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The Soviet Program for Peaceful Uses of Nuclear Explosions

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This paper presents an historical review of the Soviet program to study and utilize industrial applications of peaceful nuclear explosions (PNEs) in the Soviet Union over the period 1965 to 1988. This was a very active program that carried out 122 nuclear explosions to study some 13 applications. In all, 128 nuclear explosives with yields ranging from 0.01 to 140 kt were used, with the vast majority being between 2 and 20 kt. Over half of these explosions were used for implementation of two industrial applications: the creation of underground cavities in salt for the storage of gas condensate and deep seismic sounding of the Earth's crust and upper mantle. Other applications studied with nuclear explosions included oil and gas stimulation, closure of runaway gas wells, disposal of toxic chemical wastes, block cave mining of underground minerals, production of transplutonic elements, and the excavation of water reservoirs and canals.

In terms of the number of applications explored with field experiments, the Soviet PNE program was an order of magnitude larger than the U.S. "Plowshare" program carried out in the 1960s and early 1970s; the U.S. utilized no explosions on an industrial basis and fired only three industrial field experiments. The Soviet program also included the development of low-fission excavation explosives and specially designed hydrocarbon explosives, which mirrored the device development program in the U.S. Plowshare program.

The Soviet PNE program was terminated in 1989 as part of the unilateral Soviet moratorium on nuclear weapons testing adopted by President Gorbachev. The Comprehensive Test Ban Treaty recently signed by Russia and the United States includes a ban on all nuclear explosions, including those for peaceful uses.

EARLY HISTORY

The concept of utilizing the weapons of war to serve the peaceful pursuits of mankind is as old as civilization itself. Perhaps the most famous reference to this basic desire is recorded in the Book of Micah where the great prophet Isaiah called upon his people "to turn your spears into pitchforks and your swords into plowshares." As the scientists at Los Alamos worked on developing the world's first atomic bomb, thoughts of how this tremendous new source of

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energy could be used for peaceful purposes generally focused on using the thermal energy generated by the slow fission of uranium in a reactor, such as those being used to produce plutonium, to drive electric power stations.

However, being scientists in a new, exciting field, it was impossible to avoid letting their minds wander from the task at hand to other scientific or nonmilitary uses for the bombs themselves. During the Manhattan Project, Otto Frisch, one of the pioneers in the development of the nuclear fission process in the 1930s, first suggested using an atomic explosion as a source for a large quantities of neutrons that could be used in scientific experiments designed to expand the understanding of nuclear physics. After the war was over, many grandiose ideas appeared in the popular press on how this new source of energy should be harnessed to serve mankind.

Not to be left out of the growing enthusiasm for peaceful uses of atomic energy, the Soviet Union added their visions to the public record. In November 1949, shortly after the test of their first nuclear device on September 23, 1949, Andrei Vishinsky, the Soviet representative to the U.N., delivered a statement justifying its efforts to develop its own nuclear weapons capability. In poetic but somewhat overblown rhetoric, he said:

> The Soviet Union did not use atomic energy for the purpose of accumulating stockpiles of atomic bombs, ...it was using atomic energy for purposes of its own domestic economy: blowing up mountains, changing the course of rivers, irrigating deserts, charting new paths of life in regions untrodden by human foot.[1]

A few years later, a Russian engineer, Professor G. I. Pokrovskiy wrote:

> Progressive science claims that it is possible to utilize the noble force of the explosions builder for peaceful purposes.... With the help of directional explosions one can straighten out the beds of large rivers...construct gigantic dams...cut canals.... Indeed, the perspectives disclosed due to the new atomic energy are unlimited.[2]

However, very few of the articles written in the late 1940s and early 1950s had concrete ideas on how the explosive force of the bombs themselves could be used for scientific purposes or to transform the landscape and alter the character of geological formations deep under the earth. One of the first was written by Fred Reines, a young physicist who had come to Los Alamos in 1944 to work on the nuclear weapons program. In June of 1950, he wrote a short article for the *Bulletin of the Atomic Scientists* examining the possibilities of using atomic explosives for a few large-scale, earth-moving applications such as, making canals, mining, breaking up icebergs, and melting the polar icecap. In general, his outlook was rather pessimistic, concluding that "such uses appear at best to be extremely limited in scope, owing to the radioactivity hazard associated with atomic explosions."[3]

With the development of thermonuclear devices, new ideas began to ferment in the minds of the bomb-designers. Thermonuclear devices still required a small fission trigger, but since the thermonuclear fuel consisted of relatively cheap deuterium and lithium and produced almost no long-lived radioactive byproducts, they offered the possibility of an order-of-magnitude decrease in both the cost of an explosive and the amount of radioactivity associated with a given total yield.

The detonation by the Soviet Union of their first thermonuclear explosion on August 12, 1953, led President Eisenhower to the determination that he needed to take the initiative in dealing with the political aspects of the nuclear arms race. Toward this end on December 8, 1953, President Eisenhower delivered his now-famous Atoms for Peace speech at the U.N. calling for

> ...more than the mere reduction or elimination of atomic materials for military purposes.
>
> It is not enough to take this weapon out of the hands of their soldiers. It must be put into the hands of those who will know how to strip its military casing and adapt it to the arts of peace...this greatest of destructive forces can be developed into a great boon for the benefit of all mankind....
>
> Who can doubt, if the entire body of the world's scientists and engineers had adequate amounts of fissionable material with which to test and develop their ideas, that this capability would rapidly be transformed into universal, efficient, and economic usage.

This dramatic and stirring call to the world community to begin the process of applying this powerful new source of energy to the peaceful uses of mankind served as a powerful stimulant within the nuclear physics community and nuclear power industry. Following up on Eisenhower's Atoms for Peace speech, in early 1954 the U.S. proposed that the U.N. sponsor a Conference on the Peaceful Uses of Atomic Energy. The first of four such conferences was ultimately held in Geneva, Switzerland, in August of 1955. It was the largest scientific meeting in the world held up to that time, with over 2,500 participants in attendance; more than 1,000 technical papers were presented. For many Soviet scientists, it was their first opportunity to attend a scientific meeting outside the Soviet Union and to meet their colleagues from the West.[4]

Although no papers were presented at the Geneva Conference on the peaceful uses of nuclear explosions, the general enthusiasm for the integration of peaceful uses of nuclear energy into the fabric of society and the declassification of a broad spectrum of information about the attributes and effects of nuclear fission processes gave rise to an increasing interest in such ideas, particularly within the nuclear weapons community.

Fired by this enthusiasm, in the spring of 1956, a French scientist named Camille Rougeron wrote a monograph conjuring up images of a wide variety of applications for such explosions—building dams, changing the course of rivers, melting glaciers, breaking up ice jams, changing the climate, constructing underground power plants driven by the heat of thermonuclear explosions, and breaking rock for mining.[5] Rougeron's "dreams" added little in the way of quantitative analysis of such applications, but they did serve to raise the expectations of the general public for some peaceful benefit from the nuclear tests being fired in the Pacific and at the Nevada Test Site.

At about the same time, the Soviet engineer G. I. Pokrovskiy again wrote of his vision of using compact, powerful, low-cost nuclear explosives for removing overburden from valuable ore deposits or excavating canals:

> With the data now available, we can say that radioactive contamination in a nuclear explosion should not be considered an insurmountable obstacle to the use of such explosives in mining and construction. On the basis of the many advantages of nuclear explosions, we conclude that the time is ripe to begin actual experiments in this field.[6]

THE U.S. PLOWSHARE PROGRAM

In spite of Pokrovskiy's enthusiasm, little of substance was done over the next ten years in the Soviet Union to further explore his vision. In the U.S., however, the AEC formally established a program for nonmilitary uses of nuclear explosions in the summer of 1957. Named Project Plowshare, the emphasis in the first year was placed on studies aimed at further fleshing out the physics and engineering aspects of using underground nuclear explosions for power generation, on beginning nuclear design work on very low fission explosives especially designed for nuclear excavation, and on finding a suitable site for a near-term demonstration of this new technology.

In the fall of 1957, the AEC carried out the world's first underground nuclear explosion, the Rainier event, a 1.7-kt test emplaced in a tunnel 274 m below a mesa at the Nevada Test Site (NTS). Although it was a weapons test, the purpose was primarily to document the effects of an underground nuclear explosion. Results from the Rainier test gave the Plowshare project a tremendous boost of enthusiasm and confidence that a variety of peaceful uses for nuclear explosions were possible and could be implemented safely. Before

Rainier, all the ideas for peaceful uses were based on theoretical conjecture about the interaction of nuclear explosions with their surroundings. Now the scientists had actually fired an underground explosion, and everything happened about as expected. Thus, Rainier validated many of the Plowshare concepts that had been only sketchy ideas in scientists' minds and gave new confidence that these ideas would work.

In an angry press conference following the presentation of results by Gerry Johnson at the Second International Conference on the Peaceful Uses of Atomic Energy in Geneva in September 1958, Vasiliy Emelyanov, the Chief Soviet Delegate to the Conference, attacked the U.S. Plowshare Program as a subterfuge for continued nuclear weapons testing and scoffed at Plowshare's potential. He disavowed past statements by Soviet scientists, engineers, and politicians expressing interest in such applications and condemned such explosions "as a 'cover' to evade suspension of bomb tests" which "do not reach practical ends, but only political ends."[7]

Undeterred by Emelyanov's negative comments, the U.S. proceeded with development of the Plowshare Program. The first field experiment sponsored by the Plowshare Program was Project Gnome in 1961, a 3.1-kt explosion at a depth of 367 m in a bedded salt formation near Carlsbad, New Mexico. The general purpose was to study the effects of a nuclear explosion in salt, a unique medium that is able to sustain extremely large cavities without collapse, with a view to the use of such cavities for a variety of peaceful purposes. At that time, the possible use of such cavities for decoupling the seismic signal from clandestine nuclear weapons tests was also a controversial arms control issue in the test ban negotiations that were on-going in Geneva. The U.S. invited observers from all the U.N. countries to view the Gnome explosion, but the Soviet Union, consistent with their Geneva position, refused to participate. The Gnome explosion was a technical success, providing much data on scientific experiments and the effects of nuclear explosions in salt. It also resulted in a public relations disaster when a leak developed in the tunnel stemming, and a cloud of radioactive gases escaped shortly after the explosion.[8]

Over the next 15 years, the U.S. Plowshare Program studied a variety of possible applications for peaceful nuclear explosions. Table 1 provides a list of the field experiments sponsored by the U.S. Plowshare Program. In the early years, primary emphasis was placed on the development of technologies for nuclear excavation, the application that appeared most economically attractive and technically straightforward. Following an abortive plan to excavate a demonstration harbor in northern Alaska that was abandoned in 1962, almost all excavation research was directed at the technical challenges of using nuclear explosions to excavate a new sea-level canal through the Central

Table 1: Data on U.S. peaceful nuclear explosions.

Name or designator	Date	Yield (kt)	Depth of burial (m)	Geology	Purpose
Development of nuclear excavation technology[a]					
Sedan	7/6/62	104	193.6	Alluvium	Nuclear cratering and scaling laws to 100 kt level.
Sulky	12/18/64	0.09	27.1	Granite	Cratering mechanics at a deep scaled depth-of-burial.
Palanquin	4/14/65	4.3	85.7	Rhyolite	Cratering mechanics at a deep scaled depth-of-burial in rhyolite.
Cabriolet	1/26/68	2.2	51.8	Rhyolite	Nuclear cratering at optimum depth in hard, dry rock.
Buggy[b]	3/12/68	5.5	41.2	Basalt	Nuclear row-charge cratering in hard, dry rock.
Schooner	12/8/68	30	111.3	Bedded Tuff	Nuclear cratering explosion with a moderate yield in wet rock.
Contained experiments					
Gnome	10/12/61	3.0	360.9	Bedded Salt	Explosion effects in a salt medium. Recoverability of isotopes from salt. Scientific experiments with neutrons from a nuclear explosion. Recoverability of heat from a nuclear explosion in salt.
Handcar	11/5/64	12.0	402.0	Dolomite	Effects of a nuclear explosion in a carbonate medium.
Marvel	9/21/67	2.2	175.9	Alluvium	Hydrodynamic flow of energy from a nuclear explosion down a one-meter diameter pipe.
Gasbuggy	12/10/67	29.0	1,292.4	Shale	Nuclear gas stimulation.
Rulison	9/10/69	6	6	Shale/-Sand-stone	Nuclear gas stimulation.
Rio Blanco[c]	5/17/73	99	1,898.9	Shale/-Sand-stone	Nuclear stimulation of a thick gas-bearing formation with multiple nuclear explosions.

a. This list does not include the 0.5-kt Dannyboy nuclear cratering experiment in basalt on May 3, 1962, which was sponsored by the U.S. Department of Defense.

b. Buggy consisted of five 1.1-kt explosives spaced 45.7 m apart in an east-west line.

c. Rio Blanco consisted of three 33- kt explosives spaced about 130 m apart in a vertical line at depths of 1,780.0, 1,898.9 and 2,039.1 m below the surface. The indicated depth is the depth of the middle explosive.

American Isthmus to replace the Panama Canal. This effort was in direct support of the Atlantic–Pacific Interoceanic Canal Study Commission (APICSC), appointed by President Lyndon Johnson in 1965, and continued until the Commission delivered its final report in December, 1970.

As part of this effort, Plowshare carried out six nuclear cratering experiments between 1961 and 1968 with yields ranging from 0.1 to 100 kt. All were conducted at the NTS. In an effort to ameliorate the primary hazard from nuclear excavation—the radioactivity released to the atmosphere—a major part of this program was the development of special ultralow-fission nuclear explosives designed for excavation applications. This special excavation explosive development program required nine tests at NTS from 1963 to 1970 and resulted in an explosive design with various yields with a fission yield so low that, when used in a cratering application, the fission products released to the atmosphere by each explosive would be less than that created by a 20-ton fission explosion. With the conclusion of the APICSC study and the rising public sensitivity to environmental contamination, the nuclear excavation portion of the U.S. Plowshare Program was phased out in the early 1970s.

Starting with the Gnome experiment in 1961, the Plowshare Program provided continued support for scientific experiments, primarily as additions to weapons tests, utilizing the extremely high fluxes of neutrons available within and near nuclear explosions to conduct experiments impossible with other neutron sources. In the early 1960s, a major program effort was undertaken to look at the possibility of using these high neutron fluxes to produce heavy transplutonic elements well beyond the end of the Periodic Table. The ultimate goal was the use of multiple neutron captures to reach the predicted "island of stability" at element 114. Between 1962 and 1969, Plowshare supported the design and fielding of five dedicated experiments and "add-ons" to some ten weapons tests at NTS in a futile attempt to reach this elusive goal. However, very large quantities of some heavy elements were produced, of which only trace fractions were recovered from the melt zone. The last isotope production experiment on the Hutch event produced an estimated neutron flux on the target material of 40 mols/cm^2 and produced over 10^{17} atoms of Fm-257—10^4 more heavy elements than any previous experiment—and over 10^{20} atoms of Cm-250. More than 10^{10} atoms of Fm-157 were recovered, 100 times more than had been produced by any other method to that date.

In addition to these scientific programs, the Plowshare Program also carried out two experiments in the mid-1960s to learn more about the effects of nuclear explosions. The Handcar experiment in 1964 was a 12-kt contained explosion fired at NTS in a dolomite formation, consisting of a mixture of calcium and magnesium carbonate. Prior to the Handcar test, explosions in rock containing a high carbonate content had been avoided because of concerns regarding containment of the large quantities of non-condensable CO and CO_2 gas produced by a nuclear explosion in such a medium. Results from the Handcar explosion demonstrated that such nuclear explosions could be carried out with complete containment in such a medium.[9]

The second experiment was the Marvel test, also at NTS, in 1967 to study the propagation of a shock wave from a nuclear explosion along a horizontal, air-filled tunnel, one meter in diameter and 122 m long, which was immediately adjacent to the nuclear explosion. The primary purpose was to develop techniques for understanding the propagation of energy in a non-spherical geometry.[10]

Among the industrial applications utilizing a completely contained explosion, the most intense studies were directed at the stimulation of gas production from low-permeability gas reservoirs, the recovery of oil from the vast oil shale deposits in Colorado, the breakage of copper ore preparatory to in-situ leaching, and the creation of cavities for the storage of oil and natural gas.

Only gas stimulation found sufficient industrial support to proceed to actual field experiments.[11] From 1967 to 1973, three joint industry-government experiments were carried out in very low permeability gas fields (see table 1). In all cases, the explosions were carried out without incident, and significant increases were realized in the production of gas over that experienced from nearby conventional wells.[12]

The most significant radiological concern was the incorporation of tritium produced by the nuclear explosive into the gas produced from the stimulated region. To reduce emplacement costs and tritium levels to the lowest possible levels, the Plowshare Program developed a special nuclear explosive less than 200 mm (7.8 in) in diameter that produced an extremely small amount of tritium (<0.2 g), primarily by neutrons in the medium surrounding the explosive. Three of these special explosives were used in the same hole for the Rio Blanco event, one above the other spaced about 130 m apart.

Although projected public radiation exposures from commercial use of stimulated gas had been reduced to less than one percent of background,[13] it became clear in the early 1970s that public acceptance within the U.S. of any product containing radioactivity, no matter how minimal, was difficult if not impossible. In addition, the economic viability of nuclear gas stimulation would require the stimulation of hundreds of wells over several decades, a prospect that proved daunting to potential industrial sponsors in light of growing public concerns about environmental quality. Following completion of the post-shot gas-production testing of Rio Blanco in December, 1974, the gas stimulation program, together with the studies of other potential Plowshare applications, was rapidly phased down, and the U.S. Plowshare Program was terminated in 1977.

In summary, during its 20-year life, the U.S. Plowshare Program carried out twelve field experiments, six nuclear cratering events, and six contained explosions. Only four Plowshare events were conducted off the Nevada Test Site, one to better understand the effects of a nuclear explosion in salt and three for nuclear gas stimulation.

In addition to these experiments, the program also fully funded 16 device development tests at NTS. Five of these tests, together with eight add-ons to weapons tests, were in pursuit of the goal of developing super-heavy transplutonic elements. Nine were for the purpose of developing an ultralow-fission thermonuclear explosive for use in nuclear excavation projects, and one each were for the development of special emplacement techniques and for a small-diameter, ultralow-tritium-producing explosive for hydrocarbon applications such as Rio Blanco.

THE SOVIET PROGRAM FOR THE USE OF NUCLEAR EXPLOSIONS IN THE NATIONAL ECONOMY

An Historical Perspective

The Soviet Union did not immediately follow the U.S. lead in 1958 in establishing a program to investigate the peaceful uses of nuclear explosions. Presumably, its political position in support of a comprehensive nuclear test ban, which would have banned or strongly discouraged such explosions, forestalled any efforts to establish such a program until the mid-1960s.

At some point during this time frame, the Soviet Union formally established "Program No. 7—Nuclear Explosions for the National Economy." Alexander D. Zakharenkov, a chief weapons designer at the Chelyabinsk-70 nuclear weapons laboratory was named to head the program, and Oleg L. Kedrovskiy to be the chief scientist. Initially, the Soviet program was focused on two applications, nuclear excavation and oil stimulation, as the U.S. Program had been. However, interest in other applications quickly developed, and within five years the Soviet program was actively exploring six or seven applications involving participation by some ten different Ministries.[14]

One of the first steps in developing such a program was initiated by Efrim P. Slavskiy, former Minister of the Medium Machine Building Ministry (the ministry responsible for the entire Soviet nuclear weapons program).[15] He was undoubtedly aware of the activities of the U.S. Plowshare program and was reported to be an avid supporter of using nuclear explosions for industrial purposes. On his directive on January 15, 1965, his Ministry sponsored a large-yield (140 kt) cratering explosion carried out at a depth of 178 m on the edge of the Semipalatinsk Test Site (STS) in northern Kazakhstan, which formed a large lake. Minister Slavskiy was reported to have been the first person to have taken a swim in the crater lake.[16]

Later in 1965, in cooperation with the Ministry of the Oil Industry, Program No. 7 began field experiments looking at the possibility of using nuclear explosions to increase oil production as well as planning experiments in salt to produce cavities. The nuclear weapons laboratory at Arzamas-16 (All-Soviet Institute of Experimental Physics–VNIIEF) near Gorky initially played the major role in Program No. 7, adapting military explosions to peaceful applications. The laboratory at Chelyabinsk-70 (All-Soviet Institute of Technical Physics–VNIITF) soon became involved and, over the years, became the most active participant in the program, particularly in the design of special nuclear explosives for particular applications.[17] Models of the special nuclear explosives can be seen in the Chelyabinsk-70 Nuclear Weapons Museum in Snizhinsk.

In November of 1965, a conference was held in the Soviet Union to consider possible industrial and scientific uses for nuclear explosions. The meeting included the leading scientists and weapons designers in the Soviet nuclear weapons program, including Andrei Sakharov. The scientists evinced great interest in such a program, including the development of special explosives to facilitate the fielding of nuclear explosives in unique industrial situations and to reduce the radioactivity produced by such explosions. The ideas discussed ranged from scientific experiments and industrial applications utilizing the unique physical and electromagnetic properties of nuclear explosions to control asteroids and power rockets in deep space.[18]

In the middle of 1966, a crisis in the gas industry suddenly offered an opportunity for a new application for peaceful nuclear explosions, the extinguishing of runaway gas wells. Successfully closing several such wells in 1966 and 1967 gave growing confidence to the leaders of the program, and they began to think about a broad spectrum of new applications.

