZNTS in the Shumilikha River Valley, 500 m deep, penetrating the base of the permafrost and showing an absence of subsoil waters. (If present, such waters would be of concern in that they might spread radioactivity from underground testing.) All the adits, built but not used for explosions, are still dry. The gas content of rocks in Novaya Zemlya is $<4\%$ for sandstone but lies in the range from 8–15% for shale.[23]

A significant number of UNTs at NZTS were conducted within the permafrost layer. The coupling from explosive energy into seismic signal is strongly dependent on rock strength, which is different for frozen and unfrozen rock. This difference is high for soft soil and for porous rocks with high water content, and is low for hard rocks that are less fractured and have low water content. The rocks at NZTS at several hundred meters depth have extremely low ice (water) content and are in a less fractured state than near-surface rocks. So it appears that the influence of permafrost on seismic coupling is not very significant. There is even less effect for the megaton-level UNTs which were conducted below the permafrost layer.

The climate on the islands is extreme. The average temperature from December to March is –15°C; from April to May is –5°C; and from September to November is –7°C. Ice-cover at sea and snow cover on land are both stable from October until mid-June. Average ice thickness from January to May is about 1.0–1.2 m. Blizzards are very common in wintertime, occurring on an average of 50 to 60 days each year. The wind velocities reach 40–55 m/s.[14,21]

VELOCITY AND ATTENUATION OF SEISMIC WAVES AT NOVAYA ZEMLYA AND VICINITY

Many seismic stations were installed by military personnel at epicentral distances less than 100 km in order to record UNTs throughout almost the whole period of Novaya Zemlya nuclear testing. Fifteen UNTs were recorded by a 300 km-long profile, running along the west coast from NZNTS to NZSTS. Limited information on the seismic observations at local and regional distances has been published.[24] It is known only that *P* waves with velocity 5.3–5.8 km/s and periods 0.2–0.4 sec were observed in the near-field zone out to 10 km. At greater distances out to 300 km all five types of regional waves were observed—the *Pg* wave, *Pn*, low amplitude *Sn*, and strong *Lg* and *Rg* waves.

Detailed seismic observations of six UNTs at NZNTS were conducted on the continental mainland, at distances from 300 to 1300 km. These six explosions were recorded by six temporary stations: Belushya Guba, Amderma (which changed to permanent operation in 1983), Naryan-Mar, Vorkuta, Murmansk, and Arkhangelsk. The closest station, Belushya Guba, is located about 190 km from the epicenters of these UNTs. Observations were also obtained at permanent stations of the Soviet Seismographic Network. During seismic observations of UNTs at Novaya Zemlya it was found that *Lg* waves were not seen on paths crossing the South Barents depression, where the granitic layer is thin or even absent.[24,25] So *Lg* waves were not recorded by continental stations located southwest of this test site.

The following travel-time equations and implied seismic wave velocities were obtained by Sultanov[24] from the observations of UNTs at these stations:

$t(Pg) = R/6.2 + 0.25$ for distances $R = 10\text{–}450$ km;

$t(Pn) = R/8.2 + 8.9$ $R = 220\text{–}1000$ km;

$t(Sn) = R/4.4 + 17.5$ $R = 250\text{–}700$ km;

$t(Lg) = R/3.5 + 1.0$ $R = 120\text{–}450$ km;

$t(Rg) = R/3.0\text{–}3.0$ $R = 50\text{–}500$ km.

Sultanov also studied the attenuation of seismic waves from UNTs at Novaya Zemlya. Data were obtained for distances from 3–200 km for *P* waves and from 0.5–200 km for surface waves. The amplitudes of ground displacement were measured. Scaling to a 1 kt UNT, these amplitudes were found to decrease with distance like

$$A_{\mathrm{P}} \sim 3R^{-1.8}$$

$$A_{\mathrm{surface}} \sim 3R^{-1.4},$$

where the amplitude A is measured in mm, and distance R is measured in km.

TEST SITE HISTORY

In July 1954, most of the territory of the Novaya Zemlya Islands was declared as the Novaya Zemlya Test Site of the Ministry of Defense of the USSR. The indigenous population, 536 people, was resettled on the mainland during 1955–1957.[14] The initial code name of the Novaya Zemlya nuclear testing project was "Object-700" (the postal address for correspondence was "Moscow-300," and the Red Army's code name for the NZ garrison was Unit 77510). After 1958, the official name of NZTS became the Sixth State Test Site of the Ministry of

Defense.[14] From the beginning NZTS was under the authority of the Soviet Navy, and today it is run by the Russian Navy.

The first stage of test site construction began in October 1954, when several battalions of military construction workers arrived with their equipment. Different Russian sources mention from 10 to 13 battalions. As many as six or seven thousand soldiers are reported to have endured the winter season of 1954–1955 in tents. Their main goal was to build the support facilities necessary to carry out the first Soviet underwater test. The main site for this first stage of construction was Guba Chernaya (Figure 2). It is located on the southwest coast of the southern island. In some years, the thickness of the sea ice-cover reaches 4–5 feet in this region by the end of winter. For this reason the icebreaker *Baikal*

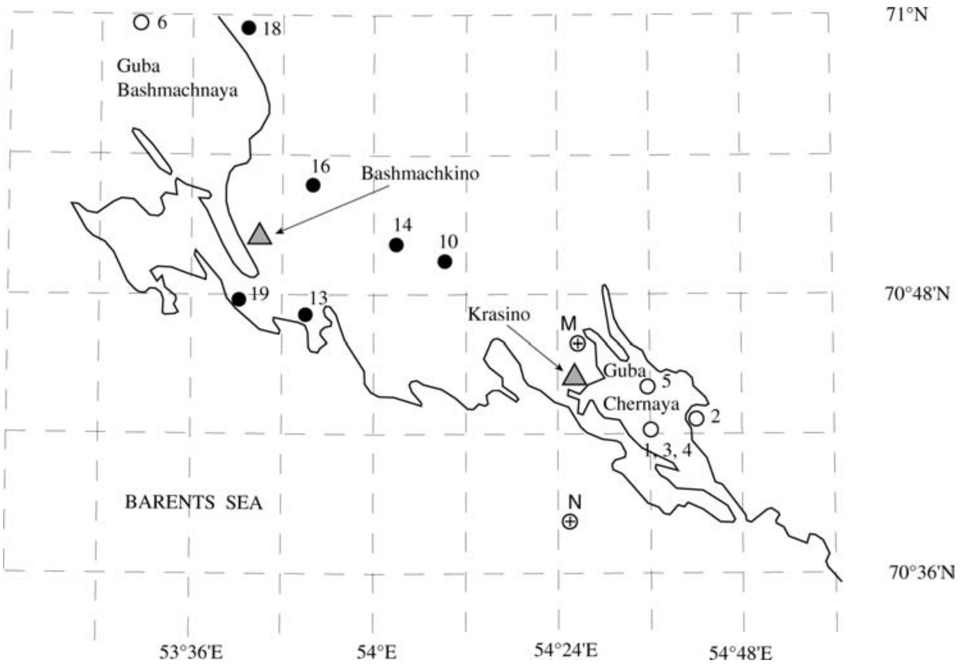

Figure 2: A map of the Novaya Zemlya southern test site (NZSTS) with positions of nuclear tests and related features. The first subzone of NZSTS was the Guba Chernaya area, where three underwater tests (1, 3, 4), one surface test (2), and one above water test (5) were conducted (open circles). Numbers correspond to Table 3. Several atmospheric nuclear explosions also took place in this region. The center of this subzone was the settlement Krasino. The command and remote control center was located on the ship *Emba* at location N during 1955–1959, and later was moved on land at location M. A second subzone was located 10–20 km to the west. Six UNTs were conducted there in six shafts (indicated by filled circles). Numbers shown are those used in Appendix 5. One above water nuclear test (6) was exploded in Guba Bashmachnaya. The center of this subzone was the settlement Bashmachkino. Locations of these tests and other features are taken from a map in reference 14. This map was published without information on latitude/longitude. We have reconstructed the coordinate net based on the shape of the coastline shown on the detailed topographic map of Novaya Zemlya (scale 1:250,000) issued by the Soviet General Staff.

was turned over to NZTS in March 1958, to establish an all-season connection between the various parts of the test site and the mainland. The main port for supplying the testing operations was Arkhangelsk, near the Kola Peninsula, 900 km away.

The steamship *Emba* was also assigned to the test site and reequipped into a command center for the remote control of the nuclear devices. Data on the results of tests were collected on the *Emba*. The ship was anchored at the position marked by the letter “N” on Figure 2, eight kilometers SW of the spot in Guba Chernaya where the underwater explosion was to be conducted. From October 1954 to September 1955 the following facilities were constructed:

1. Administrative and command center (Belushya);
2. Settlement and airport (Rogachevo);
3. Command center on board the ship *Emba*; and
4. All the facilities needed for conducting and monitoring an underwater nuclear explosion in Chernaya Bay.

As a result of this intensive activity involving several thousand soldiers and officers, the USSR’s first underwater nuclear test was exploded on 21 September 1955 (see Figure 2).

During the period from 1956 to 1961, several different areas were developed and equipped for nuclear testing experiments. The first of them was in Zone A, on NZSTS. During the nuclear testing moratorium from November 1958 to August 1961 an extensive experimental area was created especially for very large yield (100 mt-level) atmospheric tests in Zone C, Sykhoy Nos (meaning “Dry Cape”).

INFRASTRUCTURE OF NZTS

Test site operations involved a large organization with thousands of employees, mostly soldiers and officers and their families, a large seaport, and an airport. It is documented that three aviation regiments were billeted on the NZTS.[14] A modern airport was constructed near Rogachevo with a 2400 m runway, where almost any type of civilian or military aircraft could land. The local administrative and scientific center with its military headquarters (Figure 3) was called Belushya, where many five-story houses were built. During its heyday, more than one thousand officers children lived there. Several other settlements were also established on the Island, including Severny, Rogachevo, Bashmachkino, and Krasino. The total number of inhabitants on the island may have been as high as 12,000 or more during the navigable season. A large ocean steamship arrived during the summer-fall season, serving as a floating hotel for business travelers and as a restaurant for generals and other officers.

Figure 3: A view of the Officers' Club at Belushya.

Several testing fields were located within each of the three main areas (zones A, B, C), where different types of nuclear tests were carried out. The main testing fields, settlements and command posts at NZTS, along with their code names, are shown in Table 2. Additional summary information is as follows:

Zone A

At Guba Chernaya (Figure 2) between 1955 and 1962, the Soviets conducted the first and only surface nuclear explosion (# 2 in Figure 2), three underwater (#1, 3, 4) and two above-water nuclear tests (# 5, 6). Later, boreholes for conducting underground nuclear tests (UNTs) were drilled some 20–25 km west of the original testing area. Between 1972 and 1975, six UNTs were conducted in six boreholes (# 10, 13, 14, 16, 18, and 19).