In the spring of 1969, the Soviet Union approached the U.S. with a proposal to engage in a series of bilateral discussions on peaceful nuclear explosions. The first of a series of four such meetings was held in Vienna, Austria, on April 14–16, 1969. Subsequent meetings were held in Moscow (February 12–17, 1970), Washington (July 12–23, 1971), and Vienna (January 15–17, 1975).[19] In the course of these meetings with scientists from the U.S. Plowshare Program, Soviet scientists cautiously unveiled some of the technical details of the first few PNE experiments as well as general plans for several applications they were developing. In the early 1970s, the Soviet Union also provided information on the scope and technical results of some of their program activities through a series of Panel Meetings on Peaceful Nuclear Explosions at the International Atomic Energy Agency (IAEA) in Vienna, Austria.[20]

A few articles appeared in the Russian press in the early seventies describing the general purposes of the Soviet PNE Program, but no specifics on locations or results were given. Several articles were written in the U.S. in the mid-seventies and early eighties describing what was known at that time about the program from these meetings and from seismic signals coming out of the Soviet Union.[21,22,23] However, since the mid-seventies, little technical information about the program was made available until the advent of "glasnost" in the late 1980s. Since that time, there have been news reports and commentaries by environmental groups about the Soviet PNE Program in the newly "opened" press, but there has been little authoritative information. However, a recently published book by the Khlopina Radium Institute[24] and several articles in the Information Bulletin of Center for Public Information on Atomic Energy, published by the Russian Atomic Energy Ministry, have provided a good look into the overall scope, technical details, and industrial results of this program.

Overview of the Soviet PNE Program

Since its inception in 1965, the Soviet PNE program carried out 122 explosions involving approximately 128 explosives to study some 13 potential uses.[25] Five applications were put into industrial use (e.g., cavities for storing gas condensate and deep seismic sounding of the earth's mantle). Table 2 summarizes these explosions in terms of their general purpose. In all, PNE explosions were carried out at 115 sites located throughout the former Soviet Union. Two sites were re-entered for subsequent explosions, utilizing the cavities produced in salt by earlier explosions. Tests carried out at the test sites for the development of special nuclear explosives or emplacement techniques for PNEs are not included in the above totals (see Appendix C).

The Soviet program came to an end with the adoption by the Soviet Union of a unilateral moratorium on the testing of nuclear weapons at Soviet Test Sites in 1989. Although it primarily was designed to support the Soviet Union's call for a world-wide ban on all nuclear weapons tests, the Soviet Union also applied the moratorium to nuclear explosions for peaceful purposes.

Table 2: Summary of the applications studied by the Soviet Union's PNE program.

Purpose	Number	Sponsoring ministry
Cratering applications		
Water reservoir construction	5	Medium machine building
Kama-Pechora canal project	3	Medium machine building
Dam construction	2	MMB and non-ferrous metals industry
Total cratering applications	10	
Contained applications		
Oil stimulation	12	Oil/gas industry
Cavity technology development	3	Medium machine building
Elimination of gas well fires	5	Gas industry
Cavities for underground storage	25	Gas industry
Gas stimulation	9	Geology/gas industry
Deep seismic sounding	39	Geology
Ore breakage	2	Mineral fertilizer
Toxic oil field waste disposal	2	Oil refining and chemical
Heavy element production	13	Medium machine building
Decoupling experiment	1	Medium machine building
Prevention of coal gas explosion	1	Coal industry
Total contained applications	112	
Total peaceful nuclear explosions	122	

Data on the 122 explosions of the Soviet "Program for the Utilization of Nuclear Explosions in the National Economy" are presented in Appendix A. The numbers of the explosions are given in chronological order, along with their names, dates and times, seismic locations, magnitudes, and general geographic locations. Actual times and locations are also provided, when available. Figure 1 is a map of the former Soviet Union showing the geographic locations of the 122 PNE sites. Appendix B lists the 122 explosions grouped chronologically within some 13 different applications. The information provided includes the yield, depth of burial, geological medium surrounding the emplacement point, general comments about the explosions, and the sponsoring ministries. The remainder of this report discusses the activities for each application from an historical perspective.

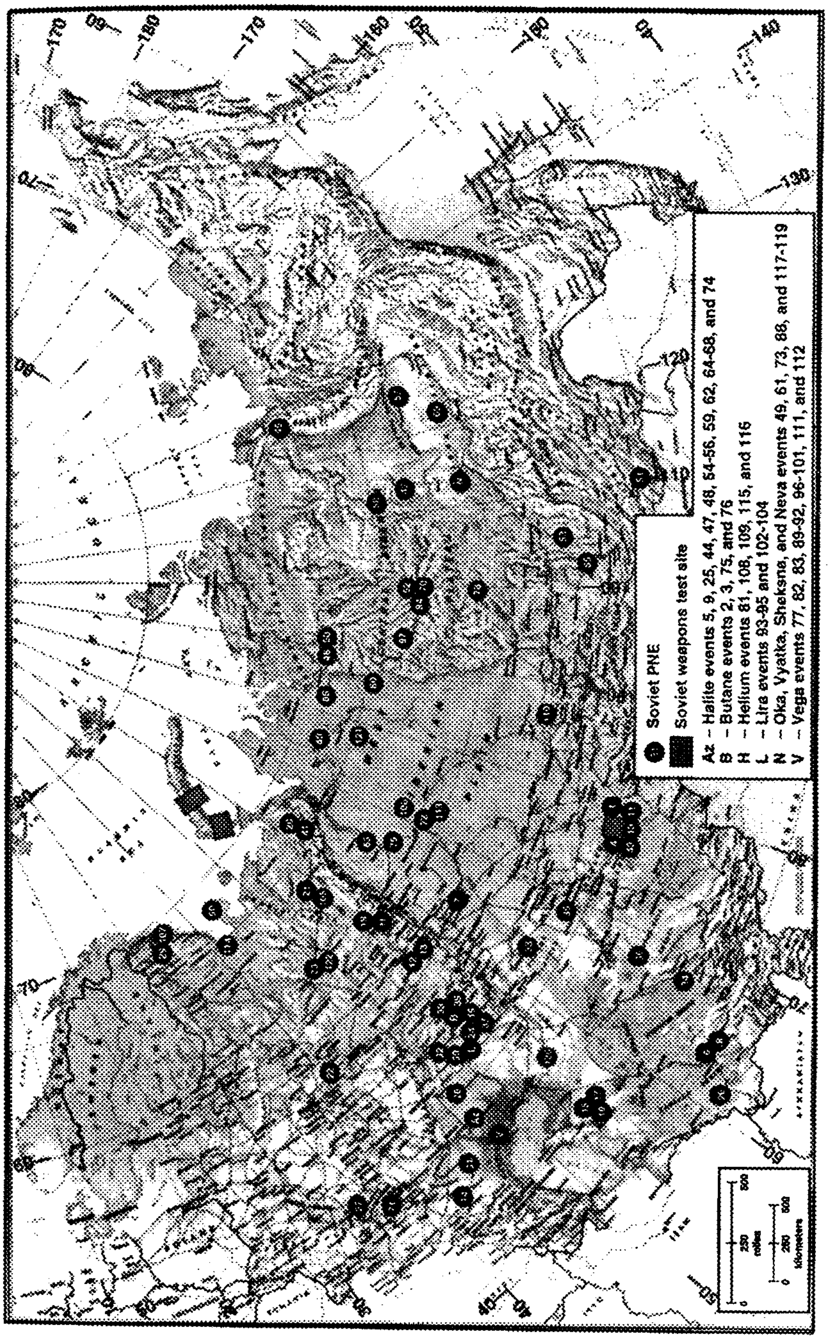

Figure 1: Map of the former Soviet Union showing the geographic location of the 122 PNE sites. Sites of multiple explosions are indicated by a letter as described in the legend.

The Nuclear Excavation Program

Water Reservoir Construction

One of the first applications considered for peaceful nuclear explosions in the Soviet Union was the development of water reservoirs to improve agriculture in such vast arid areas of Siberia as the Semipalatinsk, Kustanay, Tselinograd, Pavlodar, and Gur'ev regions. Many rivers and streams in these regions flow during times of high rainfall but are dry the remainder of the year.

The suggested application envisaged creating nuclear craters within or adjacent to these intermittent streams with volumes of 3 to 5 million cubic meters of storage capability.

Chagan

The first experiment in the Soviet PNE Program on January 15, 1965, was directed at the general goal of obtaining data on the use of nuclear explosives for cratering purposes as well as the specific purpose of demonstrating the usefulness of nuclear explosives in creating water storage reservoirs (see section A.1 of Appendix B). This experiment utilized a 140-kt explosive placed 178 m deep in Hole 1004 on the edge of the Semipalatinsk Test Site (STS) in Kazakhstan. The site was chosen to be in the dry bed of the Chagan River so that the crater lip would form a dam in the river during its period of high flow in the spring.

The crater formed by the Chagan explosion had a diameter of 408 m and a depth of 100 m, remarkably similar to the Sedan crater at NTS. A major lake was quickly formed behind the 20–35 m high upraised lip. Shortly after the explosion, earthmoving equipment was used to cut a channel through the lip so that water from the river could enter the crater. Spring melt soon filled the crater with 6.4 million m^3 of water, and the reservoir behind the crater was filled with 10 million m^3 of water. Subsidence of the crater slopes subsequently reduced the crater storage capacity by about 25 percent. A few years later, a water-control structure was built on the left bank of the river to control water levels in the reservoirs. Both reservoirs exist today in substantially the same form and are still used to provide water for cattle in the area (see figure 2).

The crater dimensions for the Chagan crater compared very well with the 100-kt Sedan crater at NTS, even though the media were quite different and the scaled depth-of-burial of Chagan was almost 20 percent less than that at Sedan. Whereas the medium at Sedan was dry desert alluvium with a moisture content below one percent, the medium at Chagan was saturated siltstone with a 12 percent water content.

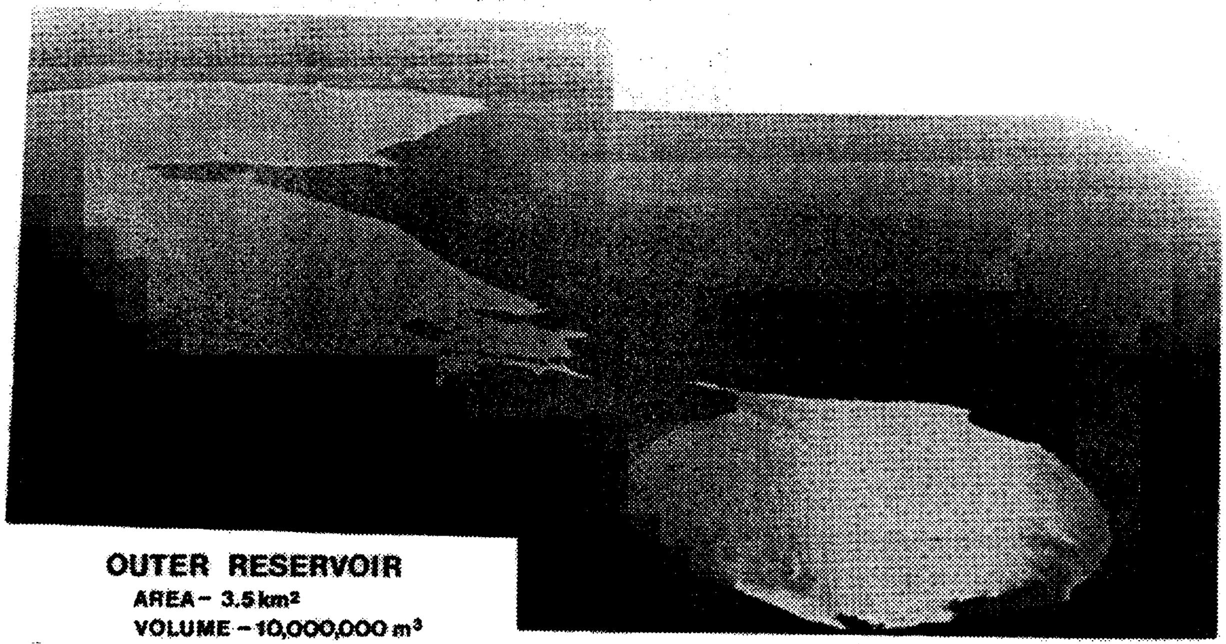

Figure 2: Photographic composite of "Chagan" Lake showing the "Inner Reservoir," formed by the Chagan crater, and the "Outer Reservoir," formed by the blockage of the Chagan River by the lip of the crater. The channel constructed through the lip into the crater shortly after the explosion is visible in the center of the photograph. The channel and control structure to bypass water around the dam is located to the left of the crater lip in the left side of the photograph.

monuclear secondary driven by a fission primary with a yield of about 5–7 kt.[26] Approximately 20 percent of the radioactive products of the explosion escaped into the atmosphere, resulting in dose levels on the lip of the crater of 20–30 R/hr several days after the explosion, most of which was from Co^{60} (5.26 year half-life). Today, the dose level on the lip is reported to be ~2.6 mR/hr.[27] Beyond a restricted area 100–150 m from the lip, the dose rate is at background levels (15–20 μR/hr).[28] Radioactivity levels in the lake water in the crater are reported to be about 300 pCi/liter.[29]

Radioactivity from the Chagan test was detected over Japan by both the U.S. and Japan in apparent violation of the 1963 Limited Test Ban Treaty (LTBT). The U.S. complained to the Soviet Union about the explosion, interpreting it as an accidental venting of a high-yield weapons test and asking for an explanation. The Soviets responded that the explosion "was carried out deep underground. The quantity of radioactive debris that leaked into the atmosphere was so insignificant that the possibility of its fallout outside the territorial limits of the Soviet Union should be excluded." After several subsequent interactions, the issue was closed without further explanation.[30]

Soviet scientists attributed the venting of 20 percent of the radioactivity in the Chagan test to the fact that the scaled depth-of-burial of the charge, 42 $m/kt^{1/3.4}$, was somewhat less than optimum. The fact that the rock surrounding the explosion was water-saturated almost certainly contributed to the relatively high escape fraction.

Sary-Uzen

Later that same year on October 10, 1965, Soviet scientists decided to carry out a second nuclear cratering experiment at a scaled depth that was thought to be closer to optimum than the Chagan test. For this explosion, a 1.1-kt explosive was emplaced in Hole 1003 at a depth-of-burial of 48 m (scaled depth-of-burst = 46.7 $m/kt^{1/3.4}$) in the dry bed of the Sary-Uzen' stream on the western edge of the Semipalatinsk Test Site. At shot depth, the geologic medium was a weak siltstone rock, similar to sandstone. However, it was overlain by about 10 m of clay-like material. The explosion produced a crater with an initial diameter of 107 m and depth of 31 m.

The dimensions of the initial Sary-Uzen' crater compared favorably with U.S. experience in dry alluvium. However, within three months, the crater flooded with artesian water from the shallow water table, resulting in sluffing of the slopes of the crater, which reduced the depth of the crater to 20 m and increased the diameter to 124 m. Soviet scientists had pre-emplaced a high-explosive line-charge under one area of the expected lip, and this was detonated several minutes after the nuclear explosion. This line-charge produced a "canal" through the crater lip to allow stream flow to enter the crater without any personnel re-entering the crater area.

For the Sary-Uzen' cratering explosion, only 3.5 percent of the radioactivity produced in the explosion escaped into the atmosphere. Five days after the test, the dose rate on the lip was 2–3 R/hr. Today it is reported to be 50 μR/hr. Beyond the lip area, dose rates are at background.[31]

Although the Soviets professed to see a widespread need in arid regions of the U.S.S.R. for more than 50 water storage reservoirs with storage capacities in the range of 3–5 million m^3, which would require cratering explosions of 20–50 kt, no further experimentation or application of the technologies demonstrated in Chagan and Sary-Uzen' were carried out.

Holes 2-T, 1-T, and 6-T

Several years after the Chagan and Sary-Uzen' experiments, the Soviet PNE program carried out three additional experiments that they reported were directed at the development of water reservoirs in arid locales. For some years, Soviet scientists had noted the U.S. experience at NTS, where large-yield nuclear explosions in alluvial media resulted in large subsidence craters on the surface above the explosion with essentially no release of radioactive material.

Such craters result from the collapse of an explosion cavity and all the material lying above it, so that at the surface above, a large fraction of the volume of the cavity appears in the form of a conical subsidence. This can only occur when the medium above the cavity is of such a nature that it doesn't "bulk"[32] when it collapses into the explosion cavity. The deep alluvial deposits at NTS are ideally suited for the formation of subsidence craters. The resulting crater has no upraised lip, and the diameter and depth can vary greatly, even in the same media.

The Soviets believed such structures might be useful for water reservoirs. Because the geological media at their test sites at Semipalatinsk and Novaya Zemlya were all igneous or sedimentary rocks, they had not experienced this phenomenon. They decided to gain some direct experience at a remote site on the Mangyshlak Plateau mid-way between the Aral and the Caspian Seas where they had found a weak, high-porosity sedimentary formation at the appropriate depth.

Three experiments described as being for the purpose of studying the formation of subsidence craters were carried out, beginning in the winter of 1969 (see table 3). The first two explosions, in Holes 2-T and 6-T, at scaled depths of burial of 130 and 113 $m/kt^{1/3}$, respectively, produced subsidence craters with

Table 3: Subsidence crater explosions on the Mangyshlak Plateau.

Name	Date	Yield (kt)	Depth of burst (m)	Scaled depth of burst ($m/kt^{1/3}$)	Diameter (m)	Depth (m)
2-T	12/6/69	31	407	130	300	13.8
6-T	12/12/70	84	497	113	500	12.8
1-T	12/23/70	75	740	175	-	-

radii somewhat larger but not inconsistent with U.S. experience. The crater depths were significantly smaller than subsidence crater depths in U.S. experience. These differences could well be the result of differences in the physical properties of the media between the explosion and the ground surface. The lack of a crater for the explosion in Hole 1-T, whose scaled depth of burial was almost 50 percent greater than 6-T, is not surprising and also consistent with U.S. experience.

Even though these craters had volumes of more than 500,000 m^3, there is no reported attempt to use them for water storage or any other use. There was also no further experimentation or application of nuclear excavation to the creation of water storage reservoirs. The explosions were completely contained without leakage, and radiation levels in the area are reported to be at background. The site is closed.[33]

In recent years, there have been several unconfirmed newspaper reports that the actual purpose of these three explosions on the Mangyshlak Plateau was a search for a new test site capable of testing megaton-scale nuclear weapons.[34,35] The history of Soviet weapons testing would appear to be consistent with such a scenario.

In the late 1960s and early 1970s, both the U.S. and the Soviet Union were developing megaton-scale warheads for the new generations of heavy missiles, and a need existed for a high-yield test site. At STS, the relative proximity of the large city of Semipalatinsk limited the yields that could be fired without significant seismic damage to buildings in that city. At the Novaya Zemlya Test Site, at the north end of Southern Novaya Zemlya along the Matochkin Shar Strait, nuclear devices were emplaced in tunnels. Terrain and permafrost significantly limited the maximum yields that could be fired without venting to the atmosphere. If the Mangyshlak Plateau was indeed a candidate, the three tests carried out there would appear to be reasonable candidates to explore its suitability for high yields.

Presumably, the site proved unsuitable, perhaps because of the proximity (230 km) of the large city and breeder reactor facility at Shevchenko on the shore of the Caspian Sea. In 1972, a year and a half after the last explosion on the Mangyshlak Plateau, the Soviet military opened a new test site at the southern end the Novaya Zemlya at Chernaya Bay with a small weapons test, followed a year later with several high-yield tests, including a multi-megaton explosion on October 27, 1973. Over the next two years, they fired three more high-yield nuclear weapons tests at this site. The 150-kt limitation of the TTBT, which became effective in April of 1976, precluded the necessity for a high-yield site, and no further tests occurred at this new test site.

Kama-Pechora Canal Project

Soon after the first two excavation explosions in 1965, another project became the primary focus of the Soviet nuclear excavation program—the construction of a canal to divert water from the Arctic region into the Volga River basin and Caspian Sea. Stimulated by a steady decline in the level of the Caspian Sea over the preceding 35 years as a result of climatic anomalies and municipal and agricultural uses of water from the Volga-Kama River system, a number of water management agencies in the Soviet Union had proposed diversion of water from the Pechora River in the Komi Republic, which flows northward into the Barent and Kara Seas, through a 112-km-long canal into the Kama and thence south to the Volga River and the Caspian Sea.[36,37]

Perhaps driven to compete with U.S. proposals to use nuclear excavation to construct a new sea-level canal to replace the Panama Canal, Soviet PNE program scientists proposed to use nuclear explosions to construct the central 65 km of the Pechora-Kama canal where it passes though higher elevations. Their proposals envisaged the use of several hundred nuclear explosives, firing up to twenty at one time with aggregate yields of as much as 3 Mt. Preliminary cost estimates indicated that the use of nuclear excavation would reduce the cost of the canal by a factor of 2 to 3 compared to usual construction methods.

Tel'kem-1 and Tel'kem-2

As an initial step in considering the use of nuclear excavation for this project, Soviet scientists carried out a pair of cratering experiments in the Tel'kem area on the southeastern corner of the STS (see section A.2, Appendix B). The first, "Tel'kem-1" on October 21, 1968, was a 0.24-kt explosion at optimum depth for cratering in a saturated quartzose sandstone (35 m). The second, "Tel'kem-2" on November 12, 1968, consisted of three 0.24-kt explosives in a row, 40 m apart, at the same depth-of-burst as Tel'kem-1.

As expected, Tel'kem-2 produced a linear crater 142 m long, 60–70 m wide, and 16 m deep, about 20 to 30 percent narrower and about 25 percent shallower than expected on the basis of Tel'kem-1. However, when judged relative to the "Sary-Uzen'" crater, Tel'kem-2 has about the expected dimensions. The results were also quite consistent with the U.S. Buggy row-charge cratering explosion when consideration is given to the differences in the geological media.

Radiation levels on the lip are reported to be 30 μR/hr, only slightly above regional background levels. Beyond the limits of throwout from the crater, the levels are at regional background.[38]

Taiga

In the fall of 1969, the Soviet Government Planning Agency, GOSPLAN, approved going forward with the Pechora-Kama Canal[39], and planning within the Soviet PNE Program took on a greater urgency. One problem had been identified that concerned PNE scientists. The northern 30 km of the section of the canal being considered for nuclear excavation was described as sandstone, siltstone, and argillite rock, media somewhat similar to the cratering media at STS. However, the southern 35 km portion was largely saturated alluvial deposits, which could present difficult slope stability problems. Because of concerns over the stability of the slopes of a nuclear canal in this portion of the canal, the Ministry of Reclamation and Water Resources sponsored a nuclear row-charge experiment code-named "Taiga" for the southern end of the portion being considered for nuclear excavation. The site was about 100 km north of the city of Krasnovishersk in the Perm Oblast'. The alluvial deposits in this area varied in depth between 90 and 130 m, being underlain by sandstone and argillites and marl. The water table was reported to be from 5 to 17 m deep.

Three explosives with yields of 15 kt each were emplaced at depths of about 127 m, roughly at the base of the alluvial deposits, to be fired simultaneously. The scaled depths of burial were about 57 $m/kt^{1/3.4}$, which placed them somewhat deeper than optimum. The spacing between the explosives was about 165 m, a spacing expected to enhance crater width by about 10 percent compared to a single crater diameter.

The explosives used for the Taiga experiment were of a special design in which the fission yield had been significantly reduced over that used for the "Chagan" event in January 1965. The design used was tested in Hole 125 at the Sary-Uzen' portion of the STS on November 4, 1970,[40,41] several months before the Taiga event. Although specific details of the explosives used for Taiga have not been provided, MinAtom has reported that special nuclear explosives for excavation were developed in the 1970s in which the fission contribution was reduced to about 0.3 kt with the remainder of the energy coming from thermonuclear reactions.[42]

The Taiga explosion was carried out on February 23, 1971, about 100 km north of the city of Krasnovishersk in the Perm Oblast'. It produced a row crater about 700 m long and 340 m wide, almost 50 percent larger than expected. However, its depth was only about 10–15 m. The final pan-shaped configuration was the result of extensive failure of the saturated alluvial slopes. Figure 3 is a sketch map of the crater and the surrounding lip and throwout area. The final crater slopes stabilized at an angle of about 8–10 degrees.[43] Although Soviet scientists remained optimistic in interpreting the results of the experiment, by almost any measure, the results of Taiga indicated that nuclear excavation was probably not appropriate for the southern portion of the canal.

Even though the Soviets used a new, low-fission explosive for the Taiga experiment that produced up to an order-of-magnitude less fission product radioactivity than the one used for the Chagan experiment, it was detected outside the Soviet Union by several countries, including the U.S. and Sweden, who lodged protests regarding violation of the LTBT. On site, the dose rate on the crater lip at about one hour after the explosion was 50–200 R/hr. Eight days after the explosion, at distances up to 8 km downwind from the crater, the dose rates were 23–25 μR/hr, only about twice natural background for the European part of Russia. Within the fallout pattern, the contour representing an accumulated dose of 0.5 Rem over the first year (about twice background) extended some 25 km.[44, 45]

Today, the general dose rate on the lip is 40–200 μR/hr with isolated hot spots of up to 1mR/hr. On the surface of the water, the dose rate is about 50 μR/hr. Radiation levels in the crater area are determined by the long-lived radionuclides Co-60, Sr-137, Sr-90, and tritium. In the lake, all the gamma-radiation emitters, Sr-90, and tritium are below standards for drinking water. A restricted area has been established within 2–300 meters of the crater, beyond which the radiation levels are reported to be at background levels and undetectable in vegetation.[46,47]

The disappointing technical results of the Taiga experiment, in and of themselves, did not appear to discourage Soviet interest in using nuclear excavation for this project. For some time, Soviet scientists continued to discuss the project in general, and the use of nuclear excavation in particular. For example, the results of the Taiga experiment were presented at the fourth IAEA meeting on PNEs in January, 1975, together with a restatement of plans to proceed with the project.[48]

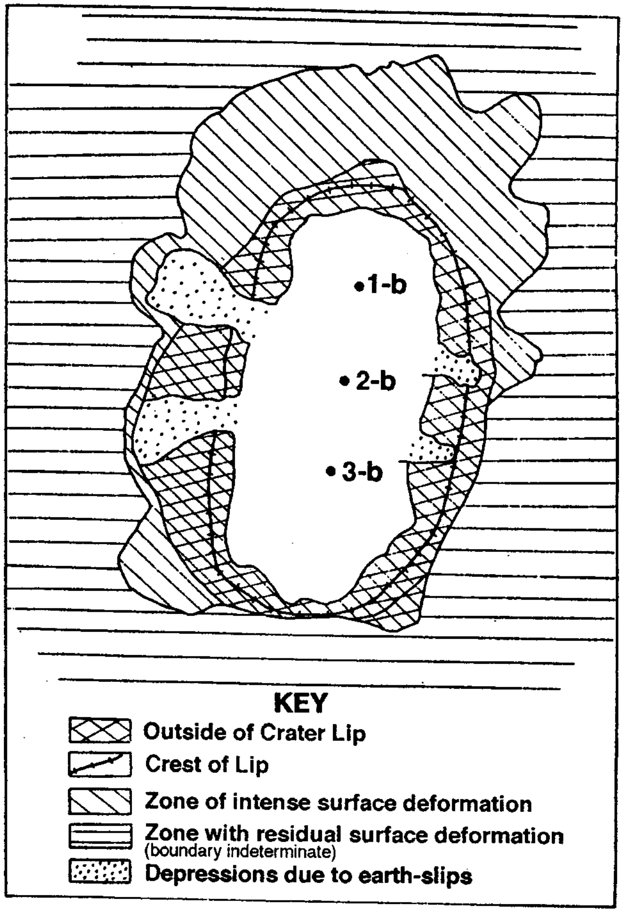

Figure 3: Sketch map of the "Taiga" Crater along the proposed alignment of the Kama-Pechora Canal showing the outline of the crater and areas where there was failure of the crater slopes (from endnote 36).

One of the principle motivations behind the Soviet interest in having U.S./Soviet PNE bilateral discussions in the early 1970s derived from their desire to jointly develop general health and safety guidelines for carrying out PNEs such as those for the Kama-Pechora Canal. They also wished to use this interaction to develop an "understanding" with the U.S. on how such large-scale cratering projects could be rationalized to be in conformance with the LTBT limitation on radioactivity from nuclear explosions across national borders. Although, there were differences in the English and Russian text of the LTBT that were less restrictive in Russian, it was clear that a project of the magnitude of Kama-Pechora could not be done without some "understanding" or perhaps modification of the LTBT.[49]

Another indication of their continuing interest in the project was the Soviet insistence that the Peaceful Nuclear Explosions Treaty, which was negotiated in 1975–76 as a companion to the Threshold Test Ban Treaty limiting nuclear *weapons* tests to 150 kt, permitted aggregate yields for PNEs that were significantly greater than 150 kt.[50] The Kama-Pechora Canal project was repeatedly cited as the *raison d'être* for this provision.

However, in the late 1970s and early 1980s, opposition began to develop in academic and governmental circles to many of the large-scale water diversion projects that were being proposed by the Soviet government. Primary concerns were about the environmental effects and possible climatological and hydrologic changes resulting from transfer of significant volumes of water from the Arctic to the southern portion of the country.[51] By the mid-1980s, these plans were largely abandoned, including any use of nuclear excavation for the Pechora-Kama Canal.

Dam Construction

Crystal

Several years after the Taiga explosion, on October 10, 1974, Soviets scientists carried out another small-excavation type nuclear explosion 3 km northeast of the small settlement of Udachnyy in Yakutia in Siberia and 90 km northeast of the town of Aikhal. This explosion was under the sponsorship of the Ministry of Light Metallurgy and a local combine called "Yakutalmaz," a diamond-mining enterprise. The purpose of the explosion was to create a small dam in the Deldyn river. This area in Siberia is in the permafrost region, and the rivers and streams only flow for a few months in the summer. The intent was to produce a small lake that would retain the tailings from the diamond mine for subsequent enrichment by Yakutalmaz (see section A.3, Appendix B).

For this experiment, a 1.7-kt explosive was placed at a depth of 98 m, a scaled depth-of-burst about twice that of Chagan and Sary-Uzen'. The explosion produced a dome-shaped mound with a diameter of 180 m, which rose to a height of 60 m and then settled back to an average height of 10 m above the original surface.[52] It is reported that the dome did not rupture, and all the refractory radionuclides were contained underground, although there would have been escape of gaseous radionuclides such as Cs-137, Xe-133, Kr-85, and perhaps tritium through fractures in the dome. There is no information regarding the use of the "dam" or the lake behind it for its intended purpose.[53]

Gamma-radiation surveys in 1990 reported the general level was 15–30 μR/hr with a peak level of 110 μR/hr after the dam was covered by a meter of soil.[54] Another source reports radiation levels in 1991 on the uplifted dome to be predominantly background levels (9–15 μR/hr) except for a limited area northeast of the dome where it reached a level of 50–60 μR/hr. After it was covered with 6 m of rock from a nearby quarry, the level dropped to background level. No radionuclides were detected in water samples taken from the dam, drilling or earthwork in the dam, or within 100 m of the dam.[55]

Lazurite

A few months later on December 7, 1974, Soviet scientists carried out a second experiment with a deeply buried cratering explosion on the edge of the STS, a few kilometers south of the Sary Uzen' crater. Their intent was to produce an upthrust dome similar to Crystal on a slope that would subsequently slide down the slope and form a landslide dam, similar to what Soviet engineers had done with large chemical explosions on a number of occasions, most notably near Alma Ata in Kazakhstan and on the Vakhsh River in Tadzhikistan.[56]

For the "Lazurite" experiment, a 1.7-kt explosive was placed under a 20° slope consisting of quartzite and flinty slate. It was positioned 75 m from the slope in a vertical direction and 70 m in the line of least distance to the slope. The scaled depth of burst was about 5–10 percent greater than that for the U.S. explosion Sulky, which produced a mound of broken rock.

The Lazurite explosion also produced a mound of broken rock, which had a diameter of 200 m and a height of 14 m. No description of the dam that was formed by Lazurite has been published. There was very little venting, and radiation levels on the mound immediately after the explosion were reported to be three to four orders of magnitude less than for cratering explosions such as Sary Uzen'.[57] Radiation levels today are described as being at background, but monitoring of the site is continuing.[58]

The Soviet interest in nuclear excavation appeared to come to an end with the Lazurite explosion. All tests after Lazurite were designed to be completely contained explosions. However, as mentioned above, their planning and public positions continued through the mid-1970s to include strong emphasis on nuclear excavation and the Kama-Pechora Canal.

Contained Applications

Stimulation of Oil and Gas Production

While MinAtom's Program No. 7 for the "Utilization of Nuclear Explosions in the National Economy" was planning the nuclear excavation program and the Chagan cratering explosion, the Soviets also began to consider the use of PNEs for various industrial applications. The first area to receive serious study was the application of nuclear explosions for the stimulation of oil production, carried out in cooperation with the Ministry of Oil Production (see section B.1, Appendix B).

Experience has shown that the efficiency of recovering oil from carbonate oil reservoirs is, in general, fairly low (<40 percent). Several secondary recovery techniques are practiced with varying degrees of success, depending on the nature of the reservoir and the character of the oil. These methods include water and gas injection, fire or hot-water flooding, hydrofracturing to increase the permeability of the formation, and the introduction of gas into the oil to reduce its viscosity. However, many fields resist such conventional techniques.

Butane

The first oil field considered for treatment was the Grachevka reservoir, located about 150 km north of the city of Orenburg in the Bashkir Republic, near the southern end of the Ural Mountains. This formation has been described as a solution gas drive reservoir in which ultimate recovery had been projected as ~25 percent of the in-place resources. The reservoir is a limestone reef at a depth of 1,000–1,500 m overlain by interbedded anhydrite and halite layers, which formed a "gas cap." The oil-producing section is isolated from an underlying pressurized water zone by a bitumenized or oxidized layer 25–50 m thick.[59]

Production from this reservoir in the first few years after it was opened increased rapidly to several hundred tons of oil per month as new holes were drilled into the reservoir. But after three years, production began to sharply decrease as the gas/oil ratio began to rise significantly. By the seventh year, production was down to about 100 tons/month, and the gas/oil ratio had risen from 100 to 500 m^3 of gas/ton of oil. The apparent cause was the development of channeling and the escape of dissolved gas from the deposit, leaving the oil behind. To reverse these trends, Program No. 7 and the Oil Production Ministry decided to make their first attempt at nuclear stimulation with this field.

The first stage of the "Butane" project involved the simultaneous detonation on March 30, 1965, of two 2.3-kt nuclear explosions about 200 m apart at depths of 1,375 and 1,341 m in the Grachevka formation. This depth placed the explosions and the associated collapse chimney totally within the oil deposit. A second explosion, which was a single 7.6-kt nuclear explosion at a depth of 1,350 m and located 350 m west of one of the two 2.3-kt explosions, was carried out later that year on June 6, 1965.[60] Because of the small yield and perhaps the porous carbonate rock, these explosions were not detected by world-wide seismic networks. The locations given in Appendix A are based on the geographical location provided in endnote 15. The devices used for this experiment have been described as specially designed and tested for this application.[61]

Over the next few years, increased production was reported for some 20 wells within 300–470 m of the stimulation wells. The oil/gas ratio dropped sharply, and oil production increased about 40 percent over previous projections. Results available to date indicate that the stimulation will increase the ultimate recovery from the formation by 40–50 percent. Table 4 summarizes the results of the first 8 years of production from the Butane project as well as the results of other oil and gas stimulation projects in comparison with the U.S. gas stimulation projects.[62]

The Butane explosions were apparently completely contained, and radiation levels in the area are reported to be at background levels. Within the collapse chimney region, tritium produced by the nuclear explosions diffused into the gas cap above the oil-bearing horizons and appeared in gas produced with the oil. Initially the average tritium level in the gas from the field was measured at 0.03 μCi/liter. Within 3 years, it had stabilized at about 0.003 μCi/liter. Tritium levels in the oil were less than 3 μCi/liter, which is approximately the same level as in the gas on a unit weight basis. Only trace amounts (<0.1 μCi/liter) of the fission product radionuclides Cs-137 and Sr-90 were reported.[63,64]

On June 16 and 25 in 1980, two additional 3.0-kt explosions were carried out in the Butane reservoir at depths of about 1,400 m. These two explosions were also not detected by the world-wide seismic networks, and the locations given in Appendix A are based on geographic information in endnote 15. No additional information has been made available on the specific purpose or results of these explosions.

Grifon

Four years after the first Butane explosions, the Soviet Oil Ministry sponsored stimulation of another oil reservoir, but of a different type. The second effort, project "Grifon," sought to stimulate the Osinskii deposit, 100 km southwest of the city of Perm on the western slope of the Urals. The Osinskii reservoir was a carbonate reef deposit being produced through the use of water injection into wells surrounding the oil reservoir.[65,66]

On September 8 and 26 in 1969, two 7.6-kt explosions were fired 1,200 m apart at depths of 1,212 and 1,208 m in the middle of this reservoir. At these depths, the explosions were about 70 m below the water–oil contact at the base of the reservoir. The collapse chimneys would have been expected to extend 50–80 m into the oil-bearing formation. Although little production data have been made available, Soviet scientists stated that early results indicated an increase of 30–60 percent in production.[67] As shown in table 4, results indicate a production increase of 50–60 percent over that for the previous 20 years.

Table 4: Comparative evaluation of U.S. and Soviet PNE stimulation projects.

	Characteristics of the natural collectors						
Projects studied	**Rock type**	**Porosity (%)**	**Permeability (mDarcies)**	**Saturating fluid**	**Number of explosions**	**Increase in hole production**	**Additional fuel[a] recovery per explosion (10^3 m^3)**
Butane	Limestone	15–20	4–64	Oil and gas	5	1.4–1.5	80
Helium	Limestone	8–10	5–20	Oil	5	1.6–1.8	-
Grifon	Limestone	10–15	20–40	Water	2	1.5–1.6	120
Neva	Limestone	10–12	0.2–0.4	Oil and gas	6	>20	80
Angara	Sandstone shale, alevrolite	10–12	0.1–0.2	Oil	1	15	-
Benzene	Sandstone shale, alevrolite	25	0.01–0.02	Water[b]	1	-	-
Gasbuggy	Sandy shale	10–12	0.1–0.2	Gas	1	6–8	-
Rulison	Sandy shale	7–9	0.2–0.4	Gas	1	10–15	-
Rio-Blanco (string)	Sandy shale	4–6	0.1	Gas	3	10–15	-

a. Oil + gas; 1 m^3 of oil = 1,000 m^3 of gas.
b. Explosion was placed below the productive section (from endnote 15).

The Grifon explosions were completely contained, but post-shot drilling into the chimney region and removal of water from the explosion region led to contamination of the surface area and equipment that was later decontaminated, and the site is reported to be at background levels. The primary radiation hazard to production from this site is associated with the presence of Cs-137, Sr-90, and tritium in the water underlying the oil that is being used to pressurize the field. However, radioactivity levels in oil produced from the field are reported by MinAtom to be similar to those reported for the Butane field.

However, there are reports in the Russian press that describe a less optimistic situation. A recent article by Academician Yanshin states that studies of the environmental effects of PNEs in the Perm area in 1991–92 indicated that by 1978, radionuclides Cs-137 and Sr-90 began to appear in holes near the explosion sites.[68] Over the next ten years, the area of contamination had spread to some 65 production holes and represented a threat of contaminating the nearby Votkinsk water reservoir, the Kama River, and even the Volga River basin. In the region of the emplacement holes, radiation levels were reported to be about 60 μR/hr and at specific injection holes 20–50 μR/hr. In some areas, radiation levels were reported to be as high as 3 mR/hr.[69,70] There are reports that the refineries in Perm have refused to accept oil from the Osin field, and several holes have been closed.[71] MinAtom confirms that oil from the Grifon site is not acceptable to regional refineries.[72]

<u>Project Takhta-Kagulta</u>

One month after the first two Grifon oil stimulation explosions, on September 26, 1969, the Soviet PNE program, with the sponsorship of the Soviet Ministry of Gas Production, carried out their first effort directed at stimulating the production of gas from low-permeability gas reservoirs. The site of this test was in the Takhta-Kagulta gas field in southern Russia on the northern slopes of the Caucasus Mountains about 90 km northeast of the city of Stavropol'.

The Takhta-Kagulta gas field is a very large geologic structure in which the production horizon is a very thin 5 to 13-m-thick section consisting of clayey siltstone lying at a depth of about 700–750 m.[73] The test was a single 10-kt nuclear explosion at a depth of 712 m.

During the second U.S./U.S.S.R. Bilateral Meeting in February 1970, Soviet scientists revealed to the Americans that such an experiment had been carried out, but no additional information on the results were made available at that time or since. Moreover, this was the only test reported to have been sponsored by the Gas Ministry. The extremely thin nature of the production horizon would appear to make this a poor candidate for nuclear stimulation since the collapse chimney would be expected to be 5–10 times taller than the thickness of the deposit. The lack of information on the results of this test would appear to confirm a very disappointing result. No escape of radioactivity has been reported, and the site is closed.[74]

Project Neva

In the fall of 1976, the Soviet PNE program, this time with the sponsorship of the Ministry of Geology, began a new gas stimulation project, subsequently referred to as the Neva project. This project consisted of a series of explosions in a hydrocarbon reservoir at a site located about 120 km south–southwest of the Siberian town of Mirnyy in the Siberian Yakut Republic. The producing formation at the Neva site, named the Sredne-Botuobinsk reservoir, consists of a dolomite and limestone section capped by a salt layer at a depth of 1,500–1,600 m containing both oil and gas, although prior to nuclear stimulation, it was only considered for gas production.[75]

At the time of the first experiment, code-named "Oka," on November 5, 1976, the field was under active development. The Oka explosion was 15 kt at a depth of 1,522 m. Initially, production tests several months after the explosion were conducted in a pre-existing exploratory hole 120 m from the Oka hole. Whereas preshot gas production from this hole had been 3,000–5,000 m^3/day, periodic post-shot production over a 75-day period produced over 100,000 m^3/day as well as 20–22 m^3/day of oil. Production testing from the Oka emplacement hole over a three and a half month period resulted in over 100,000 m^3/day of gas, but no oil which was accumulated in the central chimney region. At the end of the test period, the flow rate was still 50,000 m^3/day.

The second explosion in the Sredne-Botuobinsk formation, code-named "Vyatka," was carried out on October 7, 1978, near Oka. It had a yield and depth of burial similar to Oka and was also 120 m from another exploratory hole, which had no significant production before Vyatka. Post-shot production from the Vyatka emplacement hole averaged 60,000 m^3/day over a two-month period and was still 38,000 m^3/ day at the end of the testing period.[76]

The third explosion, "Sheksna," was fired exactly one year later on October 7, 1979, with about the same yield but about 50–70 m deeper than Oka and Vyatka. No specific results of production testing in the vicinity of Sheksna have been provided.

Three more explosions, Neva-1, Neva-2, and Neva-3, were carried in 1982 and 1987 to extend the stimulation of the Sredne-Botuobinsk formation over a larger area. In November, 1987, the Soviets carried out the seventh and last explosion at the Sredne-Botuobinsk site, "Neva-4," which MinAtom lists as a stimulation explosion. However, the yield of the explosion, 3.2 kt, and its depth of 815 m in a salt formation would suggest that this explosion was, in reality, a storage cavity used to dispose of radioactive and toxic wastes generated by the stimulation and production activities at the site. This is supported by the fact that table 4 from endnote 15 lists only 6 stimulation explosions at the Neva site.