Zone B

A settlement named Severny (meaning "Northern") was founded on the south bank of the Matochkin Shar strait near the mouth of the Shumilikha River. A mountainous area also on the south bank of the strait was chosen for conducting UNTs. Numerous adits were constructed between 1960 and 1990, and 33 UNTs were carried out in 36 of them.[26] Two main experimental fields are located in this area: field D-9 is an area where UNTs were conducted in

Table 2: The names and purpose of the main testing areas, settlements, and command posts at NZTS.

Code name	The purpose and type of activity
Belushya	The administrative and scientific center of NZTS.
Rogachevo	A large airport, equipped for almost any type of military and civil airplane landing. Runway length, 2400 m.
	Zone A **Guba Chernaya (Black Bay) area**
A-6	Experimental field for studying the influence of gamma-radiation on naval equipment and animals and other physical experiments. The small settlement Krasino, is located near this field.
A-7	Test field for conducting kiloton-level atmospheric nuclear explosions.
A-8	Experimental field for testing of tactical nuclear weapons (rockets with nuclear charges).
Yu	Field for conducting underground nuclear tests in shafts. The small settlement Bashmachkino was constructed for builders and miners.
	Zone B **Severny settlement and the location of UNTs conducted in adits in mountains on the south side of the Matochkin Shar**
D-9	The area of UNTs conducting in adits in the Moiseev and Lazarev Massifs. The settlement Severny (a former geophysical station) was built on the northern bank of Matochkin Shar in the western part of the zone.
D-11	A new area prepared for conducting UNTs. Not used.
	Zone C (former D) **Large test area on the northern island for conducting megaton-level atmospheric and high altitude nuclear explosions**
D-1	A port on the shore of Mityushikha Bay. The location of a harbor, depots, and electric power station.
D-2	A large field (several tens of km across) for testing nuclear charges dropped from airplanes. Almost all multi-megaton devices tested by the USSR were exploded above this field.
D-3	Test field for explosions of the nuclear warheads of intercontinental ballistic missiles, launched at distances of a few thousand kilometers from a rocket base in south-east Siberia.
D-4	Ostrov Mityushkov, the location of a relay station for re-transmitting the signals for operation of all instruments installed for recording the nuclear weapon effects.
D-8	Central command post in Gribovaya Bay, located 90 km from the center of the D-2 field.

adits, and includes the settlement at Severny. Another area, the field D-11, contains new adits, which were not used.

Zone C

North of Matochkin Shar is an area along the Barents Sea coast that is the only part of the North Island of Novaya Zemlya used for nuclear testing. It was used especially for the highest yield atmospheric and high-altitude explosions. In these tests, nuclear bombs were either dropped from airplanes or delivered by rockets. The largest Soviet nuclear test (30 October 1961, 58 mt) was detonated above this area at a height of about 4 km.

Within Zone C was a test field (without a code name), used as a target for payloads from heavy strategic rockets. Many smaller test fields were also built in Zone C, intended for testing atomic artillery shells, atomic torpedoes, and other atomic weapons. The tests in this case consisted of studying the effects of conventional explosives, not nuclear ones, on military hardware. Some of these fields were intended for scientific experiments. The main command center for Zone C was located too far from the testing areas (90–100 km) to ensure good transmission of all information from the hundreds of instruments installed to document the results of each test. An important factor here was that just after an atmospheric explosion the radio wave propagation became very poor for about 30 to 60 minutes (sometimes longer).

Starting in 1957, the Soviet Navy conducted annual maneuvers in the autumn at NZTS. During these maneuvers, rocket-propelled missiles (both flying and ballistic), torpedos, and shells were launched from submarines, warships, and airplanes.[27] The targets were located on the testing fields A-8, D-3 and other smaller fields. These warheads mostly carried conventional (chemical explosive) charges, but some had nuclear charges. All the nuclear explosions in these maneuvers (mostly atmospheric, and only four under or above water) were included in the official Soviet list of nuclear tests.[13]

UNDERWATER, ABOVE-WATER, AND SURFACE NUCLEAR TESTS AT NZTS, 1955–1962

Six nuclear explosions of these three types were carried out at NZTS from September 1955 to October 1962. Their locations are indicated on the map (Figure 2) by numbers from 1 to 6 in chronological order. Their parameters are shown in Table 3.[14]

The first nuclear explosion at NZTS was a test of the nuclear warhead of the torpedo "T-5." This warhead was the nuclear device "RDS–9," and it was tested

Table 3: The approximate coordinates of underwater, above water, and surface nuclear tests conducted at NZTS from 1955 to 1962.

N	Date	Time, GMT	Type	Yield kt	H, m	Lat. °N	Long. °E
1	21 Sept 1955	05:00:54	Underwater	3.5	−12	70.703	54.60
2	07 Sept 1957	08:00:01	Surface	32	+15	70.715	54.68
3	10 Oct 1957	06:54:32	Underwater	10	−30	70.703	54.60
4	23 Oct 1961	10:30:47	Underwater	4.8	−20	70.703	54.60
5	27 Oct 1961	08:30:27	Above water	16	+1.1	70.73	54.59
6	22 Aug 1962	09:00:00	Above water	6	0	71.00	53.50

for the first time in Kazakhstan at the Semipalatinsk Test Site in nonwater conditions in 1954, but failed.[28] At Novaya Zemlya this first test was detonated underwater on 21 September 1955 (Y = 3.5 kt; location N1, Figure 2), at a depth of 12 m. More than 30 ships were deployed around the nuclear charge at distances ranging from 300 to 1600 m. Among them were four destroyers, three submarines, several minesweepers and seaplanes. Many of these ships were new. More than 500 goats and sheep, about 100 dogs, and other animals, were on board the vessels. The closest destroyer (at 300 m) sunk immediately; other ships were heavily damaged.[14]

Two years later, after the end of the first stage of test site construction, the second NZTS explosion was conducted on 7 September 1957. The only surface explosion at NZTS, this test consisted of a nuclear charge (Y = 32 kt) installed on a tower 15 m in height, located 100 meters inland from the coast at Guba Chernaya Bay (at #2 in Figure 2). Many "targets" (e.g., animals, warships, and other military objects) were deployed both in the water and on land. The resulting crater was 80 m in diameter and 15 m deep. The test resulted in significant radioactive contamination; an hour after the explosion the intensity of gamma radiation near the epicenter was 40,000 roentgen per hour (a contemporary permissible dose is 2 R per year, according to one of our main sources of information on Soviet nuclear testing practices at Novaya Zemlya[14]). A second contaminated area, resulting from fallout of the above-water explosion of 27 October 1961, is also located in Guba Chernaya Bay, about 6 km to the east. Both areas are still considered to be contaminated (totaling about 100 sq. km) and access is prohibited.

A month later, on 10 October 1957, a full-yield test (Y = 10 kt) of the T-5 nuclear torpedo was conducted at the same location as the first underwater test (#3 in Figure 2) at a depth of 30 m. A standard submarine at a distance of several kilometers launched the torpedo. Three destroyers, three submarines, two minesweepers, and many smaller target ships, were sunk by the blast.[14]

The last Soviet underwater test (#4 in Figure 2) was detonated on 23 October 1961, at the same place as two previous underwater tests. This time, only rafts were deployed, along with remote control instruments (apparently, too many ships were lost in the previous tests). A new, B-130 submarine located at some distance from Guba Chernaya launched the torpedo, which had a nuclear charge of 4.8 kt. The torpedo exploded precisely under the target, at a depth of 20 m. Radioactivity from the underwater explosions was remarkably low.[14]

The first Soviet above-water explosion was conducted four days later, on 27 October 1961, also in Guba Chernaya (#5 in Figure 2). In this experiment, the same B-130 submarine, at a distance of 11 km, launched a torpedo. The torpedo traveled 11 km underwater at a depth of 12 m, rose into the air and exploded exactly above the target.[14] It was the final test of the new torpedo, which later took its place among Soviet naval weapons.

Table 4: The number of atmospheric nuclear tests conducted at NZTS from 1957 to 1962, and their annual total yield.

	Sep–Oct	Feb–Oct	Sep–Nov	Aug–Dec	Total
Year	1957	1958	1961	1962	
Number of tests	2	24	24	35	85
Annual yield, mt	4.5	16.2	86.2	132.7	239.6

The last test in this series, conducted on 22 August 1962, was the above-water test of a new antiship weapon with a nuclear warhead. The rocket, with a nuclear charge of 6 kt, was launched from a Tu-16 aircraft about 200 km from the target.[29] The warhead traveled ballistically and exploded at the water surface. The target was located in Guba Bashmachnaya (#6 in Figure 2), 45 km northwest of the sites of the previous tests in Guba Chernaya Bay. It hit the floating target with accuracy of about 5 meters.

ATMOSPHERIC NUCLEAR TESTS, 1955–1962

Eighty-five atmospheric nuclear tests (ANTs) were carried out at NZTS between 24 September 1957 and 25 December 1962. Their distribution by year is shown in Table 4, and by yield in Table 5. The list of all 85 ANTs, with yield and height of burst when available, are given in Appendix 4. Yields for 77 of these tests have been published,[13] and heights-of-burst (HoB) for 73.[14] HoB has not been published for 12 ANTs and yields are still not published for 8 ANTs.

Two atmospheric explosions failed: 19 October 1958 (HoB = 900 m, Y < 1 t) and 25 October 1958 (HoB = 300 m, Y < 100 t). Both these events are included in the official list of 85 nuclear tests at NZTS although there was no nuclear yield.

Four ANTs that exploded “somewhere above the Barents Sea” at the NZTS were carried on intercontinental ballistic missiles launched from southeast Siberia.[30]

The majority of warheads used in ANTs at NZTS were dropped by parachute from bombers. Most of these nuclear devices, covering a wide range of yields,

Table 5: The distribution of atmospheric nuclear tests at NZTS, by yield.

Yield range, in kt	Number of tests
$Y < 10$	12
$10 \leq Y < 100$	12
$100 \leq Y < 1{,}000$	21
$1{,}000 \leq Y < 3{,}000$	24
$3{,}000 \leq Y < 5{,}000$	5
$5{,}000 \leq Y < 10{,}000$	5
$10{,}000 \leq Y$	6

came from a large storage facility located about 1000 km from the test site in the military airbase called “Olenye” on the Kola Peninsula, where Tu-95 heavy bombers were also based.[15] The decisions of what type and yield of nuclear device were to be exploded in the next test were made by the State Commission in Moscow. The Head of this Commission was usually present for the test at Novaya Zemlya, and he made the final decision about the zero time depending on the meteorological conditions (including the expected wind direction). Once the decision was made, a heavy bomber (usually a Tu-95) with the nuclear device would take off from “Olenye” for the test at Novaya Zemlya.

The coordinates of ANTs were not published by the Soviet Union. The largest-yield tests were conducted on the Barents Sea coast in Zone C (test field D-2 and offshore). In cases where the interval between two ANTs was less than 48 hours the second ANT was conducted at the Kara Sea coast of Novaya Zemlya and not in any of the specified “zones” (this is confirmed by a map of ANT locations given in a Norwegian study[9]). Small and intermediate range ANTs were conducted in Zone A, of NZSTS.