The overall results of stimulation at the Neva site are shown in table 4 in comparison with other U.S.S.R. and U.S. stimulation projects. It shows that the permeability of the Sredne-Botuobinsk reservoir was comparable with that of the U.S. Gasbuggy and Rulison reservoirs, but the results of stimulation were about 2–3 times greater than those realized in the U.S. experiments. This difference could well be due the fact that the Sredne-Botuobinsk reservoir was limestone and dolomite, whereas the American reservoirs were primarily shale. Based on the fact that only four out of forty exploratory holes had commercial production potential, nuclear stimulation has made the field commercially valuable. The value of the nuclear stimulation of the field was calculated to be worth 100,000,000 rubles (1980). In addition, whereas the field was regarded as only a gas field prior to stimulation, commercially significant volumes of oil were recovered from the field.[77]

Along with the mechanical alteration of the rock surrounding the explosion, Soviet scientists also report the discovery of a new phenomena, the permanent electrical polarization of the rock (see figure 4). The region of anomalous polarization extends to distances of 200–250 $m/kt^{1/3}$ from the explosion. It is directed toward the explosion point and facilitates the motion of oil toward the center of the explosion. This phenomenon was first noted during work on the Neva project. Studies indicated that the strength of the polarization is dependent on the properties of the rock and is significant only for low-permeability reservoirs. There are no reports on whether this phenomenon was looked for or found at the other stimulation sites.[78,79]

MinAtom reports that all seven explosions carried out at this site were totally contained. Access to the emplacement holes has been closed, and they have been cemented (perhaps with the exception of Neva-4). Work at the site could be resumed. Radiation levels at the site are at background levels.[80]

Project Helium

In 1981, the Soviet PNE program began a new oil stimulation project called Project "Helium" in the Tyazhskii carbonate oil reservoir near the town of Krasnovishersk on the western slope of the Urals, about 800 km north of the first oil stimulation project, Butane. The characteristics of the formation and the technology used for producing the field are described as being very similar to those at Butane.

The first explosion on September 2, 1981, was a 3.2-kt explosion placed at a depth of 2,088 m, below the oil-bearing section. The second and third explosions were carried out three years later on August 28, 1984, timed to be five minutes apart. The yields and depths were similar to those for the first explo-

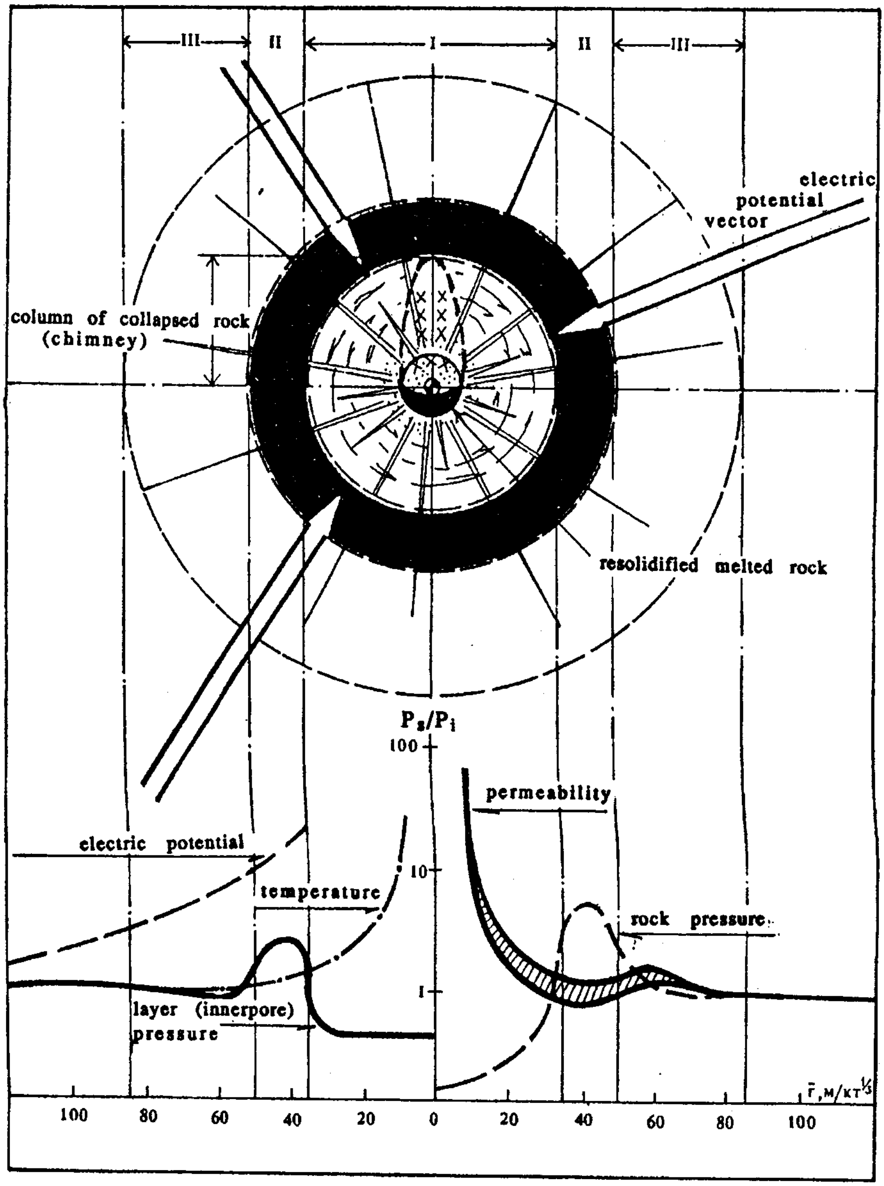

Figure 4: Sketch showing (top) the physical-mechanical alteration of homogeneous porous rock surrounding a nuclear explosion, and (bottom) changes in the basic properties of the rock including rock and pore pressure, permeability, temperature, and electrical polarization. The three large arrows indicate the vector of electric polarization field in the rock created by the explosion. The horizontal axis (bottom) is the cube-root scaled radius from the explosion. The associated vertical scale is the logarithm of the ratio of the post-shot values to their pre-shot values (from endnote 76).

sion. The last two explosions in Project "Helium" were fired about three years later on April 19, 1987, again five minutes apart with similar yields and depths of burial.

Available results of production testing are limited to the numbers in table 4, which indicate a production increase of 60–80 percent after the stimulation explosions. All of the explosions were reported to have been successfully contained, and the site is under active exploitation.[81]

Projects Angara and Benzene

The Soviets acknowledge carrying out two additional oil stimulation explosions, Projects "Angara" and "Benzene," both of which were in western Siberia in the middle of the great Ob' River basin. The first, Project "Angara," was sponsored by the Geology Ministry and was carried out on December 10, 1980, in the Yesi-Yegovskii oil field. It employed a 15-kt explosion at a depth of 2,485 m. The second, Project Benzene, was sponsored by the Oil Ministry and was fired on June 18, 1985, in the Sredne-Balykskii oil field. It was a 2.5-kt explosion at a depth of 2,859 m. No data have been published on the results of these projects, except that the Angara site is closed, but the Benzene site is under active development. Both were successfully contained.[82]

Summary of Oil and Gas Stimulation

Overall, the Soviet PNE program carried out 5 projects directed at the stimulation of oil production, all from limestone or dolomite reservoirs. Three of the projects utilized multiple explosions with yields between 2.3 and 7.6 kt. Results over 10–20 year production periods indicate an increase in production of about 40–80 percent over that projected for the fields before stimulation. Two oil stimulation projects using a single explosion have been carried out, but no results have been published. All of the explosions were completely contained, and no problems with radioactive contamination of the site or product have been reported except for Project Grifon, where product and ground water contamination appears to be a growing problem.

The Soviet program to stimulate the production of natural gas appears to have consisted of two projects, only one of which produced results that have been reported. This project, "Neva," utilized six 13 to 16-kt explosions for stimulating a dolomite reservoir and one 3.2-kt explosion in salt, presumably for storage or disposal of waste. Results over a 15-year production history indicate a recovery rate more than 20 times normal, results about 2 times more favorable than those for U.S. experience. All explosions were contained. Although the gas would be expected to contain a low level of tritium, no problems with product contamination have been reported.

As was done by the U.S. Plowshare Program, special explosives were developed by the Soviet weapons laboratories to meet the unique requirements of stimulating oil and gas reservoirs. The great depths of such reservoirs (1,000–2,000 m) place great value on reducing the diameters of the explosives and building them so they can withstand the elevated pressures and temperatures experienced at those depths. There is also a great premium on reducing the tritium produced in the explosive and the surrounding medium to reduce problems of contaminating hydrocarbon products with tritium. To meet these requirements, the Soviets developed special explosives with a 30 to 60 cm diameter and the appropriate yields capable of withstanding the emplacement and rough transport conditions.[83]

Mention should be made of a magnitude 4.4 seismic event at 9:00:06 GMT on July 19, 1982, 120 km northeast of Kotlas in the southeast corner of the Komi Republic. Russian geoscientists in the Schmidt Institute and the Institute for Dynamics of the Geosphere have associated this event with the Soviet PNE program and have referred to it by the name "Komipetroleum" indicating their belief that its purpose was oil stimulation.[84] Publications by the MinAtom make no reference to this event.

Cavity Technology Development

Project Halite

Early in the development of the Soviet PNE program, perhaps in reaction to the earlier U.S. explosions in salt that produced standing cavities Gnome and Salmon, the decision was made to develop the technology of creating cavities in salt. They chose a site about 180 km north of the city of Astrakhan at the north end of the Caspian Sea. The site for these studies was near the small village of Azgir in the middle of a large semi-desert area. The geologic medium at Azgir consisted of two large salt diapirs, the Western and Eastern Azgir Domes, that go to great depth but with relatively thin alluvial cover (5–200 m). The water table in the area is fairly shallow, near the top of the salt formation.[85]

A-1

The first experiment in this program, code-named "Halite," was A-1, a 1.1-kt explosion fired on April 22, 1966, in the Western Azgir Dome at a depth of 161 m, a scaled depth of about 155 m/kt$^{1/3}$. It produced a cavity about 25 m in diameter and a volume of 11,200 m^3.

As with all nuclear explosions in salt that produce cavities, radioactive debris from the explosion initially is embedded in the walls of the cavity that are covered with molten salt. Within a few minutes after the explosion, the molten salt on the walls runs to the bottom of the cavity, carrying the refractory radioactive debris with the salt. The molten salt forms a segment-shaped puddle at the bottom of the cavity about a third of a cavity radius deep at the center, which ultimately solidifies, trapping the refractory radioactive debris in the resolidified salt. Gaseous radionuclides appear in the gases filling the cavity.

Shortly after the explosion, the A-1 cavity began filling with water, apparently the result of poor sealing of the emplacement hole and extensive fracturing above the cavity by spalling of the ground surface. The roof also collapsed some 8,000 m^3 of rock salt into the cavity, hampering efforts to study the cavity. In addition, gaseous radioactivity from the cavity escaped into nearby instrument holes and leaked to the surface, contaminating the local environment.

A-2

The second Halite explosion, A-2, was carried out two years later on July 7, 1968, in the same Western Azgir Salt Dome but about 8 km north of A-1 at a somewhat greater scaled depth. It consisted of a 27-kt explosion at a depth of 597 m, a scaled depth of burial of about 200 $m/kt^{1/3}$. It produced a spherical cavity with a radius of about 32 m and a volume of about 140,000 m^3. This cavity also began to leak around the emplacement hole and ultimately filled with water, but there was no early vent of gaseous radionuclides.

A-1 and A-2 were thoroughly explored and provided very useful experience in making and working with explosion cavities in salt that led to ideas for using such cavities for a number of applications. A-2 was repeatedly used in a series of experiments designed to produce transplutonic elements (as discussed below).

A-3

The third explosion in the Halite series, A-3, was carried out three years later on December 22, 1971, in the Eastern Azgir Salt Dome about 16 km east of A-1 and A-2. This time, the yield was 64 kt, and the depth-of-burial 986 m for a scaled depth-of-burial of about 245 $m/kt^{1/3}$. The explosion produced a spheroidal cavity that had a horizontal radius of 38 m and a vertical radius of about 33 m. The radius of an equivalent sphere would be 36.2 m. The cavity remained dry and was subsequently used for a seismic decoupling experiment (see below).[86]

Extinguishing Runaway Gas Well Fires

Shortly after the Soviet PNE Program was established, an urgent industrial problem was brought to the leaders of the program—could an underground nuclear explosion be used to put out a gas well fire that had been raging for some 3 years? (See section B.2, Appendix B.)

Urtabulak

On December 1, 1963, while drilling gas Well No. 11 in the Urtabulak gas field in Southern Uzbekistan about 80 km southeast of Bukhara, control of the well was lost at a depth of 2450 m. This resulted in the loss of more than 12 million m^3 of gas per day through an 8-inch casing, enough gas to supply the needs of a large city, such as St. Petersburg. Formation pressures were about 270–300 atmospheres.[87,88,89]

Over the next three years, many attempts were made using a variety of techniques to cap the well at the surface or to reduce the flow and extinguish the flames. However, because the bottom 1,000 m of the casing had not yet been cemented, such attempts led to diversion of the gas into nearby wells and to serious personnel safety problems because of the high H_2S content of the gas. Underground attempts were hampered by the fact that the location of the lower portion of the hole had not been logged at the time control was lost.

Finally, in the fall of 1966, a decision was made to attempt closing the well with the use of a nuclear explosive. It was believed that a nuclear explosion would squeeze close any hole located within 25–50 m of the explosion, depending on the yield. Two 44.5-cm (13.5 in) diameter slant wells, Holes No. 1c and 2c, were drilled simultaneously. They were aimed to come as close as possible to Hole No. 11 at a depth of about 1,500 m in the middle of a 200-m-thick clay zone. This depth was considered sufficient to contain the 300-atmosphere pressure in the gas formation below. A number of acoustic and electromagnetic techniques were used to estimate the distance between Hole No 11 and inclined explosive emplacement hole at 1,450 m. The final estimate for the closest distance between Hole No. 11 and Hole No. 1c was 35 ± 10 m.

The location for the explosive in Hole 1c was cooled to bring it down to a temperature the explosive could withstand. A special 30-kt nuclear explosive developed by the Arzamas nuclear weapons laboratory for this event was emplaced in Hole 1c and stemmed. It was detonated on September 30, 1966. Twenty-three seconds later the flame went out, and the well was sealed.[90]

Pamuk.

A few months after the closure of the Urtabulak No. 11 hole, control was lost of another high-pressure well in a similar nearby field, Hole No. 2-R in the Pamuk gas field. In this case, drilling had progressed to a depth of 2,748 m before the gas-containing horizon was encountered, and gas pressures were significantly higher than those at Urtabulak (580 atm). A month and a half after the runaway well started, it blocked itself at a depth of 800–1,000. Remedial work was done in the well and appeared to have resolved the problem when, four months later, gas started coming to the surface through other holes and through the ground itself.

After several unsuccessful attempts to seal the well by hydraulic fracturing from a slant-drilled well, it was decided to again use a nuclear explosive to pinch off the runaway well. A new inclined hole, No. 10-N, was drilled to intersect Hole 2-R in the middle of a salt formation that overlay the gas producing formation. Measurements after it had been drilled indicated that the minimum separation distance at a depth of 2,440 m was 30 ± 5 m.

This time, a special explosive developed by the Chelyabinsk nuclear weapons laboratory was used, one that had been designed and tested to withstand the high pressures and temperatures in excess of 100°C expected in the emplacement hole. It also was designed to be only 24 cm in diameter and about 3 m long to facilitate its use in conventional gas and oil field holes. Its yield was 47 kt.[91]

The explosive was inserted into Hole 10-N and detonated on May 21, 1968, at a depth of 2,440 m. Because of the large amount of gas that had infiltrated the overlying strata during the preceding two years, the flow continued for seven days before it finally died out and the seal was complete. The second "success" gave Soviet scientists great confidence in the use of this new technique for rapidly and effectively controlling runaway gas and oil wells.

<u>Crater and Fakel</u>

Some four years later, two more opportunities arose for the use of nuclear explosions to extinguish runaway gas well fires. The first, code-named "Crater," was in the Mayskii gas field about 30 km southeast of the city of Mary in Central Asia. Control of the gas well was lost on May 11, 1970, and about 700,000 m^3 of gas was lost per day. The producing horizon in this field was at the 3,000-m level. No details have been made public about this application, except that on April 11, 1972, a 14-kt explosion at a depth of 1,720 m in an argillite formation was used to successfully seal the runaway well.

On July 7, 1972, another runaway gas well in the Ukraine, about 20 north of the city of Krasnograd and 65 km southwest of Karkov, was sealed with a nuclear explosion. The runaway well was in the Krestishche gas formation at a depth of over 3,000 m. No additional information has been made available except that for this event, named "Fakel," a 3.8-kt explosion at a depth of

2,483 m in a salt formation, was used. The small yield would indicate that the location of the runaway well was well known, and the explosive emplacement hole was drilled to be very close to it at shot depth.

Pyrite

The last attempt to use this application occurred in 1981 on a runaway well in the Kumzhinskiy gas deposit in the northern coast of European Russia near the mouth of the Pechora River, 50 km north of the city of Nar'yan Mar. Control of the well was lost on November 28, 1980, resulting in a loss of about 2,600,000 m^3 of gas per day. On May 5, 1981, a 37.6-kt nuclear explosion, code-named "Pyrite," was detonated at a depth of 1,511 m in a sandstone–clay formation near the runaway well. However, the nuclear explosion did not seal the well, perhaps because of poor data on the position of the runaway well. No additional details have been published on the results of the nuclear attempt or of subsequent efforts to close the well by other means.[92]

Of the Soviet attempts to extinguish runaway gas wells, MinAtom reports that all were completely contained, and no radioactivity above background levels was detected at the surface of the ground during post-shot surveys.[93]

Underground Cavities for Storage of Gas Condensate

Building on their experience with creating the two cavities in salt at Azgir in 1966 and 1968, Soviet scientists began to consider possible use of such cavities within the industrial sectors for underground storage. In the late 1960s, contacts were established with specialists at the Ministries of Oil, Gas, Chemistry and Oil Refining to assess their future requirements for underground storage and their interest in exploring the use of nuclear explosions to help meet those needs. The greatest interest was found in the Oil Production Ministry, and plans were quickly developed for a program to develop this application (see section B.4, Appendix B).

The experience at Azgir with the Halite A-1 and A-2 explosions clearly identified two of the most significant technical issues that had to be dealt with: isolation of the cavity from access to any source of water through fractures, cracks, or the emplacement or other holes near the cavity; and finding a depth that would be great enough to contain the required explosive yield without exacerbating problems of cavity stability against collapse or compression by the lithostatic pressure. Any leakage of water into the cavity, as occurred in both the early cavities at Azgir, could quickly lead to leaching of the radioactivity trapped in the recongealed salt lens at the bottom the cavity and contamination of any product stored in the cavity.

Project Magistral

The first experiment specifically directed at the use of underground nuclear explosion cavities for storage, Project "Magistral'," was carried out in the Sovkhoz gas deposit about 70 km northeast of Orenburg, and 100 km south of the first oil stimulation project at the Butane site (see figure 5).[94]

The Magistral explosion had a yield of 2.3 kt and was emplaced at a depth of 702 m in a bedded salt formation. It was fired on June 25, 1970, and produced a cavity with a volume of 11,000 m^3 (radius ≈ 14 m). After several months, the cavity was entered through the emplacement hole, and after some 6 months it was filled with natural gas from the nearby Sovkhoz gas field to a pressure of 8.4 MPa (84 atm).[95,96]

The Magistral cavity stayed in industrial use for the next 18 years.[97] Deactivation and decontamination of the site began in 1993 to clean up radiation levels reported to be 30–40 μR/hr in the immediate vicinity.[98] About 3,000 tons of soil have been contaminated, to an average level of about 5×10^5 pCi, by spillage while pumping radioactive solutions from the cavity. Beyond the industrial site, the radiation levels are described as "background."

Project Sapphire

Following the success of the Magistral project, scientists from the Soviet PNE program and the Gas Production Ministry turned their attention to another site about 100 km southwest of Magistral and 40 km south–southwest of Orenburg (see figure 5). The new site, Project "Sapphire," was a bedded salt formation that overlay the Orenburg gas condensate deposit, one of the largest in the Soviet Union at the time of its discovery in 1967.

Gas condensate is a very high-quality hydrocarbon that is a mixture of hydrocarbon gases (propane, butane, and pentane) that are liquid at high pressure. Gas condensate is quite valuable, but in some fields it is contaminated with hydrogen-sulfide and dissolved gases, which makes it very expensive to store on the surface, requiring high-pressure corrosion-resistant metal tanks. At Orenburg, the hydrogen sulfide content was reported to be 2.7 percent. It appeared that storage in salt cavities would eliminate the corrosion problems and permit the dissolved gas to outgas before the gas condensate was sent to the refinery for processing. Moreover, additional storage capacity was required because the initial capacity of the gas-condensate processing plant at Orenburg did not match the peak processing capability of the natural-gas processing plant.[99]

The first of two Sapphire explosions was detonated on October 22, 1971, at a depth of 1,142 m in the middle of the bedded salt formation. The gas producing formation was at a depth of 1,400–1,800 m. The nuclear explosion with a

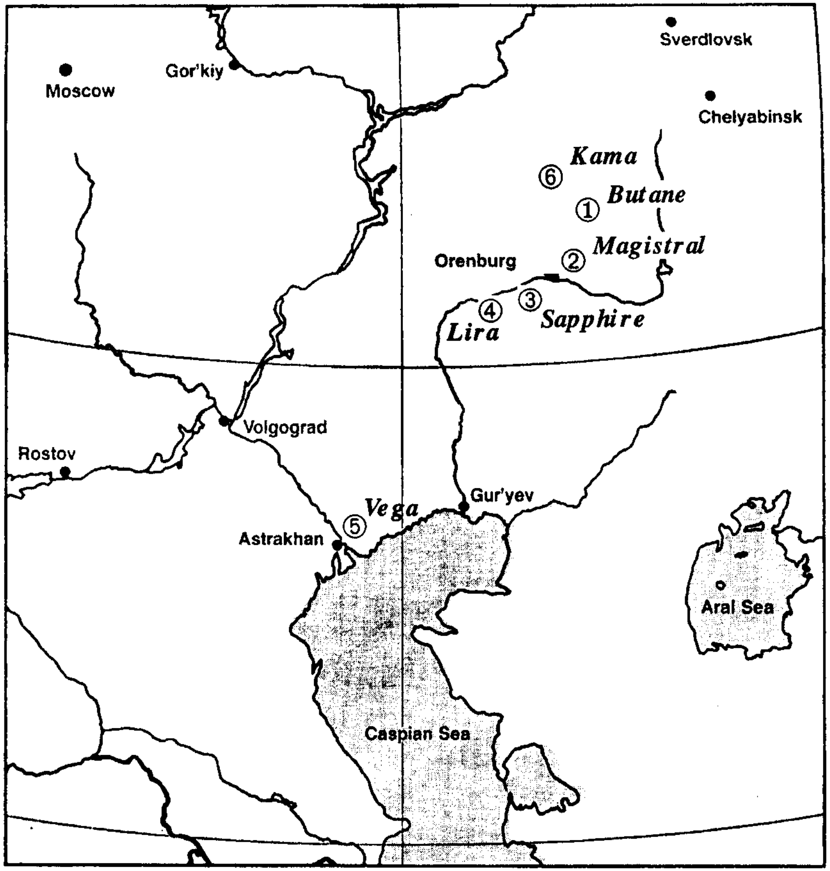

Figure 5: Map showing various PNE sites north of the Caspian Sea. (1) Butane is the first oil stimulation project. (2) Magistral, (3) Sapphire, (4) Lira, and (5) Vega are gas condensate storage projects. (6) Kama is the toxic waste storage project.

yield of 15 kt produced a 50,000 m^3 volume cavity. Reentry was made through the emplacement hole, and after flushing and cooling of the cavity with natural gas, the cavity was tested to a pressure of 8.4 MPa (84 atm) for 30 days and found to be sealed.

A second explosion was detonated at the Sapphire site two years later on September 9, 1972, a 10-kt explosion at a depth of 1,145 m, again in the bedded salt formation. It produced a similar but somewhat smaller cavity.

Both of these explosions preceded the construction of the gas-processing complex, one of the largest in the world, that was subsequently built at Orenburg by a consortium of western engineering firms. It actually consists of three plants, each with a capacity of processing 17 billion m^3 per year. Upon completion of the first phase of the gas-processing complex in 1974, gas condensate was introduced into the cavities, and the storage reservoirs were turned over to industrial use. It was operated at a working pressure of 8 MPa (80 atm) with the gas condensate being removed by gas displacement.

Use of both of these sites was temporarily stopped in 1993 to permit repair and decontamination work to clean up specific locations of above-background radiation in the industrial area. No contamination of the products stored in the cavities has been reported. Beyond the limits of the industrial area, radiation levels are reported to be at background.[100]

Project Vega

In 1980, the Soviet PNE Program and Gas Production Ministry began an extensive application of the underground storage technology proven in Sapphire at a new site about 700 km south of Sapphire, 40 km north–northeast of the city of Astrakhan at the north end of the Caspian Sea (see figure 5). This new project, called "Vega," was located on the southern edge of the newly discovered Astrakhan gas-condensate field, one of the largest gas-condensate fields discovered in the Soviet Union, many times larger than the Orenburg deposit. The Astrakhan field had a very high level of hydrogen-sulfide (25 percent), almost an order of magnitude greater than that at Orenburg, contaminating the gas. In addition, the Astrakhan field was reported to have very high levels of carbon dioxide (12 percent) that had to be separated out before the natural gas could be put in the distribution system. The Astrakhan gas-condensate reservoir occurs in a limestone formation at a depth of about 4000 m and is overlain by the Sentovskii salt massif that extends to about 500 m from the surface.[101]

The first explosion at Vega was carried out in the salt formation on October 8, 1980, at a depth of 1,050 m. Its yield was 8.5 kt. The following year on September 26, two explosions of similar yield were carried out at about the same depth and with an interval of 4 minutes between explosions. A little over a year later, on October 16, 1982, four explosions were fired at Vega with an interval of 5 minutes between explosions. Russian sources give the yield for one of the explosions as 13.5 kt with the rest being 8.5 kt.[102] On September 24, 1983, six more explosions were carried out at the Vega site at intervals of 5 minutes. The yields were all 8.5 kt at depths of about 1,000 m.

On October 27, 1984, the last two explosions were fired at the "Vega" site with a 5 minute interval between them, bringing the total at the site to 15 explosions. The depths of burial for these explosions were also 1,000 m, but their yields are given as 3.2 kt, only about a third that of the earlier explosions. Considering the very high sulfur content of the gas condensate and the size of the deposit at Astrakhan, it is suggested that these later two cavities may well be for waste storage or disposal.

The smaller yield of all the explosions at this site, in comparison with the yields at the Orenburg deposit, are attributable to the relative proximity of the large city of Astrakhan (>500,000 inhabitants) and numerous smaller towns and industrial facilities built on the Volga River delta above the Caspian Sea, all of which are susceptible to seismic damage. Seismic limitations determined the maximum single yield that was permitted, and the total storage requirements of the Astrakhan field and processing plant dictated the number of explosions. The use of several small explosions, spaced a few minutes apart, rather that one larger explosion, would allow the same storage volume to be produced with significantly lower probability of seismic damage, minimal operational costs for disruption and delay, and fewer evacuations of the local populations. The single explosion at 13.5 kt may have been a test to see what seismic damage a larger yield would incur.

Assuming that the latter two explosions were for storage, the other thirteen explosions would have produced a storage volume of about 400,000 m^3, about four times the storage volume at Orenburg. Beginning in 1986, seven of the cavities were filled with gas condensate as part of industrial operations, two were used for waste disposal, and six were placed in reserve. The availability of these cavities reportedly permitted start-up of the production and processing of gas condensate from the Astrakhan field significantly earlier than conventional storage would have permitted.

However, beginning in 1987, it was observed that the six empty cavities had started to converge, losing up to 40 percent of their volume. This was attributed to the absence of any counterpressure in the cavity and an anomolously high horizontal tectonic stress in the salt massif. Ultimately, the shrinkage led to destruction of the spherical layer of salt on the surface of the cavities, collapse of the walls into the cavity, and to fractures that allowed five of the six cavities to fill with water. The decision was made to retire the six cavities from use, and the access and other holes in the area were sealed. It is reported that none of the radioactive brine in the cavities has reached the surface.[103] However, there is a published report that water from the cavities has began to appear at the surface as artesian springs containing radioactivity.[104]

All of the fifteen Vega explosions were completely contained. The areas around some of the access holes are reported to have relatively minor above-background contamination (30–40 μR/hr), but beyond the industrial areas, radiation levels are at background.[105] No information has been provided on possible product contamination levels.

Project Lira

Three years after beginning Project Vega at the Astrakhan gas-condensate deposit, the Soviets initiated another industrial application of the underground storage technology, Project "Lira," at the Karachaganak gas-condensate field located about 140 km east of Uralsk and 130 km west of the city of Orenburg (see figure 5). The field, which was discovered in 1979 and actively developed in the early 1980s, is regarded as an extension of the Orenburg field and is about the same size as the Orenburg field. As at Orenburg, the natural gas and gas condensate contain high levels of hydrogen sulfide. The deep-lying Karachaganak gas reservoir field is overlain by a thick salt formation extending from near the surface in some places to depths of 4,000 m. Construction of a gas-condensate processing plant for the Karachaganak field was begun in 1983.[106,107]

Project Lira began on July 7, 1983, with three 13.5-kt explosions at 5-minute intervals. The first two were at a depth of 917 m, and the last at 841 m. They were followed about a year later on July 21, 1984, by another three 13.5-kt explosions at intervals of 5 minutes. Their depths of burst were 846 m, 955 m, and 844 m, respectively. The yields were almost double most of the yields at Astrakhan, presumably because of the distance of the Lira site from population centers.

These six Lira explosions would be expected to produce about 300,000 m^3 of underground storage capacity for use in conjunction with the Karachaganak gas-condensate reservoir. At last report, four of the six, 1T through 4T, were being prepared for use for storage of gas condensate and partial separation of the natural gas, and one other, 6T, was being held in reserve. The last one to be fired, 5T, developed a leak, and the cavity and emplacement hole have filled with water. As of 1994, plans were being developed for closure of that location and sealing of the emplacement/access hole.

As with the explosions at Orenburg and Astrakhan, all Lira explosions were completely contained, and radiation levels are reported to be at background levels at the Lira site.[108]

Summary of storage

Overall, the use of nuclear explosions to produce cavities in salt for the storage of liquid hydrocarbons proved to be a somewhat successful application with several serious concerns. In the three full-scale applications of the technology, over 800,000 m^3 of storage were produced capable of storing some 400,000 tons of condensate. The Russians report the possibility of storing gases up to a pressure of 14 MPa (140 atm.). In all cases, the nuclear explosive emplacement hole was successfully used for post-shot access and exploitation of the cavities. Although no measurements have been reported, the Soviets report that there has been no contamination of the stored condensate product by radioactivity from the explosions.

However, the loss of six out of twenty-three cavities by leakage of water into the cavity raises serious questions about the safety and viability of the application. Water that leaks into a cavity will begin dissolving salt from the walls and the resolidified mass of melt at the bottom of the cavity containing the majority of the radioactive residue from the nuclear explosive. With time, the walls may begin to break up, and the water will become contaminated with soluble radioactive nuclides from the walls, puddle at the bottom of the cavity, and become hazardous to bring to the surface. Any product stored in a partially water-filled cavity will tend to absorb the water and become contaminated by the radioactivity. Only experience can define the magnitude of the environmental risk presented by this sequence of events.

Deep Seismic Sounding of the Earth

In 1971, the Soviet PNE Program, in cooperation with the Ministry of Geology, embarked on the most ambitious and far-reaching application, the use of peaceful nuclear explosions for the seismic exploration of vast reaches of the Soviet Union. In the early 1960s, the Ministry of Geology had been active in carrying out detailed studies of the Earth's crust and upper mantle in the northern Eurasian part of the Soviet Union utilizing chemical explosions spaced a few hundred kilometers apart along a line. These so-called Deep Seismic Sounding (DSS) lines permitted study of the crustal structure to depths of 30–40 km over large areas. During the late 1960s, the Ministry of Geology began a program of experimental seismic studies, recording the signals from the PNEs carried out for oil and gas stimulation and for closure of runaway gas wells. Based on this experience, they developed a program for extending their DSS program to explore geologies to much greater depths over distances of a thousand kilometers and for utilizing the much stronger seismic signals of nuclear explosions (see section B.5 of Appendix B).

Figure 6 is a map of the Soviet Union showing the location of 15 DSS lines that were carried out over the next 17 years and the location of the PNEs associated with the DSS program. Section B.5 of Appendix B provides the data for the DSS explosions and indicates the DSS lines listed in figure 6 with which they were associated.[109,110]

Although the signals from PNEs carried out for other purposes and weapons tests at Semipalatinsk were undoubtedly utilized,[111] the vast majority of data were generated by the 39 PNEs specifically fired as part of the DSS program. As can be seen in Appendix B, all of the DSS explosions were carried out at depths of burial of 500–1,000 m, much greater than the minimum depth required for containment. Yields varied between 2.3 and 22 kt, with the majority less than 10 kt.

The seismic lines extended over distances that ranged from 1,500 to 4,000 km, with three to four nuclear explosions typically spaced at distances of 500 to 900 km along those lines. Hundreds of Taiga portable seismometers were located along each line, many placed by helicopters because of the remoteness of the regions, at spacing of about 10–20 km. Their signals were transmitted to central recording stations.

Almost every year from 1971 to 1984, a different DSS line was investigated with three or four explosions. The explosions for a particular line were generally carried out at intervals of 10 to 30 days in the late summer and fall. However, in one line that involved only two explosions, they were fired about one hour apart. Shot times were often late at night or early in the morning to reduce cultural background noise. In many cases, the nuclear explosions were augmented by chemical explosions, sometimes delivered as bombs from aircraft because of the difficult terrain and lack of roads.

In the early 1970s, several DSS lines in the European and Caspian regions of the Soviet Union were explored, moving from west to east. Beginning in 1975, exploration of Siberia east of the Urals began and was the focus of activity for the next ten years.

Relatively few reports have been published describing the results of these DSS lines and the crustal and mantle structure derived from them. The few to have appeared have generally referred to the nuclear explosions as "large industrial explosions."[112,113]

The first publication to include reference to one of the nuclear lines appeared in 1973,[114] but it included little detail derived from the nuclear explosions. It was not until 1977–78 that results began appearing in geophysi-

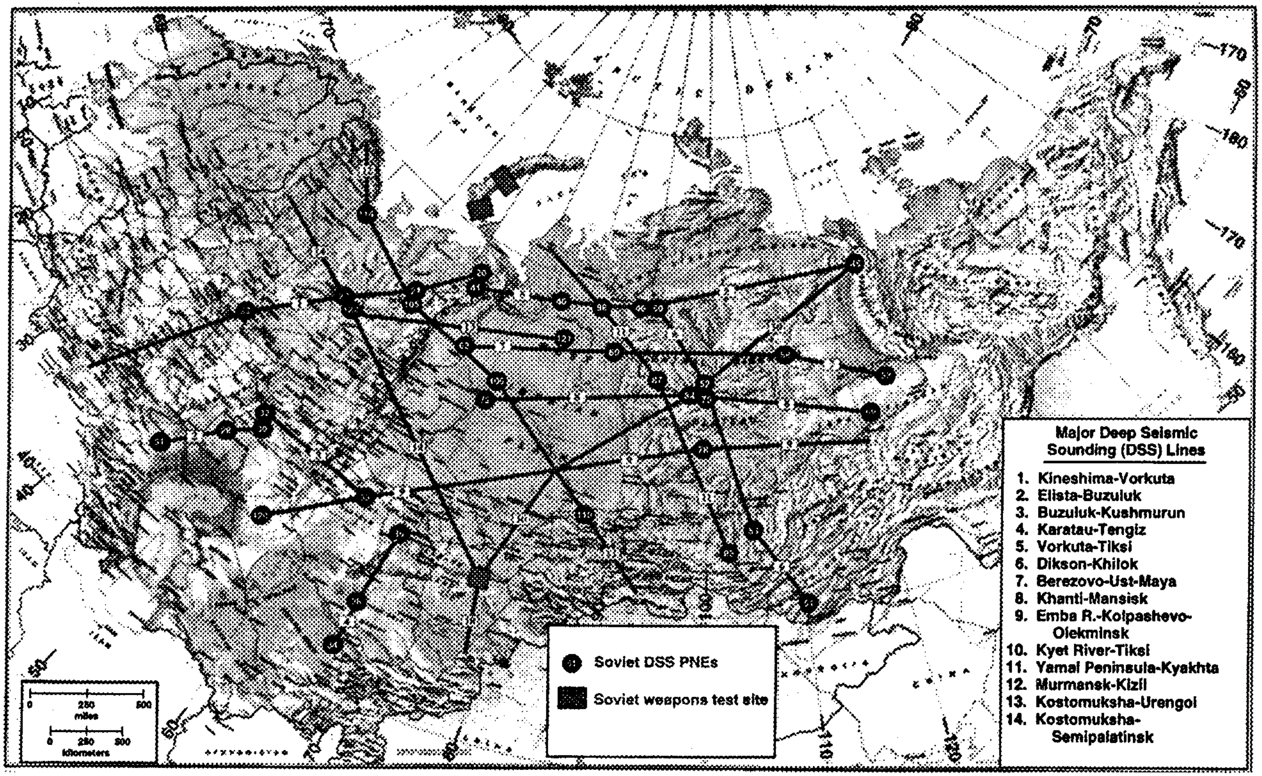

Figure 6: Map of the former Soviet Union showing the Deep Seismic Sounding (DSS) explosions and the DSS lines connecting them along which seismometers were placed every 10–20 km to record the seismic signals to learn about the structure of the crust and upper mantle.

cal journals. Generally, geologic profiles derived from DSS lines utilizing nuclear explosion sources are characterized by structural details and velocity profiles to depths of 200–300 km, well below the 35-km depth of the Morohovic velocity discontinuity, which generally limits the depth of conventional profiles. Papers describing the geologic structure of specific DSS lines utilizing PNEs can be found in endnotes 108 and 109. More recent structural studies can be found in endnotes 113–115.[115,116,117] Much of the data collected on the DSS profiles has now been made available to other agencies and, through exchange agreements, with geologists from other countries.[118] The limited results from the use of these data may well be due to the limited computational capability available to the ministry of Geology who closely held the data for many years.

Although specific details have not been provided, this work is described as being of great value not only for defining the general structure of the crust but also for identifying areas with high potential for gas, oil, and mineral development. Specifically, MinAtom claims that the existence of ten gas and gas condensate deposits in the Yenisey-Khatanga Basin east of Norilsk and about ten more in the developing areas of the Vilyuysk syncline in Eastern Siberia have been confirmed through use of data from the DSS profiles.

All of the DSS explosions were carried out without escape of radioactivity, with three exceptions. The third and fourth DSS explosions on the first DSS line in 1971, "Globus-1" and "Globus-2," suffered minor leakage of gaseous radionuclides from the emplacement hole. The areas near the emplacement holes were decontaminated, and radiation levels are at or near regional background.

A more serious vent accompanied the "Kraton-3" explosion on August 24, 1978, 120 km from the remote village of Aikhal in Siberia. This is in a region of permafrost. In the process of drilling or stemming the emplacement hole, some of the medium adjacent to the hole was melted, which resulted in a failure of the stemming seal and a dynamic vent of gaseous radioactivity and steam to the atmosphere at the time of the explosion. Measurable radioactivity was carried 150 km over unpopulated forest and tundra. Radiation surveys in 1990 showed levels of 1 mR/hr in the immediate vicinity of the hole and up to 0.2 mR/hr as far as 5 km in the fallout trace. Following decontamination of the area, levels are reported to be 30–50 μR/hr outside a 2 km exclusion zone, which is periodically monitored.[119,120]

Breakage of Ore

As experience was gained with underground nuclear explosions in hard rocks from the nuclear weapons tests, the idea of using PNEs to assist with mining ores and other minerals from the earth quickly developed both in the U.S. and the Soviet Union. In the late 1960s, the Soviet PNE Program began looking for a good site to apply this new technique. The U.S. Plowshare Program had looked at several techniques for using nuclear explosions to break up large ore bodies for in-situ processing to recover the valuable resource. Most of these techniques envisaged placing a 10–20-kt nuclear explosion at the bottom of a deposit and, depending on the collapse of the explosion cavity to form a collapsed chimney of broken rock, above the explosion point. Recovery would be carried out utilizing drifts mined back through the chimneys.

Soviet PNE scientists at Chelyabinsk, in cooperation with engineers from the Moscow Mining Institute and the All-Soviet Institute of Industrial Technology (VNIPI), developed a concept for using much smaller explosions (2–4 kt), which were more suitable for the more widespread small deposits.[121,122] This concept involved mining vertical slots about 45–60 $m/kt^{1/3}$ distant from the explosion to provide a free surface that would reflect the shock wave from the explosion, greatly enhancing the volume and extent of breakage of the rock and reducing the compaction. It was expected that five to ten times more rock would be fractured in this way than would be found in the chimney from the same yield explosion. The slot would also weaken the shock wave and help to protect any other workings or structures beyond the slot. A network of crossdrifts would be mined below the body of broken ore for recovery by the usual stope-mining methods.[123]

Project Dnepr

The first experiment using this concept was carried out on September 4, 1972, in the Kuel'por apatite (phosphate) ore deposit about 21 km north of the city of Kirovsk on the Kola Peninsula, about 150 km from the Finnish border (see section B.6 of Appendix B). A 2.1-kt nuclear explosion was positioned immediately below the ore body, which was 60–80 m thick and sloping into the mountain at about a 25- to 35-degree angle. A 50-m-high vertical slot was mined about 50 m away on the opposite side of the deposit (see figure 7.a). The shock wave produced a volume of about 100,000 m^3 of broken ore.

In an effort to reduce the possibility of contaminating the ore body with radioactivity from the explosion, "with the aid of a special device the radioactive products from the explosion cavity were ejected into barren rock" some 120 m away from the ore body. This technique was first tested by the Chelyabinsk Laboratory in the "148/1" test in the Degelen Mountains at the Semipalatinsk Test Site a year and a half earlier on April 9, 1971. No information is available on how well this technique worked, but an additional test of the idea was carried out at Degelen in the "148/5" event on December 16, 1974, this time by the Arzamas Laboratory[124,125] (see Appendix C).

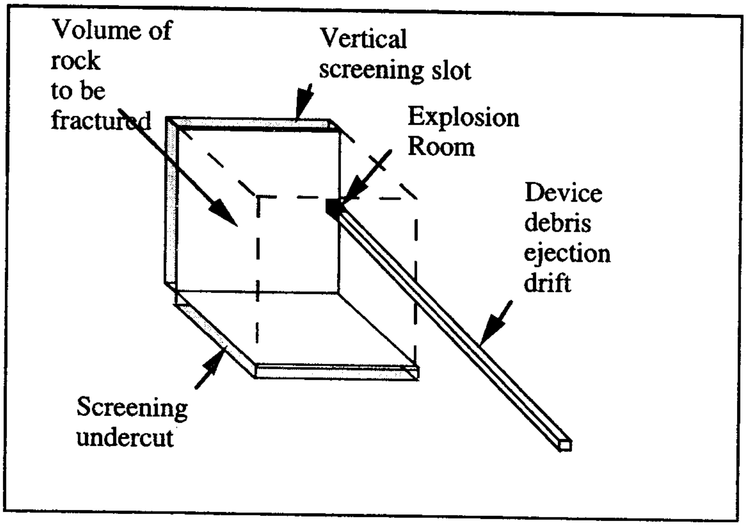

Figure 7.a: Schematic of the "Dnepr-1" experiment.