Analysis of published data on yield and height-of-burst for NZTS ANTs indicates scaled heights-of-burst exceeded 100 $m/kt^{1/3}$. Variations of the scaled height were high, ranging from 105 $m/kt^{1/3}$ (BIG IVAN, see below) to about 1000 $m/kt^{1/3}$. The lowest ANT was detonated at HoB = 250 m (Y = 6 kt), with a scaled height of 140 $m/kt^{1/3}$. The highest ANT was detonated at HoB = 4090 m (Y = 19,100 kt), with a scaled height of 145 $m/kt^{1/3}$.

On 30 October 1961, the most powerful atmospheric bomb, code name “BIG IVAN,” was exploded. This “super bomb,” weighing 26 tons, was too large to be placed inside an aircraft, so it was fastened beneath a Tu-95 (“Bear”) heavy bomber with only about 30–40% of its diameter within the fuselage, and dropped with a giant parachute from a height of 10.5 km.[31] It exploded 188 seconds after it was dropped, at a height of about 4000 m above test field D-2, near Cape Sukhoy Nos. The origin time of this explosion was 08:33 and approximate coordinates were 73.85°N, 54.50°E.[32] This is about 55 km north of the Severny settlement and 250 km north of the headquarters at Belushya, from where it was observed by the State Commission.[5,14] Although it was exploded in the atmosphere, it generated several types of seismic signal. According to a bulletin of the U.S. Geological Survey it had seismic magnitude mb = 5.0–5.25.

The zone of lethality and destruction of dwellings was out to 120 km; the zone of eye damage was out to 220 km; a shock wave in air was observed at Dickson settlement, at 700 km; windowpanes were partially broken to distances of 900 km. People felt a seismic wave exactly at the moment of the flash of light from the explosion (personal communication of a test participant). All buildings in Severny (both wooden and brick), at a distance of 55 km, were completely destroyed. The air wave that went around the world entailed a change in air density, resulting in signals on long-period vertical-component seismometers because of the change in buoyancy of the inertial mass.

The yield of 58 mt and height of 3.5 km were reported in early Russian publications[33] and in scientific papers.[34] In official publications the yield was reduced to 50 mt. We assume that the scientific data provided by people who worked on this nuclear test are the most reliable. It was claimed officially that only half of the maximum potential energy for this bomb design was released in the "BIG IVAN" test. As noted by Yu. N. Smirnov, scientific director of Arzamas-16, this design allowed "a yield of up to 100 megatons when fully loaded with nuclear fuel." Thus the test "was in effect the test of the design for a 100-megaton weapon . . . "[35]

The radioactivity released by atmospheric nuclear testing at Novaya Zemlya was recorded worldwide, and specifically within the Soviet Union by the network of more than 500 stations of the State Meteorological Survey, which, together with stations operated by other government agencies, were equipped with standard instruments for monitoring of radionuclides. From observations made in 1958–1962 and reported daily to Moscow, two main trajectories of significant radioactive fallout were observed: (1) directly to the South as far as the Caspian Sea, and (2) towards the Sea of Okhotsk stretching several thousand km to the southeast from Novaya Zemlya.

UNDERGROUND NUCLEAR TESTS

Two different Nuclear Weapon Scientific Institutes (Centers) were organized in the U.S.S.R. (just as the United States had National Laboratories at Los Alamos and Lawrence Livermore). Both Institutes were responsible for all stages of nuclear weapons development, including construction and testing.

The first Institute was organized in April 1946. Its current name is the Institute of Experimental Physics (VNIIEF). It is located in the small town of Sarov (called Arzamas during the Soviet era) about 700 km east of Moscow, and its code name was Arzamas-16. The second Institute was organized in 1955 and is now called the Institute of Technical Physics (VNIITF). It is located in the small closed city of Snezhinsk, near Chelyabinsk in the South Urals and its code name was Chelyabinsk-70.[13] The two Institutes fielded a total of 39 UNTs at NZTS during 1964–1990. Eighteen UNTs at NZTS were developed, coordinated, and conducted by Arzamas-16; thirteen UNTs were the responsibility of Chelyabinsk-70; eight UNTs involved both Institutes,[5] which competed vigorously with each other.

Information about each of the 39 UNTs at NZTS has been provided in the widely cited official Russian publication edited by Mikhailov.[13] Specifically, this source gives the date, a code for the adit or shaft, the number of nuclear devices exploded in each test, the scaled depth, and the total yield of all tests conducted during each year of the test program. According to the Protocol of the Threshold Test Ban Treaty a single UNT can consist of any number of nuclear devices provided they are exploded within a time interval less than 0.1 second and are located within a circle of radius less than 1 km. A total of 133 nuclear devices were exploded in the 39 UNTs at NZTS. The full list of these tests is given in Appendix 5.

The bilateral Threshold Test Ban Treaty signed in 1974 specifies a limit of 150 kilotons for UNTs beginning on 31 March 1976. For the 20 UNTs at NZTS prior to this date, the total yield was 23.77 megatons with average yield about 1.19 megatons. The total yield of the 19 UNTs at NZTS after March 1976 was 1.94 megatons with average yield about 100 kilotons.

Three tests (21 October 1967, 14 October 1969, and 11 October 1980) each entailed nuclear devices located in two different adits, and until 1997 many Russian and Western authors assumed these consisted in each case of two separate tests. Thus prior to 1997, many publications refer to 42 UNTs at NZTS. In the Russian Federation's official summary[13] each of these pairs is listed as a single test, so the total number of UNTs conducted at NZTS is now taken as 39. Of these, 33 were carried out at the northern site near Matochkin Shar during 1964 to 1990. The remaining six UNTs were carried out at the southern site between July 1972 and October 1975. The first of these tests (27 July 1972) was not detected seismically, and it is widely assumed that the nuclear device failed to explode.

Early preparations for underground nuclear testing began in 1959 with construction of the settlement called Severny on the south bank of Matochkin Shar. A rock massif (Mount Lazarev) near the western end of the strait was chosen as the main area for drifting adits and conducting the UNTs. Adits were excavated with entrances about 50–80 meters above sea level along the south bank of Matochkin Shar, into the northeast slope of Mount Lazarev (map, Figure 4). The drifting of five adits (G, B, A-1, A-2, A-3) started in May 1960. Adits G (200 m long) and B were ready by May 1961, but A-1, A-2 and A-3 were not completed until later, because trilateral negotiations were underway between the USSR, the United States, and the United Kingdom which resulted in 1963 in the Limited Test Ban Treaty (LTBT) banning nuclear tests in the atmosphere, space, and underwater. The Soviets therefore devoted almost all the resources at Novaya Zemlya to completing the program of atmospheric explosions, and underground construction was temporarily halted. Adit construction resumed in August, 1963, just before the signing of the LTBT.[14]

The first UNT at NZTS was conducted at 08:00 on 18 September 1964, in adit G. The intent was to conduct an exact repeat of the first UNT at the Semipalatinsk Test Site (11 October 1961). It had the same yield (1 kt), depth (100 m), length of adit (200 m), was also in hard rock, and the same type of stemming was used.[5] Nevertheless, the radiological consequence was completely different. Whereas radioactive gases from the STS test were not detected in the atmosphere near the adit for 3–4 hours, they appeared in the epicentral area of the NZ adit within only a few minutes.[14]

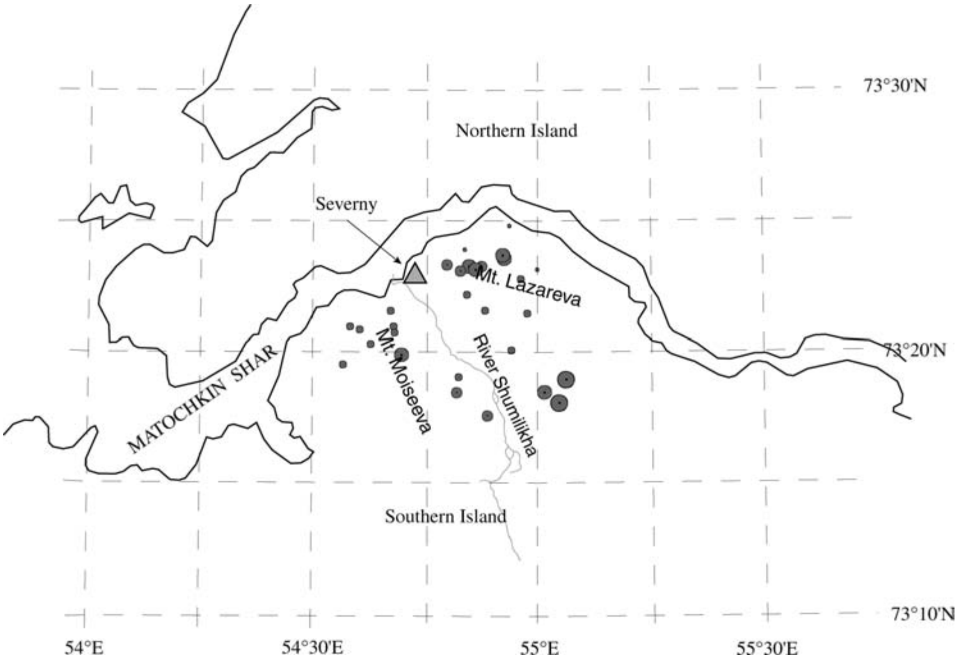

Figure 4: A map of zone B, the area of UNTs conducted in the Moiseev and Lazarev massifs. Bold circles are locations of UNTs from reference 10. Severny—a settlement for military staff and miners.

The second UNT at NZTS was conducted at 08:00 on 25 October 1964, in adit B, near the first NZ UNT. The yield of this explosion was about 20 kt, and the scaled depth was 180 m/kt$^{1/3}$. Again, whereas a nuclear test at STS with the same yield and depth was fully contained, radioactive debris was detected at the surface near the NZ UNT just 38 minutes after this second test.[14]

Later analysis showed that the difference in gas venting between STS and NZTS was a result of different gas and water content of rock at the two test sites. The rocks at the Kazakhstan test site consist mostly of granite. They have low water content (0.5–1.0% weight) and no components that under high temperature experience thermal decomposition producing significant amounts of gas. Therefore, in Kazakhstan the gas pressure in the cavity of a UNT rapidly decreased due to cooling. In the final stage it became even lower than atmospheric pressure,[5] and outer air moved into the chamber through natural rock joints and fractures. The situation at NZTS was found to be completely different. Local rocks are mostly shales and other carbonate rocks. They have high water content (1.5–2.5%) and high gas output (5–15%) under high temperature, especially for nuclear tests conducted in carbonate rocks.[23] The pressure in the cavity after cooling remained significantly higher than atmospheric pressure. This led either to seepage or rapid venting of the radioactive gases.[14]

The strategy of tunnel selection was therefore changed after the first two tests, and rock environments in which the gas content could exceed 15% (including the vicinity of shales and other carbonate or carbonaceous rocks) were ruled out.[5] As a result of a number of tests at Novaya Zemlya, it was concluded that, in rocks with gas content of 8–15%, nuclear tests must be emplaced at scaled depths of at least 150–180 m/kt$^{1/3}$. Nevertheless, a few serious accidents (containment failures) occurred. They are described below.

Beginning in 1966, underground nuclear tests were conducted systematically at Novaya Zemlya, with one or two tests per year in most years (but three in 1973). Most tests were conducted in the August–November period, before navigation routes had closed due to ice. A total of 39 underground nuclear tests were conducted, the last on 24 October 1990.

Most underground nuclear tests were of multiple devices (“salvo” tests) detonated nearly simultaneously: 133 separate nuclear devices were detonated in the 39 tests. The largest number of subexplosions—eight—was for UNT #17 on 23 August 1975 and also for UNT #39 on 24 October 1990.

In two experiments, two tests were conducted simultaneously. Thus, underground tests #3 and #4 were conducted at the same time in two different adits, separated by more than 2 km. Tests #18 and #19 were conducted simultaneously in two different shafts, separated by 22 km.

From 1966 to 1975, eleven megaton-size underground nuclear tests were conducted—eight of them in the northern area (Matochkin Shar) and three in the southern area (Krasino). The most powerful Soviet UNT (yield ~4.2 mt, seismic magnitude mb = 6.97) was conducted in the northern test area on 12 September 1973. The most powerful test in the southern area (Y = 3.5 mt, mb = 6.98) was detonated on 27 October 1973. Since March 1976, and the imposition by treaty of a 150 kt threshold, seismic magnitudes of UNTs have not exceeded mb = 6.00. Table 6 gives the distribution of teleseismic magnitudes for the UNTs at Novaya Zemlya.[36]

A surface chemical explosion (Y = 974 t) was detonated at 14:00:00 GMT on 25 August 1987 south of Matochkin Shar, about 100 meters from the coast. Its coordinates were 73.38° N and 54.78° E.[37] Its seismic signal at NORSAR (an array in Southern Norway) was reported with magnitude 3.2,[38] along with a similar magnitude (3.6) for a seismic signal on 15 November 1978. Its origin time (1400 hours) and epicenter (73.4°N, 55.0°E) are typical for UNTs, and we are sure, it, too was a chemical explosion, though we know of no Russian sources that describe this event.

Table 6: Distribution of seismic magnitudes (reference 10), for UNTs at NZTS.

mb	<4.0	4.0–4.99	5.0–5.49	5.50–5.99	6.0–6.45	>6.45
1964–1975	1	3	0	3	2	11
1976–1990	2	1	0	15	1	0

THE MOST POWERFUL UNDERGROUND NUCLEAR TEST ON NOVAYA ZEMLYA, $Y = 4.2$ MT

The two most powerful Soviet UNTs were carried out at NZTS during the fall of 1973. On 12 September 1973, four nuclear devices, with a total yield of 4.2 mt[39] were exploded in the northern area.[5,14] The scaled depth was announced as 95 $\mathrm{m/kt}^{1/3}$, and its seismic magnitude was reported as 6.97.[10] On 27 October 1973 a single 3.5 mt charge was exploded in the southern area just one month after the first successful UNT in this new area.[14,40] It was carried out in a standard borehole. Its seismic magnitude was 6.98,[41] and the announced scaled depth was 120 $\mathrm{m/kt}^{1/3}$.

Although the yields of these two tests were nearly the same, the surface effects were very different. After the southern explosion, changes in the ground surface were noted southwest of the top of the shaft. Four small ridges were created, a region 120 m in width was uplifted 2 to 3 m, and on the uplifted portion large cracks were observed 0.5–1.5 m wide and 5 m deep.[14]

In contrast, the largest UNT at the northern area produced a tremendous spall effect, a huge rockslide was triggered, and significant changes in surface relief occurred. More than 80 million cubic meters of material cascaded down in a massive rock avalanche. The rockslide blocked the entrance of a valley and the flow of two glacial streams. A lake, 2 km long, formed behind the slide debris. The extent of the rockslide is shown schematically in Figure 5 (in vertical section) and in Figure 6 (a map view of the slope collapse and the area covered

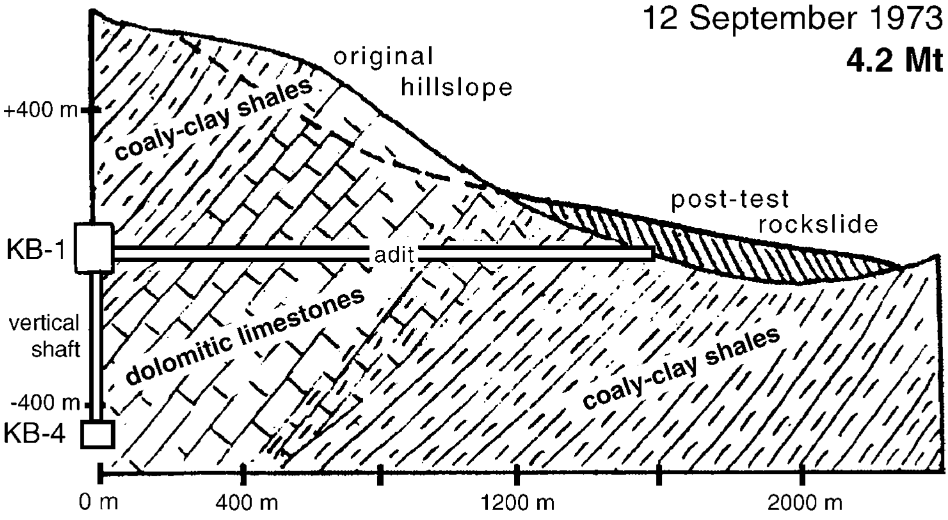

Figure 5: A vertical schematic cross-section (based on ref. 14) of the adit–shaft combination of the UNT of 12 September 1973, indicating the position of chambers KB-1 and KB-4. The mountainside is shown before and after the landslide caused by the explosion.

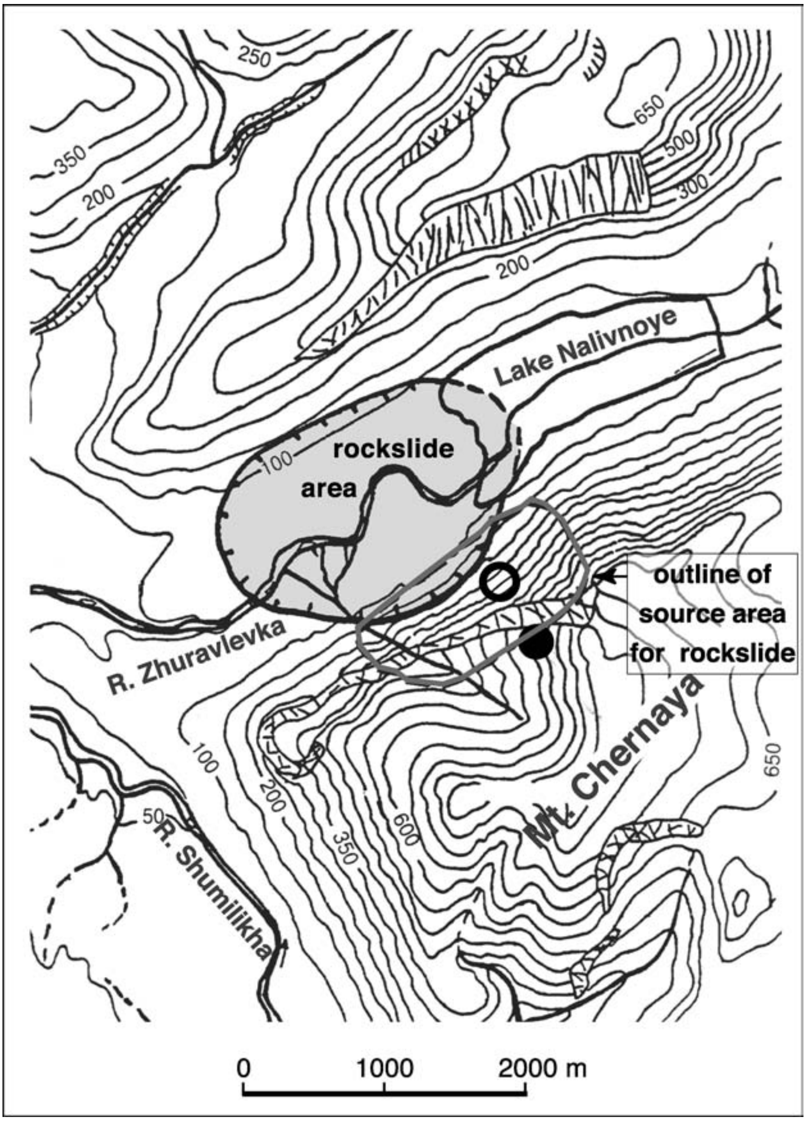

Figure 6: A topographical map (from ref. 13, English edition) of the region above the UNT of 12 September 1973. The contour interval is 50 m. The beginning (source) and ending areas of the rockslide are outlined. Filled circle—chambers KB-1 and KB-4; open circle—end of the line of least resistance (LLR), emergent at the surface from KB-4.

by rockslide debris). The size of the collapse area is 800 m × 1700 m, and the area covered by debris is 1600 m × 2200 m with thickness 20–50 m.[14,42]

The contrasting outcome of the two multimegaton underground nuclear tests is due to the differences in relief and yield distribution. The test geometry in the south was relatively simple: a single charge was exploded in a deep shaft. The northern test entailed four separate nuclear devices exploded almost simultaneously, but in a complicated configuration beneath Mount Chernaya. At safe scaled depths of 100 m/kt$^{1/3}$ or greater, a yield of 4.2 mt needs at least 1600 m for the line of least resistance to the free surface (LLR). But the height of Mount Chernaya is only 900 meters, and its relief cannot provide a value of LLR more than 650 m using only a horizontal adit. The Soviets therefore designed a unique adit-plus-shaft hybrid excavation inside the mountain (Figure 5). An adit 1223 m long was first excavated.[42] The big KB-1 chamber was made at the end of the adit B-1. A vertical shaft (3 m diameter) was then excavated to an additional 500 m depth, and a chamber KB-4 was constructed at the bottom of this shaft. Additional chambers, KB-2 and KB-3, are listed for this nuclear test. The positions of KB-2 and KB-3 are unknown. They were located somewhere along the adit, not far from KB-1 (and possibly collocated there).

The aggregate yield of approximately 4.2 mt for this UNT thus resulted from four separate explosions located in different chambers. One way to carry out the test would be to place all the devices in the deepest chamber, KB-4. The LLR for this chamber, estimated from the cross-section in Figure 5, was about 1200 m. The scaled depth of burial (SDOB) for 4.2 mt at 1200 m is 74 m/kt$^{1/3}$, only marginally greater than the estimated minimum needed to prevent cratering in hard rock,[43] 70 m/kt$^{1/3}$. How then might the total yield be distributed in a way that reduced the SDOB?