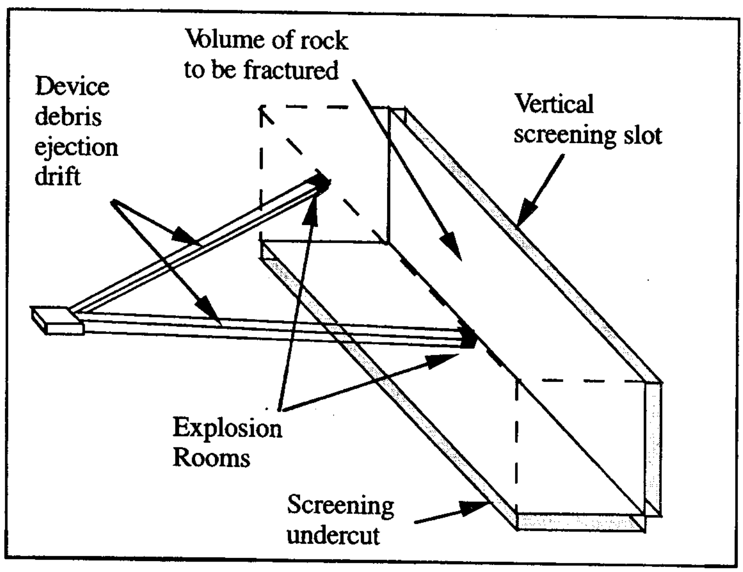

Figure 7.b: Schematic of "Dnepr-2" experiment.

Twelve years later, a second explosion, "Dnepr-2," was carried out in the mine on August 27, 1984. For this experiment, two 1.8-kt explosions were fired simultaneously in separate drifts 75 m apart. The scheme for ejecting the device debris out of the cavity and down a 120-m tunnel was again utilized to remove radioactivity from the region of broken ore. Although details have not been provided, the method of ejecting the radioactive debris from the explosion down a tunnel and out of the valuable ore deposit is described by MinAtom as a success.[126]

Again, in preparation for this explosion, a vertical screening slot was constructed about 50 m from the explosions that was 125 m wide and extended 40 m above the explosion horizon and 50 m below. Screening drifts were also mined below this block of ore (see figure 7b). The shock wave from the Dnepr-2 explosions fractured about 500,000 to 600,000 m^3 of ore. In total, the two experiments were calculated to have broken over one and a half million tons of apatite ore.

A total of 396,000 tons of ore broken by Dnepr-1 and Dnepr-2 were removed from the Kuel'por mine over the period from 1972 to 1990 using standard stope-mine practices in the drifts below the blocks broken by the explosions. Secondary blasting required only about 12–13 g of HE per ton to break up oversized blocks instead of the 80–100 g per ton required by the usual mining practice in this deposit.

Immediately after the Dnepr-1 explosion, leakage of gaseous radionuclides led to exposures in the city of Kirovsk of 30–40 mR, about 10 percent of annual background doses, during its passage and dissipation. Leakage from the 1984 explosion was delayed by up to 10 hours and led to little exposure off site.

Radiation conditions in the mines were reported to be essentially the same as in normal mining operations and did not exceed established safety norms; thus, no special measures were required for miner safety beyond standard practices. Radioactivity levels in the ore were also reported to be below permissible levels. Air and water within the mine and in the nearby rivers and lakes were routinely monitored for various radionuclides such as Sr^{90}, Cs^{137}, Pu^{239}, and tritium. MinAtom reports that no radioactivity levels above maximum permissible dosage were observed, except for tritium in water from the ore body, which exceed maximum permissible levels by a factor of 1.5 to 2 on occasion. In general, radiation levels in the area surrounding the site are reported to be at background levels.[127]

The Dnepr site has been closed since 1992, but it is subject to periodic monitoring. Overall, the experiments are described by MinAtom as being successful, although, as of 1994, the mined ore was awaiting the construction of an access road before it could be sent to a refinery for processing. However, as

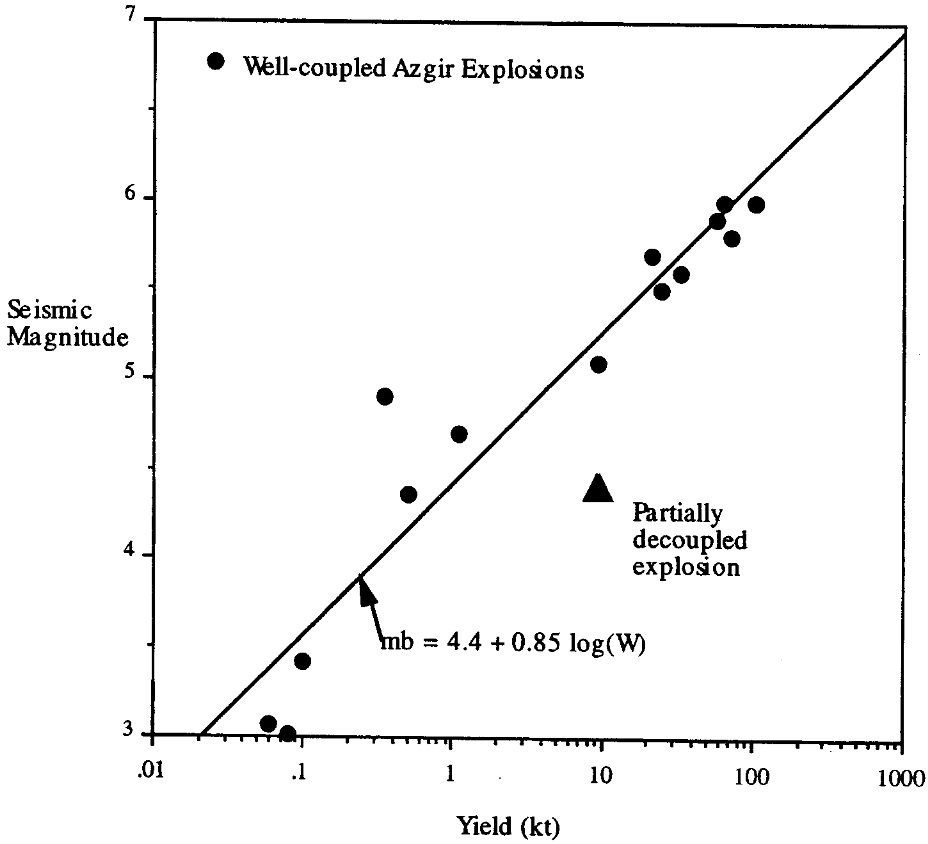

Figure 8: Plot of seismic magnitudes vs. yield for 102 contained Soviet PNEs. (many data points do not appear on the plot because they have the same coordinates and are on top of one another.) The various symbols indicate the purpose of the PNEs. Also shown is a regression fit to the PNE data (solid line) and, for comparison purposes, a fit often associated in the past with estimates of the yields of Soviet weapons tests and PNEs (dashed line).

information about the Dnepr experiments became public in the late 1980s and early 1990s, environmental organizations in the area have raised protests and called for an end to any further such experiments.[128]

Disposal of Toxic Waste

Industrial development in the Soviet Union over the last 60 to 70 years has left a legacy of industrial contamination that is probably unparalleled in the modern world. Contamination of water supplies by dumping industrial wastes of chemical and oil industries into rivers and lakes has endangered the drinking water supplies of many towns and cities. In an effort to develop a technol-

ogy that could be used to dispose of some of the worst types of industrial effluents and buy time for the development of better industrial waste treatment procedures and facilities, early in the 1970s the scientists from the Soviet PNE Program and the Ministry of the Oil Refining and Oil Chemical Industries proposed two experiments using nuclear explosions to produce deep disposal facilities (see section B.7, Appendix B).

Deep-well disposal utilizes the fact that a 5- to 10-kt nuclear explosion creates a large fractured region, which, in some cases, extends to 100–200 m from the explosion, and that the chimney produced by the collapse of the cavity would contain 100,000 to 150,000 m^3 of broken and crushed rock and 30,000 to 50,000 m^3 of void space. The large central chimney provides surface area and volume for the deposition of suspended particulates, and the large fracture radius provides an enormous area for liquids to percolate into the surrounding formation. To assure that percolation of the chemical wastes or any radioactivity leached from the glassy melt would not contaminate potable water supplies, the geologic layer must be deep and isolated from any mobile water layers.

Project Kama

The sites chosen for the two "Kama" waste-disposal experiments were not far from the first oil stimulation site (Butane) and the gas-condensate storage sites (Magistral, Sapphire, and Lira) in the Bashkir Republic, 30 km west of the city of Sterlitimak (see figure 5). A depth of burial about 2,000–2,100 m was selected that would place the explosion and chimney in the middle of a 400-m-thick, dense carbonate section (dolomite), which was isolated from potable water sources. Both explosions used special 10 kt devices, sufficiently small that the size of the emplacement holes were determined by pumping requirements.

The first Kama explosion, "Kama-2," was fired on October 26, 1973. Exploitation of the site did not begin until 1976, when industrial waste began to be pumped from the Sterlitimak soda factory into the chimney through three holes. Flow from the soda factory contained 50–100 mg/L of suspended solids that were chemically incompatible with the water in the injection layer resulting in the precipitation of more than 1,000 mg/L of additional solids. In a normal injection hole, this would have rapidly led to plugging of the hole. However, in the case of Kama-2, more than 23,000,000 m^3 of industrial wastes carrying more than 1,000 tons of suspended solids have been disposed of in the period between 1976 and 1993. Use of the "enlarged" disposal hole continues with an average flow of 4,000–5,000 m^3 per day. Savings to the environment over that same period of time through the use of this site have been put at more than 70 million rubles (1990).

The second Kama explosion, "Kama-1," was fired 10 months later on July 8, 1974. Exploitation of this site did not begin until 1983 when the disposal of highly toxic waste flows from the Salavat oil refinery began. This waste contained suspended particulate with resinous materials having an exceptionally high capability to clog pores in any conventional disposal site. These flows contained between 100 and 1000 mg/L of these particulates and were not disposable by any other method known at the time. In the period between 1983 and 1993, about 700,000 m^3 of industrial waste from the Salavat oil refinery were disposed at an estimated savings to the environment of 100 to 200 million rubles (1990).

Observation holes are being used to monitor water tables in the area for the transport of waste materials and radionuclides from the sites. To date, no industrial waste material has been detected in the water layers overlying the injection layer. Observation holes 500–1,000 m from the explosion sites at the depth of the injection layers detected radioactivity in the water flowing out of the chimney into the carbonate formation, but within 5 to 6 months after injection began, the gamma activity level was essentially at background.

The explosions were completely contained with no prompt vent or leakage of radioactivity. Although there are some slightly contaminated areas near the emplacement holes—probably due to reentry drilling and water table observation holes—beyond the industrial area the radiation levels are reported to be at background.[129,130]

Overall, this would appear to be a highly successful application. For that reason, it is curious that it was not used at any other sites in the Soviet Union or Russia in more recent times.

Transplutonic Element Production

From the beginning, Soviet scientists at the nuclear weapons laboratories were interested in the possibilities of using the large flux of neutrons generated in a nuclear explosion for scientific purposes and to breed new, heavier elements. Interest in such applications played a key role early in the U.S. Plowshare Program. Such applications are the subject of papers at both the first and second Plowshare Symposiums in 1957 and 1959[131,132] and of the design of the first U.S. Plowshare experiment, Project "Gnome."[133] As discussed above, interest by the U.S. in using the high flux of neutrons focused on designing special nuclear devices to produce new, super-heavy elements well beyond uranium and plutonium through multiple neutron capture. The ultimate goal was to determine the physical properties of any new elements produced and to advance our understanding of the atomic nucleus.

Early on, the interest of Soviet scientists in the use of large neutron fluxes was directed at the possibility of using them to produce trace quantities of transplutonic actinide elements through multiple neutron capture as well as useful quantities of plutonium 238 and 239 and uranium 232 and 233 through single or double neutron capture. Any such elements produced would then be recovered and used for isotope production or as fissile material. Such elements can be produced internal to a nuclear device as well as by capturing the neutrons produced by a nuclear explosion in a uranium 238 or thorium 232 blanket placed around the nuclear device. The difficult problem is recovering the isotopes in an economical and timely fashion. The Arzamas Laboratory was the lead laboratory for this program (see section B.8, Appendix B).[134]

One of the primary purposes of the first two explosions in the salt domes at the Azgir site, Halite A-1 and Halite A-2, was to provide an experimental site for studying the potential of salt cavities for use in the production of these new isotopes. A nuclear explosion detonated in a large water-filled cavity will deposit the vast majority of its energy in the water. A small portion of the water would be immediately vaporized, but if the cavity is sufficiently large, the average temperature of the water in the cavity will be elevated only a few degrees. For example, if a 1-kt explosion were detonated in the Halite A-2 cavity containing 140,000 m^3 of water, it would raise the temperature of the water about 7°C. The water would then cool and congeal the vaporized debris of the device and any material close to it. The condensed debris would then settle to the bottom of the cavity where it could be easily recovered.

Halite A-2-1 to A-2-6

Beginning in April 1975, Soviet scientists began carrying out small explosions in the water-filled Halite A-2 cavity, using nuclear explosives designed to enhance neutron capture for the production of transplutonic and other actinide elements. The first test, A-2-1, was 0.35 kt at a depth of 583 m, about 14 m above the center of the 32-m-radius cavity. Access was through the original emplacement hole. It has not been reported whether attempts were made to recover debris from the bottom of the cavity for this explosion, but two years transpired before the next experiment.

The next experiment, A-2-2, was a 0.10-kt explosion carried out in the A-2 cavity on October 14, 1977, which was quickly followed by the third explosion, A-2-3, an explosion of only 0.01 kt 16 days later on October 30. Again, no information is available on whether any recovery was attempted between these two explosions.

The last three transplutonic element experiments were carried out about two years later. On September 12, 1978, a 0.08-kt explosion was again detonated in the A-2 cavity. Three months later, on November 30, a 0.06-kt explosion followed. Two months later, on January 10, 1979, the last explosion in this series was fired. It was the largest of the six at 0.5 kt.

All of these explosives were fired at a depth of about 581–585 m, which would place them about 14 ± 2 m above the center of the initial cavity. Since the resolidified melt occupies a spherical segment on the bottom of the cavity about 10 m thick, such a position for the explosions would place them approximately in the center of the water volume.

Unfortunately, no further information has been provided by MinAtom on the details of the experiments, the methods used to recover debris from the explosions, or to what extent the program was successful in producing transplutonic and other actinide elements.

All of the transplutonic explosions were carried out without venting. However, recovery operations undoubtedly resulted in some contamination of the general area around the emplacement hole. The Halite A-2 cavity has now been closed, and the area has been decontaminated. Beyond the working area, radiation levels are at natural background levels.[135]

Halite A-4 to A-11

About a year after the first transplutonic element experiment, the Soviets began to carry out a series of large-yield explosions in the Eastern Azgir salt dome. The first of this series, A-4 on July 7, 1976, was a 58-kt explosion at a depth of 1,000 m, an almost exact duplicate of the A-3 explosion in 1971. It was followed a little over a year later on September 9, 1977, by A-5, a 9.3-kt explosion at a depth of 1,503 m.

Over the next two years, the Soviets carried out five more large yield explosions, A-7 to A-11, in the Eastern Azgir Dome with yields that varied from 21 to 103 kt at depths that ranged from 630 to 1,500 m.

As with the cavities created for gas-condensate storage, the Soviets experienced unexpected results in at least one case. The cavity created by A-9, the largest yield of all the explosions at Azgir, collapsed at an early time. and the collapse propagated to the surface. This resulted in the formation of a subsidence crater 500 m in diameter and 18 m deep. However, there was no release of radioactivity during or after the collapse. The other six cavities initially were sealed with respect to water leakage and stable.

MinAtom has not reported on the purpose for the series of seven explosions, but there are several possibilities. They could well have been intended to be a stockpile of cavities for possible use in future production of fissile materials, using the "breeding" ideas then being studied in the transplutonic production experiments in the A-2 cavity. However, the great variation in the yield and size of the resultant cavities would be somewhat inconsistent with such use. In addition, four of these explosions (A-7, A-8, A-10, and A-11) were multiples, with two or three explosions in the same emplacement hole being fired simultaneously. This would suggest that they were actually weapons

Table 5: Summary of data on the "halite" cavities at Azgir.

Cavity name	Yield (kt)	Depth (m)	Actual radius (m)	Calculated radius (m)	Calculated volume (m^3)
A-1	1.1	161	12–14	17	19,400
A-2	27	597	32	32	137,500
A-3	64	986	36.2	37	204,050
A-4	58	1,000		35	182,900
A-5	9.3	1,503		17	21,040
A-7	73	971		38	235,400
A-9	103	630		49	487,200
A-8	65	995		37	205,500
A-11	21	982		25	68,600
A-10	33	982		29	106,900
				Total volume	= 1,668,490

tests diverted from the Semipalatinsk Test Site. Such a purpose would also explain why the yields were so variable.[136] Finally, they could be a combination, weapons tests that were used to create cavities at Azgir for future industrial use.

Table 5 summarizes the data on the Halite cavities at Azgir together with calculated radii and volumes using the formula developed in the U.S. Plowshare program.[137] Although there is relatively little agreement for A-1, which was poorly documented because of collapse, the agreement for A-2 and A-3 is excellent. Of particular interest is A-5, which had an order-of-magnitude greater yield than A-1 but which, because of the much greater depth of burial, produced a cavity about the same size as A-1. The total volume calculated for all the cavities at Azgir is about 1,670,000 m^3, in good agreement with the MinAtom number of 1,600,000.[138] In all, nine standing cavities with diameters ranging from 34 to 76 m were formed with a total volume of about 1,200,000 m^3, two of which are full of water.

All of the Azgir explosions in this series were completely contained except for A-8, which experienced early leakage of inert radioactive gases at 60 min. Of particular interest is A-5, which had almost an order-of-magnitude greater yield than the emplacement hole. During planned reentry into the explosion cavities for post-shot examination and utilization, a total of 4.7 mCi of radionuclides were vented to the atmosphere under controlled conditions.

At present, five of the nine standing cavities (A-1, A-2, A-3, A-4, and A-5) have been flooded by water leaking in from overlying aquifers. By late 1990, sites A-1, A-4, A-7, A-8, and A-11 had been closed and decontaminated. Radiation levels in the areas near the emplacement/access hole were 8–20 μR/hr, about equal to background. As of April 1993, sites A-2, A-3, A-5, and A-10 were being closed and decontaminated, if necessary. The A-10 cavity is being used for burial of soil from throughout the Azgir complex. The radiation conditions of the entire site have been well documented and are under periodic radiation monitoring.[139]

Seismic Decoupling Experiment

Early in the history of test ban discussions between the U.S. and the Soviet Union, the concept of decoupling or reducing the seismic signal from a nuclear explosion was introduced. In the fall of 1958 at the Geneva Conference on Banning Nuclear Tests, the U.S. submitted the argument that any test ban agreement must take into consideration the possibility that a nuclear weapon test carried out inside a large cavity would have its seismic signal reduced by a factor of 100–300, making it very difficult to detect by seismic means.[140] The Soviet Union very strongly rejected the concept and refused to consider any of the theoretical arguments made by U.S. scientists.

In an effort to prove the feasibility of the decoupling concept, the U.S. Vela Program sponsored a pair of tests in the mid-1960s. In the 1964 SALMON explosion, the U.S. fired a 5.3-kt device at a depth of 828 m in a salt dome near Hattiesburg, Mississippi, to create a 34-m-diameter cavity.[141] Two years later, in the STERLING test, a 0.35-kt nuclear explosion was detonated in the SALMON cavity. The scaled radius of the cavity was only 24 $m/kt^{1/3}$. The seismic signal was partially decoupled by a factor of about 72, confirming the decoupling concept although not testing the full decoupling capability of the technique. That would have required a larger cavity or a smaller-yield decoupling explosion.[142]

In the spring of 1976, the Soviets decided to carry out a similar seismic-decoupling experiment in the A-3 cavity (see Section B.9, Appendix B). On March 29, they fired "Halite A-3-1," a 10-kt nuclear explosion at a depth of 990 m in the A-3 cavity.[143] That depth would place it approximately at the center of the cavity. The scaled radius of the cavity was only 16 $m/kt^{1/3}$ in terms of the decoupled explosion yield. Because of the smaller scaled radius of the cavity relative to the STERLING explosion, it was decoupled even less.

Figure 8 is a plot of the seismic body wave magnitudes recorded for most of the explosions in salt at Azgir, including the transplutonic production explosions in the water-filled A-2 cavity as well as the signal from A-3-1, the decoupled explosion in the A-3 cavity. Also shown is a regression fit to the fully-coupled Azgir data. Based on calculations by U.S. scientists, the decoupling factor for A-3-1, using a yield of 10 kt, would be about 15 based on teleseismic data, and 23 based on close-in data (recorded at less than 100 km).[144]

The relatively low degree of decoupling produced by this equipment would contribute little to the issue of how full decoupling could be used to hide weapons tests under a comprehensive ban on testing, raising questions as to whether this was the primary purpose of this test. An alternative rationale, reported by Vitaly Adushkin, Director of the Russian Institute for Dynamics of the Geosphere, is that the purpose of the second explosion in the cavity was for investigating how much additional volume such a secondary explosion could produce in a cavity with minimal seismic disruption to the surrounding territories. Some of the locations being considered for storage applications were sufficiently close to populated regions that the permissible yields were severely limited. In an effort to produce the required storage volume with a minimum number of seismic disruptions of the region, the concept of enlarging small cavities with partially decoupled secondary explosions was under consideration in the mid-1970s. Unfortunately, results of this experiment showed that little additional volume was produced, and no subsequent application of the idea was made.[145]

Mine Gas Dispersal

Coal mining in the Donets Basin of the Ukraine has long suffered from the dangers of rock bursts and explosions resulting from pockets of methane gas, which has resulted in the deaths of miners by explosions and suffocation. As the coal mines in this area went to deeper and deeper levels, the problem worsened. By the end of the 1970s, the number had reached over 200 explosions or rock bursts per year. At some point in the late 1970s, scientists from the Ukrainian Academy of Sciences' Fuel Physics Institute and the All-Soviet Institute of Scientific Industrial Technology suggested using a relatively small nuclear explosion to open incipient fractures and equalize stresses in the rock to avoid these sudden and dangerous occurrences. A similar effect had been observed in the Sakhalin area of Siberia as a result of frequent earthquakes in that area (see section B.10, Appendix B).