Reference 13 gives the yield range for each of the four devices in this test as 1.5–10 mt for the largest, presumably in KB-4; and 150–1500 kt for each of the others, presumably in KB-1, -2, -3. The LLR values for KB-4 and KB-1 were about 1200 m and 600 m, respectively, from the cross-section shown in Figure 5, and approximately 600 m for KB-2 and KB-3 also. A distribution of the aggregate 4.2 mt yield, which significantly raises the overall SDOB from 74 m/kt$^{1/3}$, would be to have 380 kt in each of KB-1, -2, -3 and the remainder (about 3 mt) in KB-4. The SDOB for each chamber would then be about 83 m/kt$^{1/3}$. If the chambers KB-1, -2, -3 were not far apart, it would be more appropriate to group the three smaller devices into one, for purposes of finding a value for the SDOB. In this case the value is 77 m/kt$^{1/3}$ with 3.7 mt in KB-4 and about 500 kt at the upper level.

Whatever the distribution of yields in this test, the safety rule LLR $\geq$ 100 m/kt$^{1/3}$ appears not to have been followed, and the reported value LLR = 95 m/kt$^{1/3}$ is inconsistent with the aggregate yield of 4.2 mt and the LLR values we have discussed. Naturally, the superposition of shock waves from the main charge at KB-4 together with those of other charges in KB-1, KB-2, KB-3 exceeded the seismic effect associated with that from each chamber taken separately. The rockslide was a result of this superposition. It may also be noted that any distribution of yield which placed significant seismic sources at the upper level of the main adit would lead unavoidably to larger seismic signals compared to a total of 4.2 mt at the KB-4 level, since underground explosions of fixed charge size generate larger seismic signals when fired at shallower depths.[44]

As well as the difference in surface effects for these two largest underground tests, there was a difference in that the largest UNT in a shaft (27 October 1973) led to a significant swarm of aftershocks.[38,45] Thus Logachev[14] wrote that 19 earthquakes were recorded during the 14 hours after this explosion. Nine events among them, with teleseismic magnitudes mb ranging from 4.0 to 4.6, were located by the International Seismological Centre. But no significant aftershock activity was reported following the UNT of 12 September 1973.

ACCIDENTS AND RADIOACTIVE CONTAMINATION

Three accidental releases of significant radioactivity occurred at NZTS during the underground nuclear testing program, though only two of these resulted in what official Russian sources[5,14,46] describe as "emergency situations."

The first accident occurred on 14 October 1969, when two nuclear charges totaling 540 kt (the announced yield[13]) were detonated in separate adits at Matochkin Shar (A-7 and A-9). This was the most serious accident of the UNT program at NZTS. A gas-stream jet burst to the surface one hour after the test from a tectonic fault on a mountain slope at some distance from adit A-9. The level of gamma radiation jumped to several hundred roentgens per hour. For some 40–50 minutes, many test personnel were exposed to the resulting radiation hazard. Most were subjected to a radiation dose of about 40–80 roentgens. An action plan for emergency situations was absent, and apparently the leadership was panic-stricken and immediately left the test field, abandoning a few hundred remaining people.[14] Only 40–60 min later were personnel evacuated to a safety area. Ten days later, people who had suffered radiation exposure were transported to a hospital in Moscow, by ship and train, to have their first medical examination about three weeks after the accident.[14] More than 80 people were subjected to a radiation dose of about 40 roentgens, and 344 participants of the test suffered from the high level of radiation.[14] Radiation in this area is now described as near the background level.

No official explanation for this radioactive release has yet been published. The informal opinion of experts is that there was a thermal decomposition of a dolomite cement that was used for tamping the charge chamber, and for stemming along the length of the adit. The pressure in the chamber may have reached 45 atmospheres due to high levels of carbon dioxide, following a reaction with CO_2 content in the rocks and stemming exposed to the nuclear explosive charge.[14]

Here we may note that Mikhailov, in his personal description of nuclear testing at Novaya Zemlya,[18] explained why the spreading of radioactive gas was associated with the smell of hydrogen sulfide: "it meant that pyrite crystals [which were present in abundance near the shot point underground] . . . were decomposing."

The second acknowledged accident occurred on 2 August 1987, following the detonation of a 150 kt test in adit A-37A at Matochkin Shar (yield from Mikhailov[13]). A powerful burst of a radioactive "gas-jet-stream" occurred just above the mouth of the adit, just 1.5 minutes after the explosion. It was later established that gas penetrated along a geologic fault that extended along the adit axis and hot gases melted the surface ice. In this case, an emergency program was immediately instituted. Fourteen helicopters, waiting two miles away, evacuated all staff within a period of several minutes. It is reported that not one case of radiation sickness occurred among the test site personnel.

Another accident, which occurred on 27 September 1973, is described only in Logachev's book.[14] In this case, 20 minutes after an explosion was conducted in the borehole Yu-4 at Krasino, a radioactive gas-stream-jet suddenly burst to the surface some 1500 m away from the epicenter. The yield of this explosion, based on its seismic magnitude of 5.89,[10] was about 120 kt. It was found later that gas from the cavity left by the explosion penetrated along a tectonic fault. A small area (about 0.2 sq. km) around this fault is still a restricted zone. Even recently, the radiation level there is 40–50 times higher than near the mouth of the borehole. Other published Russian summaries of the radioactive aftermaths of UNEs at NZTS do not mention this case, only that "low gas seepage was observed near the mouth of the shaft." It is seen clearly from this case, that postexplosion radiation effects were commonly ignored by authors of official Russian publications. Note that in all three accidents described here, radioactive gas rapidly migrated to the surface through a geologic fault.

A description of the radiological consequences of each UNT at the NZTS is summarized in Appendix 6 of this article. The record of containment failures listed in this Appendix translates into a series of significant technical challenges for a nation that would attempt to execute and confidently conceal a militarily significant nuclear test program. A review of Soviet nuclear test containment practice was published in 2001.[47]

HYDRONUCLEAR AND EXPOSURE-TO-RADIATION EXPERIMENTS

Besides the nuclear explosions, NZTS was used for so called hydronuclear[48] and hydrodynamic experiments to study the behavior of nuclear materials and the physical processes taking place in a developing nuclear explosion of a nuclear charge. Several test areas were equipped especially for studying models of nuclear devices and nuclear weapons components.

A hydronuclear explosion has been defined as "a physical experiment with models of nuclear devices without significant nuclear energy release (not higher than the energy of the chemical explosives). HNEs are the unique way to study physical processes in the nuclear charge during the explosion."[14] A total of 89 hydronuclear experiments were conducted in the USSR before 1990, two of them in the atmosphere, 72 on the surface, and 15 underground. Four of these experiments were done in NZTS.[14]

Concerning a relevant Russian characterization of "hydronuclear" and "hydrodynamic" experiments (see the Introduction to Chapter 3 of reference 13), we note that "Experiments with nuclear energy release less than one ton of chemical explosive are not included into the list of nuclear tests (both military and PNEs). Such experiments are laboratory explosion experiments with radioactive fissionable materials and they are not classified as atomic weapon tests. Following the American classification such experiments are called HYDRONUCLEAR experiments. More than 90 such experiments were conducted in the USSR. The nuclear energy release during most of these experiments was less than 100 kg of chemical explosive equivalent."

The same reference also remarks that: "Into the list of nuclear tests, experiments with nuclear and fissionable materials were naturally not included. Such experiments were conducted at nuclear test sites. They are not connected with nuclear explosive charge or the realization of the explosive chain reaction or any type of chain reactions. Following the American classification such experiments are called HYDRODYNAMICAL TESTS or experiments. These experiments entail laboratory study of the materials and parameters of non-nuclear processes."[49]

Since 1994, numerous additional hydrodynamic and hydronuclear experiments have been successfully carried out at NZTS. Their main goal was simulating nuclear accidents and developing methods to prevent unintended nuclear explosive energy release.[14] A series of hydrodynamic experiments was carried out in 1995–1996. Mikhailov writes in his preface to reference 14 that the results of these experiments were "super positive" and allowed Russia subsequently to sign the CTBT. Successful experiments were also carried out in 1997.[50]

As in the U.S., experiments were also done to evaluate the ability of different items of military equipment, including rockets, to function properly when subjected to high levels of radiation. Logachev[14] mentions two tests that were used for this purpose (9 October 1977 and 26 August 1984), and indicates that such experiments accompanied most UNTs. A sophisticated system was constructed to transport the intensive radiation along the tunnel to a specially-constructed closed chamber, in which the equipment to be subjected to radiation was emplaced.

CONCLUDING COMMENTS

The main official Russian publication[13] describing nuclear testing of the USSR notes that

> Nuclear tests set standards and in an important way were a unique technological activity which was based on the efforts of enormous groups involving tens of thousands of specialists. The results of this activity gave a foundation for the military effectiveness, reliability, and safety, of the nuclear arsenal and national security of Russia. . . . The program of nuclear tests in the USSR from 1949 to 1962 was a decisive step in the creation of a system of nuclear weapons for the USSR and transformed the USSR into a nuclear superpower.

In this article we have presented activities at the Novaya Zemlya Test Site with few comparisons against nuclear testing elsewhere, but of course these activities at NZTS did not occur in isolation. The same publication just quoted notes that, in carrying out the nuclear test program of the USSR, it was almost always necessary to catch up with the United States. The first U.S. nuclear test and two nuclear bombs used against Japan in 1945 were followed only four years later by the USSR's first nuclear test, in August 1949. The first fully-contained U.S. underground nuclear test in 1957 was followed about four years later by the first USSR UNT. Other "firsts" in the U.S. nuclear test program usually took less than four years for the USSR to emulate. This applies to the first test of a nuclear explosion at the 100 kt level, the first test of a thermonuclear device, and the first high-altitude nuclear explosion. On the other hand, the Soviet Union led the U.S. with the first test of a thermonuclear weapon dropped from a plane, and the yield of BIG IVAN has never been exceeded. Both superpowers blew up many ships with underwater nuclear tests, and tested the effects of nuclear explosions on soldiers. Thus it seems more appropriate to note how similar the U.S. and Soviet nuclear test programs were, rather than to emphasize where one was ahead of the other. The driving imperative of each side was the success of the other, and the perceived need to compete in nuclear testing became one of the most direct expressions of the nuclear arms race between the two countries. In part it was perhaps "saber-rattling" on a grand scale, rather than a dispassionate series of technical evaluations of new nuclear devices.

Of course the decades of Soviet nuclear testing on Novaya Zemlya were the subject of intense monitoring efforts by western nations. We have not described these efforts here, but note that over time it has become possible to monitor even the underground environment on Novaya Zemlya for the possibility of nuclear testing down to very small yields. A practical example of a small earthquake, detected and identified in August 1997 but initially misinterpreted (according to news stories) within the U.S. government as a small nuclear test, was a celebrated cause[51] that resulted in several open papers demonstrating the earthquake origin of the recorded signals. Earthquakes of magnitude 3.0 and 2.5 near the Novaya Zemlya test site were detected in February 2002 and October 2003, respectively, with high signal-to-noise ratios, by sensors of the International Monitoring System operated for the Comprehensive Test Ban Treaty Organization.[52] Such magnitudes, if due to well-coupled underground nuclear tests, would be associated with yields down at the level of a few tens of tons of TNT equivalent.