Project Cleavage

The site chosen for the "Cleavage" experiment, sponsored by the Soviet Coal Ministry, was in the "Young Communist" coal mine 5 km east of the Ukrainian village of Enakievo. A 0.3-kt nuclear device was emplaced in the "Yunkom" mine in a sloping drift between two of the most dangerous layers, 45 m below a layer named "Devyatka" and 31 m above the "Kirpichevka" layer. The yield was small to minimize damage to the mine and underground structures as well as the housing in the Yunkom area and the town of Enakievo. The particular location in a sandstone rock was chosen to assure that the resolidified melt containing about 95 percent of the radioactivity of the explosion would be insoluble in water to minimize the transport of radioactivity from the explosion area. The inclined shaft was sealed with concrete to prevent release of the gaseous radionuclides to the surface or into other workings in the mine. Radiation levels in the air and water within the mine and at the surface were continuously monitored.

The explosive was fired at 05:00 local time on September 16, 1979, at a depth of 903 m. Post-shot inspection of the mine revealed little structural damage beyond the immediate vicinity of the explosion. Mining in the Devyatka layer in 1980–82 indicated that the effective radius of the explosion for elimination of the dangerous blowouts was about 150 m, but there was a significant reduction of the number and intensity of bursts beyond that distance as well. The occurrence of bursts in this time frame are reported to have been reduced to less than one per million square meters, and the intensity of any single burst to less than 50 tons, a factor of 4–5 less than that reported earlier.

Radiation levels in the coal mined from the Devyatka layer near the explosion were reported to be at background levels. Work in the mine in subsequent years proceeded with no complications from the explosion, and production increased significantly from 1980 through 1982.[146]

Unfortunately, the test was carried out without the knowledge of the local population, and much suspicion of the results remains in the local area. Several recent articles in the popular press have cast doubts on the efficacy of the test, quoting the director of the Yunkom mine, V. G. Revskovo, as saying there were essentially no positive results of the explosion in the mine and claiming that the high residual radiation levels from Chernobyl have made it difficult to confirm the statements made by the ministry of Atomic Energy regarding radiation conditions.[147,148,149] The fact that in the nine years following Cleavage, there were no subsequent nuclear explosions for this purpose in Yuncom or any other mine, would suggest that the results were less favorable than expected.

Overall Seismic Coupling

Figure 9 is a plot of the seismic magnitude, determined by the National Earthquake Information Service or the International Seismic Center, versus the MinAtom yield for 102 of the Soviet contained PNEs. Several of the contained PNEs were not detected by the world-wide seismic networks because of the small yield or "noise" from large earthquakes. The two Dnepr mining shots are also not included because of their relatively shallow burial. The six explosions in the water-filled A-2 cavity have been included because they would have been very well coupled. Also shown is the decoupled explosion Halite A-3-1 fired in the A-3 cavity.

The solid line in figure 9 is a least-squares regression fit to the 102 well-coupled PNE explosions. The standard error is about 0.29, corresponding to a factor of about 2.5 in yield. The large scatter of the data can be attributed to the wide variation in the depths of burial and types of geology, ranging from porous carbonates to high-coupling granites and salt. The dashed line is the magnitude–yield equation used for many years to determine the yield of Soviet nuclear explosions from seismic magnitudes.[150,151] Virtually all of the Soviet PNEs have yields much less than those predicted by the dashed curve, some by up to an order of magnitude or more. Use of the dashed curve or even one with a constant 0.1 or 0.2 units higher would have consistently overestimate the yield of most Soviet PNEs.

Epilogue

When President Gorbachov declared a moratorium on nuclear weapons tests in the fall of 1989, he included a ban on peaceful nuclear explosions as well, ending this active and ambitious program. While the new technology appears to have been warmly accepted and encouraged by some ministries such as the Geology, Oil and Gas Production ministries, some of the applications such as toxic waste disposal were not. Seismic data from the deep seismic sounding program continue to be used by the scientists from the various geophysical institutions in Russia to better understand the deep geologic structure of the country. Oil and gas continue to be produced from most of the fields stimulated by nuclear explosions. Many of the salt cavities in the Caspian region continue to be used to store gas condensate for the gas industry. The Kama disposal sites presumably continue to be used, but there was no interest on the various chemical production industries to develop other sites when it was possible to do so. The apatite mining operations at the Dnepr sites on the Kola peninsula have been closed since 1992.

Chetek

Early in 1991, news reports began to appear regarding the establishment of a new private company in Russia called Chetek, which was proposing to carry out peaceful nuclear explosions on a commercial basis. Chetek was reported to have been established by scientists from Arzamas and to have close ties to the Ministry of Atomic Energy. One of their most widely promoted proposals was to use nuclear explosions to destroy the enormous stocks of chemical weapons (CW) distributed around Russia.[152]

Their proposal called for mining a number of tunnels off a central adit at the Novaya Zemlya Test Site, and constructing a room some 20 m high and 80 m long at the end of each tunnel. The chemical weapons, without disassembly, would be placed in these large chambers with a 10- to 50-kt nuclear device located in the center of the mass of chemical weapons. The high-intensity shock wave from the nuclear explosion would instantly vaporize and decompose the chemical weapons—casing, high explosives, chemical agent, and all—rendering them harmless. The non-condensable gases produced would be difficult to contain, but they would be relatively harmless if they escaped to the atmosphere in an area such as Novaya Zemlya. Chetek argued that one or perhaps two 150-kt explosions, involving multiple explosions in adjoining tunnels, could destroy the Russian CW stockpile reported to be in the neighborhood of 50,000 tons.[153]

While such a proposal would have a significant economic and time advantage over conventional methods of CW destruction, particularly since Russia reportedly does not have an operational CW destruction facility, some concerns have been expressed regarding this proposal. The primary concerns center on the consequences of an accident before or during the nuclear explosions. While the remote nature of the Novaya Zemlya site would be a significant advantage, it would also pose difficult and dangerous problems for the shipping and storage of chemical weapons. The accumulation of such a large mass of chemical weapons, including their high explosive detonators, in one location would represent a terrifying potential for even a minor accidental explosion. In addition, while it would could be assured with a high degree of confidence that the nuclear explosions would completely decompose the chemical weapons, any misfire in which the yield was significantly lower that expected could lead to release of enormous quantities of CW toxins.

In an effort to move their proposals forward, Chetek proposed a small demonstration explosion on Novaya Zemlya in the spring of 1992, involving the destruction of 20 tons of chemical weapons. However, they were apparently unable to gain approval of the new Yeltsin government for suspension of the moratorium on nuclear tests and the experiment was never carried out. Although Chetek continued to seek support for their proposals for the next year or so, by the end of 1993, Chetek appears to have disappeared.

High-Level Radioactive Waste Disposal

More recently, several proposals have surfaced within Russia regarding a similar idea for the disposal of high-level radioactive waste from nuclear power reactors and naval propulsion reactors. Scientists from Arzamas and the Defense Ministry's Central Institute of Physics and Technology have suggested placing fuel rods and other highly contaminated components in a relatively small room surrounding a nuclear explosive device, again in a tunnel at Novaya Zemlya. In this case, the room would be limited in size to assure that all of the radioactive materials would be vaporized and melted, along with enough rock to ensure entrapment of the radioactive waste in the resolidified rock melt. Such burial would ensure isolation of such radioactive waste from the biosphere for 10,000 years or longer. Using such a method, a 100-kt explosion could be expected to permanently dispose of up to 200 tons of radioactive waste at an estimated cost of about $20 million.[154]

While both these proposals may have merit from a technical viewpoint and would help to solve several serious national problems facing Russia, there appears to be little resolve to overcome the many formidable political problems, including the recently signed Comprehensive Test Ban Treaty, which prohibits all nuclear explosions, including peaceful nuclear explosions.

ARMS CONTROL ASPECTS OF THE PEACEFUL USES OF NUCLEAR EXPLOSIONS

Conference on the Discontinuance of Nuclear Weapons Tests

Almost from the beginning, the concept of using nuclear explosions for peaceful purposes was recognized as an impediment to the achievement of a ban on the development and testing of nuclear weapons. Early in the 1958 Geneva Conference on the Discontinuance of Nuclear Weapons Tests, U.S. Ambassador James Wadsworth noted, inter alia, the U.S. interest in retaining the capability to carry out peaceful nuclear explosions under a ban on nuclear weapons tests. In a paper on the basic provisions for a control regime, Ambassador Wadsworth included the provision that one of the responsibilities of the Control Commission would be to authorize PNEs subject to unspecified inspection and control requirements. The Soviets did not respond, at least initially, to this U.S. suggestion.

The fundamental problem posed by permitting PNEs to be carried out under a ban on all testing of nuclear weapons devices is how to prevent nuclear explosions carried out for peaceful purposes from contributing knowledge useful to the development of nuclear weapons. Whereas PNE and weapon devices could well have different design requirements in terms of size, weight, radiation output, and residual radioactivity, learning how to design better PNE devices would directly contribute to designing better weapons. Development of "cleaner" explosives with much lower fission-to-fusion ratios were essential for nuclear excavation applications. How could the side conducting PNEs be prevented from testing new device design ideas, with or without diagnostic measurements of device performance, even if such improvements were prohibited? The final yield or radiochemical analysis of microscopic particles of the debris from a PNE explosive could provide sufficient proof of the validity of many new ideas, but only to those who designed the device.

Initial ideas within the weapons laboratories for how these problems might be handled included four ideas:

(i) Using whatever device a country desired for the PNE, under observation by representatives of the U.N. and other countries, including the Soviet Union, but without diagnostics to measure the device performance.

(ii) Establishing an international stockpile with each country desiring to conduct PNEs, placing some number of devices in the stockpile on the date a test ban went into effect.

(iii) Using only devices provided by the Soviet Union for PNEs conducted by the U.S. and the U.K., and vice versa.

(iv) Using devices that were subject to inspection by all the nuclear weapons states party to the test ban, including the U.S.S.R.

The first idea would obviously have been the best for those interested only in PNE applications, but it had the major difficulty of how to convince the other parties that no militarily useful information would be gained absent obvious diagnostic measurements. On the other hand, it was recognized that the other three ideas would most probably lead to the use of obsolete devices for Plowshare projects without any prospect of using low-fission excavation explosives yet to be developed.[155] The USAEC ultimately recommended the international stockpile option to the interagency group developing the U.S. negotiating position.[156]

When the U.S. tabled specific language in December, 1958, that called on the future Control Commission to "establish procedures... for the surveillance of nuclear devices and observation of nuclear detonations for peaceful purposes,"[157] the Soviet representative Semyon Tsarapkin immediately took issue, arguing that "the purpose of our Conference is to work out a treaty on the cessation of nuclear weapons tests everywhere and for all time, and to adopt the necessary measures to ensure that the parties to the treaty comply with it. Our contention is that no nuclear detonations should be set off for any purpose whatsoever."[158]

This blanket Soviet opposition to any testing for any purpose under a test ban was rather short-lived when 10 days later, on December 25, in a speech to the Supreme Soviet, Foreign Minister Andrei Gromyko said it might be possible to have nuclear detonations for peaceful purposes under a test ban if, among other conditions, there would be an equal number of such shots between East and West and if all the devices to be used were subject to complete internal and external examinations.[159] Nine months earlier, Edward Teller had made a similar suggestion in testimony before Congress that "in order to have an effective international inspection (of peaceful nuclear explosions) it is necessary not only to have the explosion inspected, but to open up the explosive, look into it and see that it is an ordinary type of nuclear explosive. This could be done, but it certainly would give away a lot of information which at present is kept very closely guarded."[160] This statement was part of a long list of reasons why he believed a test ban was a bad idea, a motive that may well have been the reason the Soviets picked up on the same idea.

Perhaps heartened by this apparent change in the Soviet point of view, on January 30, 1959, Ambassador Wadsworth presented a draft article containing suggested procedures for carrying out PNEs based roughly on the second of the four ideas listed above. Four months before the PNE explosion, the party proposing the test would be required to provide a description of the project, including the purpose, the date and location, the expected yield, the measurements and experiments to be carried out in conjunction with the explosion, and "the measures taken to assure that there will be no substantial fall-out outside the immediate vicinity."[161]

Further, the U.S. proposal called for the establishment of a depository, under the surveillance of the Control Commission, in which any of the parties to the agreement, prior to the effective date of the agreement, could place a stockpile of nuclear explosives planned for use in their PNEs. To meet concerns about safety and reliability, it provided for checks by the depositing party of any devices in the depository under the watchful eye of the other parties.

As an alternative to this procedure, the U.S. proposed that new nuclear devices could be used at any time so long as the other parties could inspect "the internal and external features of the nuclear device, including...detailed drawings." Presumably this provision was aimed at permitting the U.S. to carry out nuclear excavation projects with new devices with significantly lower fission yields than those available in 1959. As noted above, development of such devices was one of the principle elements of the U.S. Plowshare Program.

Wadsworth argued that the end result of the provisions on the devices to be used for PNE projects would "be to ensure either that devices based on past technology will be used, thus foreclosing the possibility of advancing weapons' design by the detonation, or that the other...parties will be given detailed knowledge of the device, thus assuring there will be no military advantage to the party detonating. The first method requires the use of devices which have been developed before the agreement to discontinue nuclear weapons testing goes into effect..." and "the second method...is intended to confine the devices used under that option to relatively obsolete designs and to designs especially developed which could be, perhaps because of weight or bulk, not useful militarily and which could, therefore, be revealed to the other nuclear powers, but would allow the non-military purposes of such explosions to be carried on more efficiently and more cheaply."[162]

Three weeks later on February 23, 1959, Ambassador Tsarapkin made a more formal reply to the U.S. proposal. Leading off with a condemnation of any proposal to permit PNEs under a test ban, he noted that their "position is clear that the direct and only task of this Conference is to prepare a treaty on the cessation of all types of nuclear weapons tests forever. We cannot agree with the attempt of the United States delegation to transform this Conference on the discontinuance of tests into a conference on the legalization, in one form or another, of the continuation of nuclear tests."[163]

However opposed the Soviet Union was to including PNEs in the test ban, Tsarapkin paradoxically went on to say that the Soviets were nevertheless willing to allow them, but under their own set of conditions, which he then placed on the table. The conditions provided for equal numbers of PNEs between the U.S. and U.K. on the one hand and the Soviet Union on the other. Such a procedure would have effectively given the Soviet Union veto power over any Western PNE projects and was clearly unacceptable.

Rather than creating a stockpile of PNE explosives, Tsarapkin proposed:

- "submitting beforehand to the other [party] a complete description and the blueprints" and
- "permitting the inspection of the internal and external construction of the device to be exploded."[164]

Little was said by the U.S. in response to this Soviet proposal at the time, although the requirements for internal inspection and turning the blueprints of U.S. devices over to the Soviets for their perusal would have, at first hand, appeared to be out of the question. Nevertheless, the U.S. accepted the proposal for the time being, and later that year announced at the U.N. that "agreement in principle has been reached that nuclear explosions for peaceful purposes will be allowed...under carefully prescribed conditions under international observation."[165] During the ensuing two years, most of the discussion at the Conference was directed toward the development of a joint program of seismic research using nuclear explosions, to be carried out under the existing moratorium. However, each country's position on where the nuclear explosives to be used would come from was based on their previous positions regarding PNE explosives. Finally, on March 21, 1961, the U.S. accepted the Soviet position providing for full disclosure and inspection of devices to be used for seismic experiments as well as for PNEs.[166]

Little more was done on the development of an accommodation for PNEs during the Geneva Conference before it ended in January 1962, following the August 1961 Soviet decision to end their moratorium and resume nuclear weapons testing, or in the U.N. Committee on Disarmament which followed.

Limited Test Ban Treaty (Moscow Treaty)

Eighteen months later in July 1963, ad hoc negotiations in Moscow resulted in the Limited Test Ban Treaty (LTBT) (or Moscow Treaty), which banned "any nuclear weapon test explosion, or any other explosion, at any place under its jurisdiction or control:...if such explosion causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted...." The initial U.S. draft had contained a provision to allow PNEs in the prohibited environments if there was unanimous agreement and if they were carried out in accordance with provisions of an annex which had not yet been drafted, but presumably along the lines of what the Soviets had suggested at earlier Geneva discussions.[167] However, the Soviets demurred, and the provision was dropped.

The construction of the above article clearly was intended to apply to nuclear explosions for peaceful purposes as well as for weapons. However, the choice of words, "...radioactive debris to be present outside the territorial limits..." were interpreted by the AEC as allowing a nuclear cratering explosion so long as it did not result in "a quantity of radioactive debris delivered outside the country's territorial limits in amounts sufficient to establish that such contamination resulted from a recent test within that country."[168] All of the U.S. nuclear crater experiments after 1963 were carried out within this interpretation of the LTBT, although AEC Chairman Seaborg made the point during ratification testimony that it would be impossible to carry out a major project, such as excavating a new Trans-Isthmian Canal in a small country, without renegotiating the treaty. As previously noted in the section entitled, "Kama-Pechora Canal Project," and in endnote 47, the Russian language version of this particular section of the treaty is much more permissive than the English language version, although probably not sufficient to permit major projects such as the Kama-Pechora Canal to be carried out.

Concerns about possible violations of the LTBT, if it were to carry out the Kama-Pechora Canal project, led the Soviet Union to participate in a series of bilateral technical meetings on PNEs with the U.S. during 1969–76. In these meetings, they hoped to reach a joint understanding with the U.S. for interpretation or amendment of the LTBT language, which would allow large-scale nuclear excavation projects to be carried out under appropriate radiation safety guidelines, rather than the "detection-level" standard of the LTBT. Although several concepts were discussed, there was no resolution of the issue.[169]

Non-Proliferation Treaty (NPT)

Later in the 1960s, at the time of the negotiation of the Non-Proliferation Treaty, the Plowshare Program was still under active development in the U.S. as was the Soviet "Program for the Use of Nuclear Explosions in the National Economy," although at a less developed stage. This treaty provides for the non-nuclear weapons states of the world to forego any effort to acquire nuclear weapons and the nuclear weapons states not to transfer any weapons, materials, or technology useful for weapons to the nonnuclear weapons states. In exchange for the nonnuclear weapons states giving up the right to acquire nuclear weapons, the NPT committed the nuclear weapons states to make available the peaceful uses of nuclear uses of nuclear energy—the materials and the technological information—under appropriate safeguards through the International Atomic Energy Agency (IAEA).

In an effort to meet demands and build support for the NPT among some of the more reluctant nonnuclear weapons states (e.g., India, Argentina, and Brazil), the U.S. suggested, and the Soviet Union readily supported, the inclusion of a provision, Article V, which explicitly committed the nuclear weapons states to make available the "potential benefits from any peaceful applications of nuclear explosions...on a non-discriminatory basis...pursuant to a special international agreement..." or "...pursuant to bilateral agreements." Although several international projects were subsequently studied by the U.S. jointly with other countries, no international projects were ever carried out.[170] Article V of the NPT did lead to the establishment of an office within the IAEA for coordinating international interests in peaceful uses of nuclear explosions. It also led to five international panels or technical meetings on PNEs between 1970 and 1976, which provided a forum for technical interaction of scientists from the U.S., the Soviet Union, and other countries.[171]

One of the participants in the IAEA Technical Panels on PNEs in the early 1970s was the state of India, which expressed an interest in one particular application, the use of nuclear explosions in the mining of non-ferrous metals in general and copper in particular.[172] On May 18, 1974, India carried out a "peaceful nuclear explosion experiment" in the Rajasthan Desert in western India, describing it "as a step towards studying fracturing effects in rocks, ground motion, containment of radioactivity and the problems involved in access of the shot-environment." The explosion triggered a storm of vehement protests from around the world, rejecting the claimed peaceful purpose for the explosion and decrying the attempt by India to establish itself as a nuclear weapons state.

Up until the end of 1995, there was no evidence of any additional activity by India towards pursuing their professed interest in peaceful nuclear explosions. Since that time, however, there have been sporadic reports of preparations for an additional nuclear test, but to date, there have been none.[173,174] The Indian explosion is perhaps the most clear demonstration of the conflict between efforts to limit the spread of nuclear weapons technology and desires to acquire the technology required for peaceful nuclear explosions.

Threshold Test Ban (TTB) and the Peaceful Nuclear Explosion Treaties (PNET)

The conflict between the efforts to achieve an arms control agreement and the potential promise of peaceful nuclear explosions next arose in the negotiations of the Threshold Test Ban Treaty in June 1973. By this date, the Plowshare Program in the U.S. was rapidly fading, while its star was just beginning its ascent in the Soviet Union. The roles of the two countries regarding the desirability of an exemption for PNEs was beginning to be reversed.