Given the remote setting of Novaya Zemlya, with its high winds, rugged topography, and permafrost conditions, and given the execution there of nuclear tests having a total yield of about 265 mt, it is appropriate to conclude by using a phrase taken from the sentences quoted above: nuclear testing at Novaya Zemlya was indeed a “unique technological activity,” albeit one in which both superpowers engaged.

ACKNOWLEDGEMENTS

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NOTES AND REFERENCES

1. V. I. Khalturin, T. G. Rautian, and P. G. Richards, “Absolute locations for underground nuclear tests at Novaya Zemlya,” ms. in preparation for the *Bulletin of the Seismological Society of America*, 2005; and V. I. Khalturin, T. G. Rautian, and P. G. Richards, “Yields for underground nuclear explosions at the Novaya Zemlya Test Site,” ms. in preparation for the *Bulletin of the Seismological Society of America*, 2005. The magnitude-yield relation for the northern area of underground testing at Novaya Zemlya differs slightly from this relation for the southern area.

2. F. von Hippel, “Arms Control Physics: the New Soviet Connection,” *Physics Today* 42:39–46 (1989).

3. V. S. Bocharov, L. P. Vladimirsky, and A. M. Novikov, “Estimation of the Accuracy of Explosion Yield by the Seismic Method for UNTs Conducted Under Known Conditions” (in Russian), *Atomic Energy* 65:114–119 (1988); and V. S. Bocharov, M.N. Georgievsky, V. V. Kirichenko, and A. V. Peshkov, “Estimation of the Yield of UNEs Taking Account of their Actual Seismic Efficiency” (in Russian), *Atomic Energy* 65:653–659 (1988); and V. S. Bocharov, S. A. Zelentsov, and V. I. Mikhailov, “Characteristics of 96 Underground Nuclear Explosions at the Semipalatinsk Test Site” (in Russian), *Atomic Energy* 67:210–214 (1989).

4. Y. E. Shipko and N. P. Filonov, “Northern Test Site” (in Russian), *Information Bulletin of the Center of Public Information of Atomic Energy* (Moscow, 4 June 1990), 22 pp.; V. N. Mikhailov, G. A. Tsirkov, V. M. Ivanov, Y. E. Shipko, and 19 co-authors, “Novaya Zemlya, Report of Soviet Experts Given at Soviet-Finland Meeting” (Moscow 28 February, 1991); V. N. Mikhailov, G. A. Tsirkov, V. M. Ivanov, Y. E. Shipko, and 19 co-authors, “Novaya Zemlya, Report of Soviet Experts given at International Symposium” (Ottawa, 21–26 April 1991); V. N. Mikhailov, G. E. Zolotukhin, A. M. Matushchenko, and Yu V. Dubasov (eds.), “USSR Nuclear Explosions,” *Issue 1. Northern Test Site: Nuclear Explosions, Radiology and Radiation Safety. Reference Information* (in Russian), (St. Petersburg: Khlopin Institute, 1992), 195 pp.; K. N. Andrianov, V. N. Bazhenov, and 29 co-authors, “Nuclear Explosions in the USSR,” *V.1, Northern Test Site, Information Handbook* (in Russian), (Moscow, 1992); and V. N. Mikhailov, G. E. Zolutukhin, and A. M. Matushchenko (eds.), “Northern Test Site: the Reports and Presentations of the

Russian Experts at the International Conferences," *Meetings and Symposiums during 1990–1992* (in Russian) (St. Petersburg: Khlopin Institute, 1993), 406 pp.

5. Y. V. Dubasov, A. M. Matushchenko, and V. N. Mikhailov (eds.), "Nuclear Explosions in the USSR. Northern Test Site," *Reference Publication* (in Russian), (St. Petersburg: Khlopin Radium Institute Publishing House, 1999), 163 pp.

6. These 10 collections are as follows:

IDG (1990), V.V. Adushkin and A.A. Spivak (eds.), *Explosions in heterogeneous media* (in Russian), (Moscow: Nedra), 287 pp.

IDG (1994a), *Mechanical Effects of Underground Explosions* (in Russian), (Moscow: IDG), 390 pp. 28 papers published by IDG authors during last 25 years.

IDG (1994b), *Dynamic Process in Geospheres* (in Russian), (Moscow: IDG), 333 pp. 35 papers.

IDG (1995), *Dynamic Processes in the Internal and External Geospheres* (in Russian), (Moscow: IDG), 285 pp. 33 papers.

IDG (1996a), *Physical Processes in Geospheres under the High Energy Signals* (in Russian), (Moscow: IDG), 327 pp. 35 papers.

IDG (1996b), Seismic Monitoring of UNEs. *Federal System of Seismic Observations and Earthquakes Prediction Bulletin*, special issue v.3 (in Russian), (Moscow: IDG), 104 pp. 12 papers.

IDG (1998), *Dynamic Processes in the Geospheres* (in Russian), (Moscow: IDG), 320 pp. 37 papers.

IDG (1999), *Physical Processes in the Geospheres* (in Russian), (Moscow: IDG), 390 pp. 39 papers.

IDG (2001), *Main results of Scientific Projects Conducted and Finished in the Institute during 1996–2001* (in Russian), (Moscow: IDG), 119 pp. (Short review of 64 projects), and

IDG (2002). *Non-stationary Processes in the Upper and Lower Geospheres* (in Russian), (Moscow: IDG), 627 pp. 58 papers.

7. W. Leith, J. R. Matzko, J. Unger, and D. W. Simpson, "Geology and Image Analysis of the Soviet Nuclear Test Site at Matochkin Shar Novaya Zemlya, USSR," *Proceedings of the 12th Annual DARPA/PL Seismic Research Symposium, DARPA*, Arlington, VA (1990).

8. J. R. Matzko, "Underground Nuclear Testing on Novaya Zemlya: The Physical Background," *Post-Soviet Geography* 35(3):123–141 (1994); J. R. Matzko, "Physical environment of the Underground Nuclear Test Site on Novaya Zemlya, Russia." *Open File Report 93–501*, U.S. Geological Survey (Reston, VA, 1993), 28 pp.

9. J. Skorve and J. K. Skogan, "The NUPI Satellite Study of the Northern Underground Nuclear Test Area on Novaya Zemlya," *Report N 164*, Norwegian Institute of International Affairs (NUPI), (1992), 51 pp.

10. P. D. Marshall, D. Porter, J. B. Young, and P. A. Peachell, "Analysis of short-period seismograms from explosions at the Novaya Zemlya test site in Russia," *Atomic Weapons Establishment Report O 2/94*, available from Her Majesty's Stationery Office (London, U.K., 1994).

11. P. G. Richards, "Accurate Estimates of the Absolute Location of UNTs at the Northern NZTS," *Proceedings of Second Workshop on IMS Location Calibration*, 10–24 March 2000 (Oslo, Norway, 2000).

12. “Revolution in Map Making facilitates Verification Research,” in *The MONITOR*, newsletter of the Nuclear Monitoring Research Office, DARPA, vol.3/No.1, Fall 1992.

13. There are two Russian editions and one English edition of this book: V. N. Mikhailov, et al., *USSR Nuclear Tests, vol. 1. The goals, general characteristics, and organization of nuclear tests. First nuclear tests* (in Russian), (Sarov: VNIIEF, 1997). 287 pp. V. N. Mikhailov, et al., *USSR Nuclear Tests* (in Russian), (Moscow: Atomizdat, 1997). 303 pp. V. N. Mikhailov, et al., *USSR Nuclear Tests, vol. 1* (in English), (Begell-Atom, 1999).

14. V. A. Logachev, et al., *Novaya Zemlya Test Site. Ensuring the General and Radiological Safety of the Nuclear tests. Facts, Testimonies, Memories* (in Russian), (Moscow: IzdAT, 2000), 485 pp.

15. B. I. Ogorodnikov, compiler, *Nuclear Archipelago* (in Russian), (Moscow: IzdAT Pub. House, 1995), 255 pp. A collection of the memoirs of participants in the nuclear test program at NZTS.

16. *History of Atomic Project* (in Russian), 17 volumes (Moscow: Russian Scientific Center Kurchatov Institute, 1994–1998). Memories of several hundred participants of the Soviet Nuclear Weapon project.

17. A. P. Vasiliev, et al., *The Service born in the Atomic Century: The History of the Soviet Special Monitoring Service (SSK)* (in Russian), first edition in two volumes (Moscow: SSK, 1998), 840 pp. Also a second edition in three volumes (Moscow: SSK 2002), 1112 pp. that includes hundreds of pictures and declassified early documents.

18. V. N. Mikhailov, *I am a Hawk. Memoirs of Atomic Energy Minister Mikhailov*, (The Pentland Press: Durham), 195 pp.

19. V. S. Bocharov, S. A. Zelentsov, V. N. Mikhailov, “Characteristics of 96 Underground Nuclear Explosions at the Semipalatinsk Test Site” (in Russian), *Atomic Energy* 67: 210–214 (1989): See also reference 13.

20. Principally, we use announced yield information to calibrate seismic magnitudes. See reference 1. The magnitude—yield relation is slightly different for northern and southern testing subareas.

21. K. A. Kondratieva, “Glacial Thicknesses and Cryolithozones of Novaya Zemlya: Mapping on a Scale of 1:2,500,000” (translation from Russian), *Moscow University Geology Bulletin* 33(6):57–69 (1978); and K. A. Kondratieva, “Frozen-Temperature Map of Novaya Zemlya, Scale 1:2,500,000” (in Russian), *Problems of Cryology* 18:80–101 (Moscow, 1979).

22. K. A. Kondratieva, S. Y. Parmuzin and I. I. Petrozhitsky, “Cryological Mapping in Study the Novaya Zemlya as a Place for Burial the Radioactive Waste” (in Russian), *Geoecology* 6:83–92 (1996).

23. With reference to UNTs, the gas content is usually defined in the Soviet literature as the weight % of the gas, mostly carbon dioxide, which emanated under thermal decomposition of the rock at 1000°C. The presence of pyrite crystals in rocks in the adits led to hydrogen sulfide gas being released by several UNTs.

24. D. D. Sultanov, “Seismic Observations of UNTs on the NZTS” (in Russian), *The Problems of Seismic Monitoring of Underground Nuclear Explosions. Federal System of Seismological Observations* 3:23–26 (Moscow, 1996). See also reference 14.

25. L. A. Daragan-Sushcheva, A. D. Pavlenko, and Yu. I. Daragan-Sushcheva, “Crustal Structure of the South Barents Depression,” *Russian Academy of Sciences, Proceedings*

343, 2:217–219 (1995); B. M. Shipilov and B. V. Senin, "Deep Structure of the Floor of the Barents Sea" (in Russian), *Geotectonics* 3 (1988); T. Zhang and T. Lay, "Effect of crustal structure under the Barents and Kara Seas on short-period regional wave propagation for Novaya Zemlya explosions: Empirical relations," *Bull. Seism. Soc. Amer.* 84(4):1132–1147 (Aug. 1994).

26. According to Volume 2, page 13 of Nuclear Tests of the USSR (Sarov, 1997, see reference 13) the typical adit for UNTs (at the Semipalatinsk and Novaya Zemlya test sites) had cross-sectional area of about 10 to 12 sq. m and a gradient of about 0.25 to 0.30 degree toward the exit. The standard rate of adit construction was about 100 m per month.

27. E. A. Shitikov, "In interests of the Navy," *Nuclear Archipelago* (in Russian), (Moscow: IzdAT, 1995), pp. 60–75.

28. V. D. Khristoforov, "Underwater explosions on Guba Chernaya" (in Russian), *History of Atomic Project* 6:110–117 (Moscow, Kurchatov Institute, 1997).

29. See p. 73 of reference 15.

30. See pp. 144–148 of reference 14.

31. The BIG IVAN bomb was 8 m long and had a diameter of 2.1 m, according to pp. 82–84 of reference 42.

32. K-L. Grönhaug, "The Nuclear Atmospheric Explosions on Novaya Zemlya. Estimates of Positions, Energy and Radiation Release," *Conference on Radiological Problems in the Nordic Regions.* (Tromse, Norway, November 21–22, 1991).

33. See for example the newspaper *Komsomolskaya Pravda*, 31 October 1991.

34. V. V. Adushkin and K. I. Goreliy, "Reaction of the ionosphere to atmospheric nuclear explosions" (in Russian), in *Dynamic Processes in Geospheres*, (Moscow: IDG, 1994), pp. 239–248; V. V. Adushkin and K. I. Goreliy, "Global Variation of layers fo-F2 after Atmospheric Nuclear Explosion 58 mt at NZTS" (in Russian), in *Dynamic Processes in the Internal and External Geospheres* (Moscow: IDG, 1995), pp. 82–87.

35. Yu. N. Smirnov, "Three interesting episodes in the Soviet nuclear program", in E. S. Husebye and A. M. Dainty (eds.), *Monitoring a Comprehensive Test Ban Treaty*, (Kluwer Academic Publishers, 1996), pp. 11–24.

36. Magnitudes, from reference 10.

37. V. D. Garnov, "Twelve nuclear explosions in the atmosphere in the Guba Suleymenova region" (in Russian), *History of Atomic Project* 11:215–219 (Moscow: Kurchatov Institute, 1997); M. Enerva, J. L. Stevens, and J. Murphy, "Analysis of Russian hydroacoustic data," *Technical Report DTRA-TR-01-19* to the Defense Threat Reduction Agency, 193 pp., November 2004.

38. F. Ringdal, "Study of Low-Magnitude Seismic Events near the Novaya Zemlya Nuclear Test Site", *Bull. Seism. Soc. Am.* 87(6):1563–1575 (1997).

39. Our value of 4.2 mt for the total yield of the 12 September 1973 UNT is derived as follows: the annual total of all tests at NZ for 1973 is given by Mikhailov et al. (1997) as 7820 kt; and there were just three UNTs that year with magnitudes 6.97 (12 Sept., Matochkin Shar), 5.89 (27 Sept. Krasino), and 6.98 (27 Oct, Krasino). The yield of the last test, Y = 3500 kt has been given by Adushkin et al. (1996) and Logachev (2000, p. 241). The relatively small event at Krasino with mb 5.89 corresponds to a yield about 120 kt with error not more than about 50 kt. Hence the 12 Sept. UNT yield was about 4200 kt. The accuracy of this number depends principally on 3500 kt and 7820 kt being accurate values for the yield of the 27 Oct UNT, and the total yield at NZ in 1973.

40. V. V. Adushkin, Yu. V. Dubasov, A. M. Matushchenko, et al., *Description and Estimation of the Environmental Conditions at Novaya Zemlya Test Site* (in Russian), (Sarov: Russian Federal Nuclear Center, 1996), 114 pp.

41. In terms of yield and depth of burial, this single-fired 3.5 mt shot in a deep shaft was quite similar to the U.S. underground nuclear test “CANNIKIN” conducted in the Aleutians in 1971.

42. V. N. Mikhailov, et al., *USSR Nuclear Tests, vol. 2, Technology of Nuclear Tests* (in English), (Begell-Atom, 1999), 302 pp.

43. F. A. McKeown, “Buried pressurized cavity model of venting from nuclear explosion cavities,” *U.S. Geological Survey report 474–146 to the Nevada Operations Office,* U.S. Atomic Energy Commission (NTS 236), (1972), 44 pp.

44. See, for example, P. G. Richards, and W. Y. Kim, “Equivalent Volume Sources for Explosions at Depth: Theory and Observations”, ms. accepted for publication, *Bull. Seism. Soc. Am.*

45. H. Israelsson, R. Shunga, and O. Dahlman, “Aftershocks caused by the Novaya Zemlya explosion on October 27, 1973,” *Nature* 247:450–452 (1974).

46. V. P. Bazhenov, V. P. Dumik, et al., “Northern Test Site: Chronology and Radiation Phenomenology of UNTs.” (Moscow, 1992. English translation in *Science & Technology*, 1993). Also V. N. Mikhailov, V. P. Dumik, A. M. Matushchenko, and V. G. Safronov, “Ecology Safety of the Underground Nuclear Explosions at Novaya Zemlya,” *Proceedings of Conference: The Radiological Problems in Nordic Region,* (Norway, 21–22 November 1991), 50 pp.

47. V. V. Adushkin and W. Leith, “The containment of Soviet underground nuclear explosions,” *U.S. Geological Survey Open File Report 01–0312*, (2002), 52 pp.

48. V. N. Mikhailov, et al., “Nuclear Tests of the USSR. Hydronuclear Experiments” (in Russian), (Sarov: Russian Federal Nuclear Center, 1998), 22 pp.

49. From these definitions it may be inferred that the term hydronuclear applies to experiments that reach criticality and entail some nuclear energy release, whereas the term hydrodynamic applies to experiments that remain below criticality. For an experiment to be considered hydronuclear its nuclear energy release is required to be limited, for example (in one definition) to not be more than about four pounds of TNT equivalent. During the mid-1990s and prior to deciding that the Comprehensive Nuclear-Test-Ban Treaty would be a zero-yield treaty, various upper limits larger than four pounds were considered.

50. These experiments are described in Mikhailov’s introduction to Logachev’s book (see reference 14).

51. See news stories in the *Washington Post*, Oct 20 and Nov 4, 1997; also P. G. Richards and W. Y. Kim, “Testing the nuclear test-ban treaty,” *Nature* 389:781–782 (1997).

52. NORSAR Scientific Report No. 2-2004, Semiannual Technical Summary, 1 January–30 June 2004, Frode Ringdal (ed.), pp. 36–37.

APPENDIX 1

Content of the V.N. Mikhailov et al., 1997 book “USSR NUCLEAR TESTS”

Page numbers here refer to the Sarov edition of reference 13

The full official list of Soviet nuclear tests is included in Chapter 3/Appendix 1. The following information about each test is presented in the list:

1. Number of explosions. The total was 715 nuclear tests, including 496 UNTs.
2. Date (based on Moscow time = GMT + 3 hours).
3. Place (for Peaceful Nuclear Explosions) or weapons test site (for UNTs).
4. Before 1963: medium and indication of position—e.g., atmospheric, surface. Since 1963: the tunnel or shaft number, for each component explosion in the test.
5. The main purpose of the nuclear explosion, for each component explosion.
6. One of four yield ranges for each single nuclear device in the test: less than 0,001 ton, 0.001–20 kt, 20–150 kt, 150–1500 kt. The yield range 1,500–10,000 kt is indicated only for the two most powerful explosions at NZTS: 12 Sept 1973 and 27 Oct 1973. A specific yield was indicated for all 124 PNEs, including 7 PNEs conducted at the Semilapatinsk Test Site (STS) and 20 UNTs at STS. Yield intervals are shown for each of other UNTs.

APPENDIX 2

Content of the V. Logachev et al., 2000 book

Page numbers here are for reference 14

APPENDIX 3

Content of the Dubasov et al., 1999 book "Nuclear Explosions in the USSR, Northern Test Site"

Editorial Board: Yu. V. Dubasov, A. M. Matushchenko, and V. N. Mikhailov, Radium Institute Publishing House, St. Petersburg, 1999, 163 pp.
Page numbers here are for reference 5

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APPENDIX 4

Chronology, Yield and Height of 85 Atmospheric Nuclear Explosions Conducted at Novaya Zemlya Test Site from 1957 to 1962

N	Date	Y, kt	H, m	Comment
1	Sep 24 1957	1600	2000	
2	Oct 06 1957	2900	2120	
3	Feb 23 1958	860	2500	
4	Feb 27 1958	250	2500	
5	Feb 27 1958	1500	n/a	
6	Mar 14 1958	40	n/a	
7	Mar 21 1958	650	2500	
8	Sep 30 1958	1200	1500	
9	Sep 30 1958	900	2500	
10	Oct 02 1958	290	1400	

(Continued on next page)

Appendix 4: *(Continued)*

N	Date	Y, kt	H, m	Comment
11	Oct 02 1958	40	n/a	
12	Oct 04 1958	9	800	
13	Oct 05 1958	15	1200	
14	Oct 06 1958	5.5	1200	
15	Oct 10 1958	68	n/a	
16	Oct 12 1958	1450	n/a	
17	Oct 15 1958	1500	2150	
18	Oct 18 1958	2900	n/a	
19	Oct 19 1958	40	n/a	
20	Oct 19 1958	0	900	Failure
21	Oct 20 1958	440	n/a	
22	Oct 21 1958	2	270	
23	Oct 22 1958	2800	2070	
24	Oct 24 1958	1000	1525	
25	Oct 25 1958	190	1500	
26	Oct 25 1958	<0.1	300	Failure
27	Sep 10 1961	2700	2000	
28	Sep 10 1961	12	390	
29	Sep 12 1961	1150	1190	
30	Sep 13 1961	6	250	
31	Sep 14 1961	1200	1700	
32	Sep 16 1961	830	n/a	ICBM
33	Sep 18 1961	1000	1500	ICBM
34	Sep 20 1961	150–1500	1600	
35	Sep 22 1961	260	1300	
36	Oct 02 1961	250	1500	
37	Oct 04 1961	1500–10000	2100	ICBM
38	Oct 06 1961	4000	2700	
39	Oct 08 1961	15	1450	
40	Oct 20 1961	1450	n/a	
41	Oct 23 1961	12500	3500	
42	Oct 25 1961	300	1450	
43	Oct 30 1961	58, 000	4000	
44	Oct 31 1961	5000	2200	
45	Oct 31 1961	150–1500	1530	
46	Nov 02 1961	120	1400	
47	Nov 02 1961	280	1500	
48	Nov 04 1961	15	1770	
49	Nov 04 1961	150–1500	1750	
50	Nov 04 1961	6	2240	
51	Aug 05 1962	21100	3600	
52	Aug 10 1962	150–1500	1560	
53	Aug 20 1962	2800	2500	ICBM
54	Aug 22 1962	1600	1700	
55	Aug 25 1962	1500–10000	2980	
56	Aug 27 1962	4200	3000	
57	Sep 02 1962	80	1300	
58	Sep 08 1962	1900	1730	
59	Sep 15 1962	3100	n/a	
60	Sep 16 1962	3250	n/a	
61	Sep 18 1962	1350	2000	
62	Sep 19 1962	1500–10000	3280	
63	Sep 21 1962	2400	3000	
64	Sep 25 1962	19100	4090	
65	Sep 27 1962	>10000	3900	

(Continued on next page)

Appendix 4: *(Continued)*

N	Date	Y, kt	H, m	Comment
66	Oct 07 1962	320	1400	
67	Oct 09 1962	15	3000	
68	Oct 22 1962	8200	3230	
69	Oct 27 1962	260	1550	
70	Oct 29 1962	360	1550	
71	Oct 30 1962	280	1500	
72	Nov 01 1962	240	1500	
73	Nov 03 1962	390	4000	
74	Nov 03 1962	45	710	
75	Dec 18 1962	110	1600	
76	Dec 18 1962	69	1500	
77	Dec 20 1962	8.3	1070	
78	Dec 22 1962	6.3	1050	
79	Dec 23 1962	430	1460	
80	Dec 23 1962	8.3	1470	
81	Dec 23 1962	2.4	1270	
82	Dec 24 1962	1100	1320	
83	Dec 24 1962	24200	3750	
84	Dec 25 1962	3100	2250	
85	Dec 25 1962	8.5	990	

Notes: 1—The height was not announced for 12 atmospheric nuclear explosions (ANEs) and the yield was not announced for eight ANEs. Information is from references 13 and 14.
2—ANEs on 19 October 1958 and 25 October 1958 failed and had near zero yield.
3—For four ANEs the nuclear charges were delivered by intercontinental ballistic missiles (ICBMs), launched from a base in South East Siberia at a distance of 3000–4000 km from NZTS. They were exploded "somewhere above the Barents Sea" and are included as NZTS tests.

APPENDIX 5

Information on 39 UNTs at NZTS , including their seismic magnitude and annual yield (kt)

1 Test NN	2 Year	3 Date	4 Tunnel or shaft	5 Number subexpl.	6 mb AWE	7 Annual yield
1	1964	Sep 18	tun G	1	4.19	20
2	1964	Oct 25	tun B	1	4.82	
3	1966	Oct 27	tun A-1	1	6.49	1,400
4	1966	Oct 27	tun A-2	1		
5	1967	Oct 27	tun A-4	1	5.98	260
			tun A-5	1		
6	1968	Nov 07	tun A-3	3	6.13	330
7	1969	Oct 14	tun A-7	2	6.18	540
			tun A-9	1		
8	1970	Oct 14	tun A-6	3	6.79	2,200
9	1971	Sep 27	tun A-8	4	6.67	2,450
10	1972	Jul 27	sh Yu-31	1	<3.0	
11	1972	Aug 28	tun A-16	4	6.49	1,130
12	1973	Sep 12	tun B-1	4	6.97	7,820

(Continued on next page)

Appendix 5: *(Continued)*

1 Test NN	2 Year	3 Date	4 Tunnel or shaft	5 Number subexpl.	6 mb AWE	7 Annual yield
13	1973	Sep 27	sh Yu-4	1	5.89	
14	1973	Oct 27	sh Yu-1	1	6.98	
15	1974	Aug 29	tun A-11	5	6.58	3,430
16	1974	Nov 02	sh Yu-5N	1	6.81	
17	1975	Aug 23	tun A-10	8	6.55	4,190
18	1975	Oct 18	sh Yu-6N	2	6.75	
19	1975	Oct 18	sh Yu-7	1		
20	1975	Oct 21	tun A-12	5	6.60	
21	1976	Sep 29	tun A-14	2	5.83	140
22	1976	Oct 20	tun A-15	5	4.98	
23	1977	Sep 01	tun A-17	4	5.66	130
24	1977	Oct 09	tun A-7P	1	4.36	
25	1978	Aug 10	tun A-18	6	6.00	240
26	1978	Sep 27	tun A-19	7	5.63	
27	1979	Sep 24	tun A-32	3	5.77	280
28	1979	Oct 18	tun A-20	4	5.79	
29	1980	Oct 11	tun A-25	4	5.76	130
			tun A-30	3		
30	1981	Oct 01	tun A-23	4	5.97	140
31	1982	Oct 11	tun A-37	4	5.58	80
32	1983	Aug 18	tun A-40	5	5.91	250
33	1983	Sep 25	tun A-21	4	5.77	
34	1984	Aug 26	tun A-100	1	3.80	110
35	1984	Oct 25	tun A-26	4	5.82	
36	1987	Aug 02	tun A-37A	5	5.82	150
37	1988	May 07	tun A-24	3	5.58	220
38	1988	Dec 04	tun A-27	5	5.89	
39	1990	Oct 24	tun A-13N	8	5.61	70

Notes: Comments on specific columns of the Table:
1—number NN of each UNT corresponds the number on the official Russian list (reference 13);
4—tunnel codes (tun) are for UNTs in the northern subarea (Matochkin Shar), shaft codes (sh) are for the southern subarea (Krasino);
5—number of single nuclear devices in each tunnel or shaft;
6—teleseismic magnitude of each test (from reference 10);
7—total yield of all UNTs (in kt), for each year (from reference 13).

APPENDIX 6

Summary of information from Russian sources on radioactive pollution, including radioactive rare gas seepage, gamma radiation, and venting episodes, for 39 UNTs at NZTS

					6 Radioactive pollution	7	
1 #	2 Year	3 Date	4 Containment or Type of pollution	5 T min	Gamma radiation, R/h	Area	8 Comment
1	1964	Sep 18	SoR	1	2	Onsite	
2	1964	Oct 25	SoR	30	1.5	Offsite	

(Continued on next page)

Appendix 6: *(Continued)*

					6	**7**	
			4		**Radioactive pollution**		
1 #	**2 Year**	**3 Date**	**Containment or Type of pollution**	**5 T min**	**Gamma radiation, R/h**	**Area**	**8 Comment**
3	1966	Oct 27	SoR	10	7	Offsite	
4	1966	Oct 27	SoR	10	7	Offsite	
5	1967	Oct 21	SoR	23	20	Onsite	
	1967	Oct 21	G.cont.	No	No	Contain.	
6	1968	Nov 07	SoR	60	5	Onsite	
7	1969	Oct 14	G.cont.	No	—	Contain.	
	1969	Oct 14	V.R.!	60	1000	Venting, accident	A
8	1970	Oct 11	SoR	15	250	Offsite	
9	1971	Sep 27	SoR	15	1	Offsite	
10	1972	Jul 27	G.cont.	No	No	Contain.	
11	1972	Aug 28	SoR	10	100	Offsite	
12	1973	Sep 12	SoR	10	2.2	Offsite	
13	1973	Sep 27	SoR	12	3	Offsite, accident	B
14	1973	Oct 27	G.cont.	No	No	Contain.	
15	1974	Aug 29	SoR	12	3	Offsite	
16	1974	Nov 02	G.cont.	No	No	Contain.	
17	1975	Aug 23	SoR	50	1.5	Offsite	
18	1975	Oct 18	SoR	3	0.4	Onsite	
19	1975	Oct 18	G.cont.	No	No	Contain.	
20	1975	Oct 21	SoR	10	250	Offsite	
21	1976	Sep 29	SoR	10	3	Offsite	
22	1976	Oct 20	G.cont.	No	No	Contain.	
23	1977	Sep 01	SoR	15	n/a	Offsite	C1
			G.cont.	No	No	Contain	C2
24	1977	Oct 09	SoR	5	1000	Offsite	D
25	1978	Aug 10	SoR	7	7	Offsite	
26	1978	Sep 27	G.cont.	No	No	Contain.	
27	1979	Sep 24	SoR	10	300	Onsite	
28	1979	Oct 18	SoR	10	1.5	Onsite	
29	1980	Oct 11	G.cont.	No	No	Contain.	
		Oct 11	SoR	10	8	Offsite	
30	1981	Oct 01	G.cont.	No	No	Contain.	
31	1982	Oct 11	SoR	12	0.25	Onsite	
32	1983	Aug 18	SoR	10	0.5	Onsite	
33	1983	Sep 25	SoR	15	0.5	Onsite	
34	1984	Aug 26	G.cont.	No	No	Contain.	
36	1987	Aug 02	V.R.!	1.5	>500	Venting, radioact. accident	E
37	1988	May 07	SoR	10	1	Onsite	

(Continued on next page)

Appendix 6: *(Continued)*

1 # 	2 Year	3 Date	4 Containment or Type of pollution	5 T min	6 Radioactive pollution Gamma radiation, R/h	7 Area	8 Comment
38	1988	Dec 04	G.cont.	No	No	Contain.	F
39	1990	Oct 24	G.cont.	No	No	Contain.	F

Columns:
1—Number of UNT in official Russian list (reference 13).
4—Containment or Type of radioactive pollution:
G.cont.—gas containment;
SoR—seepage of radioactive inert gases;
V.R.!—venting of radioactive gases and debris.
5—Time (in minutes) after the explosion when gas seepage appears.
6—Gamma radiation intensity in roentgen per hour near the tunnel or shaft after the UNT.
7—Area, where the radioactive gases were detected. Four levels of radioactive pollution intensity used in the Table:
contain.—gas and debris containment;
onsite—radioactive gases were detected only in Test Site area;
offsite—radioactive gases were detected outside the Test Site;
venting radioact.—venting of radioactivity, outburst of hot gases including steam. Emergency situation.
8—Comments:
A—The emergency situation described in the text of the article.
B—Accident described in the present article. Both main Russian summaries of radioactive aftermaths of UNTs leave out this case.
C1—After reference 14.
C2—After reference 5 and different from reference 14. Indicative of several contradictions in Russian official publications describing levels of radioactive pollution.
D—The intensive seepage of radioactive gases caused a high level of gamma radiation (>1000 R/h!). This was the second UNT in tunnel A-7 (first one was on 14 Oct 1969). Repeated usage of the same tunnel was the main reason of the intensive gases seepage.
E—The last and most dangerous accident. See description in the text of the article.
F—The two last UNTs were conducted at the scaled depth $\gg 120$ m/kt$^{1/3}$. This was during Gorbachev's "*perestroika*" and "*glasnost*." Strong public opinion (and movement) against nuclear tests started at that time. It was the first occasion when representatives of the public visited NZTS. Authorities ordered an increase in the depth of these explosions to avoid possible accidents.