The U.S. adamantly supported the position that any yield limit on nuclear weapons tests should equally apply to PNEs, whether they were fired on the weapons test site or not. The Soviet Union was represented by Igor Morokhov, the First Deputy Chairman of the State Committee for the Utilization of Atomic Energy and one of the leading advocates for PNEs in the Soviet Union. Equally adamantly, he supported the Soviet position that the yields of PNEs away from the test sites should not be held to the same limit as weapons, or else the limit should be placed high enough (400–600 kt) that PNE projects such as the Kama-Pechora Canal could be done. In the end, it was agreed a 150-kt limit would be imposed on all tests at the declared weapons test sites, and a separate PNE agreement would be negotiated over the next 18 months before the TTBT went into effect. The subsequent PNE agreement was to provide for extensive exchange of information on geology and other details regarding forthcoming PNEs and, for the first time in any U.S. arms control agreement, was to include on-site observation of PNE activities by the other party.

Negotiation of the PNE Treaty required the full 18 months and resulted in one of the most detailed agreements for the exchange of information and conduct of on-site observations in the history of arms control to that date. The PNET, signed in May 1976, provided for a single device yield of 150 kt but permitted simultaneous group explosions with a total yield of up to 1,500 kt. For any explosion with an aggregate yield greater than 150 kt, the other side would be allowed to place sensors in holes near the explosion, which would allow them to measure the yield of individual explosions in the group.

Although the TTB and PNET were not ratified, both sides agreed to observe the limitations pending ratification. However, by the time the PNET was signed in May of 1976, the U.S. Plowshare Program was dead, and the Soviet Union's interest in the Kama-Pechora Canal project had waned. As a result, neither side has ever carried out a PNE with a yield large enough to trigger the on-site provisions of the PNET. The Protocols to the TTBT and PNET were subsequently renegotiated in the late 1980s to tighten the verification provisions, requiring on-site inspection of any PNE with an aggregate yield greater than 35 kt and on-site hydrodynamic yield measurement for any PNE with an aggregate yield greater than 50 kt. The revised TTBT and PNET were ratified in the fall of 1990, but neither party has carried out a weapons test or PNE that was subject to the provisions of the treaties since they went into effect.

Comprehensive Test Ban Treaty Negotiations (CTBT), 1977–80

In the fall of 1976, the U.S. and the U.S.S.R. once again began negotiations of a comprehensive ban on all nuclear weapons tests, this time with the participation of the U.K. The issue of PNEs very quickly became one of the principal issues with the Soviet Union, again represented by Igor Morokhov, strongly pushing for some kind of separate agreement that would permit PNEs. This time, the U.S., with U.K. support, was adamant in refusing to consider any such agreement, and the issue became one of the major sticking points in the negotiations.

After several weeks of serious discussion of the issue, it became apparent that a major decision regarding the PNE issue was being developed on the Soviet side. One night, in informal conversations outside the negotiations, Morokhov and his deputy on the delegation, Roland Timerbaev, asked several members of the U.S. delegation to consider three possible alternatives for carrying out PNEs under a CTBT:

(i) The Soviet Union would use U.S. devices for their PNE projects, and vice versa.

(ii) The U.S. would have complete access to the design of any devices used by the Soviet Union in a PNE, and vice versa.

(iii) The U.S. and the Soviet Union would undertake a joint program of developing and manufacturing the devices to be used in any PNE.

The first two proposals were similar to those discussed in 1958–59 at the Geneva Conference, but the last one was an idea that would have been unthinkable at that time. The U.S. delegation gave little attention to Morokhov's overture. Within two weeks, on November 2, 1977, Soviet General Secretary Brezhnev announced that the Soviet Union would accept a moratorium on all PNEs for the duration of the CTBT. Shortly thereafter, Morokhov was replaced as head of the Soviet Delegation by Andronik Petros'yants, Morokhov's superior as Chairman of the State Committee for the Utilization of Atomic Energy. Although the PNE issue had been resolved, other issues led to a stalemate in the negotiations before they were abandoned by the Reagan Administration in 1981.

CTBT Negotiations, 1994-96

On October 19, 1989, the Soviet Union began an unannounced year-long moratorium on nuclear weapons tests. As with an earlier announced 18-month moratorium on weapons testing during 1985–86, the Soviet Union carried out no PNEs during this moratorium. Although the Soviet Union carried out one last weapons test in October of 1990, no additional PNEs have been fired since September 6, 1988.

Following several extensions of the Soviet Union's moratorium, testing limitations imposed by the U.S. Congress, and a French moratorium, negotiations among the five nuclear weapons states on a Comprehensive Test Ban Treaty were begun in January 1994 in Geneva. As in earlier negotiations, the PNEs immediately became a significant issue. From the beginning of these negotiations, the U.S. and U. K. advocated a ban on all nuclear explosions, including any for "peaceful purposes." France, which studied the potential of PNEs for use in and around their country in the early 1970s, also supported a ban on PNEs. Although China had never evinced any previous interest in the use of nuclear explosions for peaceful purposes, it began the negotiations with a demand for inclusion of a provision that would permit PNEs at some future date. Russia took the position of acquiescing in their elimination, but not

Table 6: Frequency distribution of Soviet PNE yields.

Yield range (kt)	Number of explosions
<0.25	8
0.25–0.5	3
0.5–1.0	1
1.0–2.0	6
2.0–5.0	23
5.0–10	40
10–20	30
20–50	9
50–100	6
>100	2

actively advocating it. All of the nuclear weapons states maintained their initial positions on PNEs throughout 1994 and 1995, but on June 6, 1996, China yielded to the growing pressure for an agreement and dropped its insistence on an exclusion for PNEs in the comprehensive test ban agreement, proposing instead that the question of PNEs should be reconsidered at a review conference, expected to be held in 10 years. As a result, final agreement on a CTBT was quickly reached among all the delegations, with the exception of India, Pakistan and North Korea. It was signed by all five declared nuclear weapons states on September 24, 1996.

SUMMARY

During a period of some 23 years between 1965 and 1988, the Soviet Union's "Program for the Utilization of Nuclear Explosions in the National Economy" carried out 122 nuclear explosions to study and put into industrial use some 13 applications. In all, 128 explosives with yields ranging from 0.01 to 140 kt were used, with the vast majority being between 2 and 20 kt (see table 6).

Most peaceful applications of nuclear explosions in the Soviet PNE Program were explored in depth with a number of tests, but unfortunately little has been reported on the technical results other than general outcomes. Two applications, deep seismic sounding of the Earth's crust and upper mantle and the creation of underground cavities in salt for the storage of gas condensate, found widespread use, representing over 50 percent of all the explosions. Explosions to explore the technical possibilities of stimulating the production of oil and gas reservoirs accounted for an additional 17 percent.

The deep seismic sounding program produced an enormous volume of seismic data that still are being analyzed to better understand the deep geologic structure of the vast reaches of the Russian subcontinent. Although it may assist in the discovery of a few new major hydrocarbon or mineral resources in the future, its main value will probably be in the geotectonic area.

The two main projects to create underground storage for gas condensate from newly developing gas fields appear to be a quite valuable resource for the industries involved, and may have expedited their development. However, the failure of almost half of the explosion cavities created in salt at the Vega and Azgir sites raises serious questions about the general applicability and long-term viability of this or any other application utilizing such cavities. Clearly, the leakage of water into salt cavities is a serious problem because of possible loss of the cavity as well as the leachability of radionuclides trapped in the fused salt and the surface contamination that will inevitably result.

The studies of oil and gas stimulation were much broader and longer-term than those carried out in the U.S. The results reported to date are quite favorable in terms of increased production versus costs, but the application was not used on an industrial scale in the Soviet Union. The reason may be due to the contamination problems encountered at the Grifon field, but, more likely, it is because of the same difficulties experienced in the U.S. Plowshare program—the necessity of large-scale utilization for a significant impact on the national oil or gas industry, and the resistance of the public to accept a product containing any added radioactivity, no matter how minimal the level.

The use of nuclear explosions for closure of four runaway gas wells that defied all other techniques available in the Soviet Union proved to be a valuable application. It is possible that these wells could have been closed with conventional techniques available in the U.S., but the experience of the Soviet PNE Program in this area is unique and may prove useful in some future emergency somewhere in the world. It is important that Russians make available more information on why the attempt at Nar'yan Mar failed.

The Dnepr ore-breakage experiments on the Kola peninsula appeared to have been successful, but the lack of implementation on a broader scale raises questions about the acceptability of the application. Similarly, the Cleavage mine gas-dispersal explosion would appear to be an application with limited applicability, significant problems of acceptability, and little support within the industry.

The use of nuclear explosions to produce actinide and transplutonic elements in water-filled cavities is an interesting and imaginative application, but it is difficult to imagine that such a procedure could produce significant quantities of such nuclides in comparison to nuclear reactors. On the other hand, such an approach might prove quite useful in a heavy-element production program similar to that carried out by the U.S. in the 1960s to produce super-heavy elements beyond element 110.[175] Many of the heavy elements produced by multiple neutron capture within a nuclear explosive have very short half-lives. Through the use of this technique, significant quantities of transplutonic elements produced in an initial heavy-element explosive could be rapidly recovered from a cavity, processed, and incorporated as target nuclei in a second heavy-element explosion. Similarly, any super-heavy elements produced in the second explosion could be rapidly recovered and processed, maximizing the possibility of detecting any short-lived isotopes.

One of the most useful applications, from the standpoint of Russia and other countries with serious environmental contamination problems, would appear to be the Kama experiments demonstrating the use of deeply buried nuclear explosions for the deep-well disposal of toxic industrial flows. Results from these two experiments indicate that such facilities can be used for the disposal of large quantities of very hazardous chemical pollutants over long periods without significant problems. In view of the apparent success of these experiments, it is difficult to see why there have been no subsequent use of this application at other sites.

The nuclear excavation element of the Soviet PNE Program proved to be relatively short-lived, suffering from the world-wide growth of public concerns about environmental issues and atmospheric radioactivity and the disappointing Taiga experiment. In addition, the Soviets had serious concerns about dealing with the restrictions of the Limited Test Ban Treaty on the release of radioactivity from nuclear explosions across national boundaries, particularly for a project the size of the Kama-Pechora Canal. In the early 1970s, environmental concerns about diversion of water from the Arctic Ocean led to the loss of governmental support for the Kama-Pechora Canal. In addition, the slumping of the Taiga cratering experiment in 1971 demonstrated that the geology along much of the alignment of the canal was not suitable for nuclear excavation. Although the project continued to be included in future plans for several years, it ultimately was dropped, and with it, any further support for the Soviet nuclear excavation program.

An important element in the Soviet PNE Program was the effort by both the Arzamas and Chelyabinsk weapons laboratories to develop special nuclear explosives designs to reduce the radioactivities and fielding costs associated with specific applications (see Appendix C). The earliest effort was the development of small-diameter, high-temperature explosives for use in the closure of runaway gas wells. At the same time in the late 1960s and early 1970s, a major effort was put into developing a very low-fission explosive for nuclear excavation projects. Unfortunately, the Russians have not provided any details on the extent to which they succeeded in meeting their objectives in these device development programs.

In 1971 and 1974, the Soviets carried out two experiments at the test site to explore the possibilities for ejecting the radioactivity from an explosion down a tunnel to separate it from the physical effects of the explosion. The results of these tests were subsequently used in the Dnepr 1 and 2 mining experiments. These tests were similar in geometry to the 1967 Marvel test in the U.S. Plowshare Program, although the purpose of Marvel was to drive hydrodynamic energy, not radioactivity, 100 m down a 1-m-diameter tube. In the mid-1970s, emphasis in the Soviet device development program presumably was on the development of small-diameter, low-tritium-producing explosives for hydrocarbon applications, such as oil and gas stimulation and gas condensate storage. MinAtom says this program was successful in meeting its goals, but it provides no details.[176]

The Soviet programs to develop low-fission excavation and hydrocarbon explosives mirrored device development programs in the U.S. Plowshare Program in the mid-1960s and early 1970s. The Russians have not provided any information on whether the devices used in the transplutonic element production program were specially designed for that purpose as were the devices used in the U.S. heavy element program.

With the exception of the cratering explosions at the test site and at Taiga on the Kama-Pechora canal alignment, the vast majority of the other 112 Soviet PNEs were completely contained (camouflet) explosions. Five resulted in the prompt release of radioactivity, the most serious of which was Kraton-3, a DSS explosion in Siberia, which suffered a prompt vent of gas and particulate radioactivity when the permafrost around the emplacement hole melted. The Crystal retarc dam in Siberia also resulted in the escape of gaseous radioactivity, as had been expected in the design of the experiment. Three other explosions, Globus-1, Globus-3, and Halite A-8, suffered leaks of gaseous radionuclides at early times as a result of leaks in the emplacement hole stemming. In all, there was escape of gaseous radioactivity at 26 sites, largely during operations to re-enter the cavities or chimneys or during industrial exploitation of the sites. In all cases of camouflet explosions, except Kraton-3 and Crystal, the sites have been decontaminated, and radiation levels outside the limited industrial areas are at regional background.

The Soviet PNE Program was conducted as a "secret" program in the Soviet Union, as were many other governmental operations during that time. Although a few articles appeared in the popular press in the 1970s, there were no details on the number or location of explosions. As a result, local populations were seldom informed of the nature or scope of PNE activities in their vicinity. With the arrival of Glasnost in the late 1980s, many "exposes" began to appear in Russian newspapers and journals listing the many PNEs that had been carried out throughout the country and, in many cases, viewing with alarm their consequences. Because of the generally low standards of industrial safety and environmental protection in the Soviet Union and Russia, the public is quite prepared to believe the worst. The lack of hard data from MinAtom on the good and bad results of their PNE experiments has made it difficult to develop a rational discussion of their costs, risks, and benefits.

The Soviet PNE Program was many times larger than the U.S. Plowshare Program in terms of both the number of applications explored with field experiments and the extent to which they were introduced into industrial use. Several PNE applications, such as deep seismic sounding and oil stimulation, have been explored in depth and appear to have had a positive cost benefit at minimal public risk. Several others, such as storage, developed significant technical problems that cast a shadow on their general applicability. Some, such as closure of runaway gas wells, demonstrated a unique technology that may yet find application in a situation where all other techniques fail. Still others were the subject of one or two tests but were not explored further for reasons that have not been explained. Overall, the program represents a significant technical effort to explore a promising new technology, and it generated a large body of data that appears to be quite favorable, although only a small fraction of the data has been made public.

However, the fundamental problem with PNEs—first identified by James Schlesinger shortly after he became Commissioner of the U.S. AEC in 1971—is the fact that, if they are to be economically significant, there must be widespread use of the technology, and such use must inevitably involve large numbers of sites, each of which presents a potential source of radioactivity to the environment in general and to nearby communities in particular. Russia now has more than 100 sites where a significant amount of high-level radioactivity has been buried, albeit at a deep, safe environment. However, activities at these sites must be restricted and monitored forever. Even though each site can be operated well within appropriate radiation-safety standards, and the industrial products exported from the sites may be many times below maximum permissible levels, experience over the last 20 years in the U.S. and in today's Russia shows that it is virtually impossible to gain public acceptance of such applications of nuclear energy.

In addition to the problems of political and economic acceptability, PNEs also pose a difficult problem in the arms-control arena in the context of a total ban on nuclear weapons tests. In the absence of any other form of nuclear testing, any nuclear explosion for peaceful purposes has the potential for providing useful information to those who designed and constructed the nuclear device. Thus, under a CTB, any country conducting PNEs would, in appearance if not in fact, receive information useful for designing new nuclear weapons or maintaining an existing nuclear stockpile, information denied to the other parties to the treaty. Although several imaginative ideas for reducing this risk have been offered in the course of negotiations on a CTBT over the last 40 years, none have been suggested that would appear to overcome this critical problem.

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95. Mikhailov, *op. cit.,* pp. 35–39. This reference gives the gas pressure in the cavity as 8.4 Pa (Pascals). This would appear to be an error. Since lithostatic pressure would be expected to be about 140 atmospheres (14 megaPascals), this author has assumed the units should have been MPa (megaPascals).

96. A 1972 paper presented at the IAEA by K. V. Myasnikov describes testing an explosion cavity at lithostatic pressure, presumably "Magistral," with both oil and gas, leading to the conclusion that its effective volume for storage of liquids was 10 percent larger than its geometric volume; for gases at lithostatic pressure it was 24 percent larger.

97. Endnote 15 says the site was in industrial exploitation for 11 years on p. 37 and 18 years in Appendix 1. Endnote 12, p. 8, says the site was in exploitation for 18 years.

98. Although the endnote 15 text refers to these radiation levels as "above background," they would appear to be at or near normal levels.

99. Borg, *op. cit.*

100. Mikhailov, *op. cit.*

101. Borg, *op. cit.*

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APPENDIX A: PEACEFUL NUCLEAR EXPLOSIONS IN THE SOVIET UNION (BY DATE)*

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magni-tude (m_b)	Geographic vicinity
1	Chagan	1/15/65	05:59:59	49.89 49.9350	78.97 79.0094	6.0	Semipalatinsk Test Site, Kaz. ASSR[a]
2	Butane	3/30/65	08:00	— 53.10	— 55.87		15 km nw of Meleyz, Bashkir, ASSR[b]
3	Butane	6/10/65	07:00	— 53.10	— 55.87		15 km nw of Meleyz, Bashkir, ASSR[b]
4	Sary-Uzen'	10/14/65	04:00	— 49.9906	— 33.6357		Semipalatinsk Test Site, Kaz. ASSR[a]
5	Halite A-1	4/22/66	02:58:04 02:58:00.3	47.86 47.8292	47.72 47.9347	4.7	180 km n of Astrakhan, Gur'yev Ob.[c]
6	Urta-Bulak	9/30/66	05:59:53	38.80	64.50	5.1	80 km s of Bukhara, Bukhara Ob.
7	Tavda	10/6/67	07:00:03	57.69	65.27	4.7	70 km nne of Tyumen, Tyumen Ob.
8	Pamuk	5/21/68	03:59:12	38.916	65.159	5.4	70 km w of Karshi, Kashkadar'in Ob.

* The seismic magnitudes and upper set of numbers for times and geographic coordinates are based on seismic data provided by the National Earthquake Information Service (NEIS) or the International Seismic Center (ISC) unless otherwise indicated. When there is a lower set of times and geographic coordinates, they are actual data provided by the source indicated.

Chronological number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magnitude (m_b)	Geographic vicinity
9	Halite A-2	7/1/68	04:02:02 04:02	47.922 47.9086	47.950 47.9119	5.5	180 km n of Astrakhan, Gur'yev Ob.[c]
10	Tel'kem-1	10/21/68	03:52	— 49.7279	— 78.4863		Semipalatinsk Test Site, Kaz. ASSR[a]
11	Tel'kem-1	11/12/68	07:30	— 49.7124	— 78.4613		Semipalatinsk Test Site, Kaz. ASSR[a]
12	Grifon	9/2/69	04:59:57	57.415	54.860	4.9	10 km s from Osa, Perm Ob.
13	Grifon	9/8/69	04:59:56	57.365	55.108	4.9	10 km s from Osa, Perm Ob.
14	Stavropol'	9/26/69	06:59:56	45.890	42.472	5.6	100 km nne of Stavropol', Stav. Kr.
15	Hole 2T	12/6/69	07:02:57	43.832	54.783	5.8	100–115 km sse of Sai-Utes, Mangyshlak Ob.
16	Magistral'	6/25/70	04:59:52	52.201	55.692	4.9	70 km ne of Orenburg, Orenburg Ob.
17	Hole 5T	12/12/70	07:00:57	43.851	54.774	6.1	100–115 km sse of Sai-Utes, Mangyshlak Ob.
18	Hole 1T	12/23/70	07:00:57	43.827	54.846	6.1	100–115 km sse of Sai-Utes, Mangyshlak Ob.

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magni-tude (m_b)	Geographic vicinity
19	Taiga	3/23/71	06:59:56	61.287	56.466	5.6	100 km nnw of Krasnovishersk, Perm Ob.
20	Globus-4	7/2/71	17:00:02	67.66	62.00	4.7	30 km sw of Vorkuta, Komi Rep.
21	Globus-3	7/10/71	16:59:59	64.168	55.183	5.3	140 km sw of Pechora, Komi Rep.
22	Globus-1	9/19/71	11:00:07	57.777	41.098	4.5	30 km ene of Kineshma, Ivanovsk Ob.
23	Globus-2	10/4/71	10:00:03	61.613	47.116	5.1	80 km ene of Kotlas, Arkh. Ob.
24	Sapphire	10/22/71	05:00:00	51.575	54.536	5.3	40 km wsw of Orenburg, Orenburg Ob.
25	Halite A-3	12/22/71	06:59:56	47.872 47.8967	48.222 48.1333	6.0	180 km n of Astrakhan, Gur'yev Ob.[c]
26	Crater	4/11/72	06:00:05	37.367	61.996	4.9	30 km se of Mary, Mary Ob., Turkmen.
27	Fakel	7/9/72	06:59:58	49.78	35.42	4.8	20 km n of Krasnograd, Kharkov Ob.
28	Region-3	8/20/72	02:59:49	49.462	48.179	5.7	310 km sw of Uralsk, Uralsk Ob.

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magni-tude (m_b)	Geographic vicinity
29	Dnepr-1	9/4/72	07:00:04	67.689	33.445	4.6	20 km n of Kirovsk, Murmansk Ob.
30	Region-1	9/21/72	09:00:01	52.127	51.994	5.1	80 km ssw of Buzuluk, Orenburg Ob.
31	Region-4	10/3/72	08:59:58	46.848	45.010	5.8	80 km ne of Elista, Kalmyk Rep.
32	Region-2	11/24/72	09:00:08	52.779	51.067	4.7	90 km ssw of Buzuluk, Orenburg Ob.
33	Region-5	11/24/72	09:59/58	51.843	64.152	5.2	160 km sse of Kustanay, Kust. Ob.
34	Meridan-3	8/15/73	01:59:58	50.550	68.395	5.3	90 km sw of Turkestan, Chimkant Ob.
35	Meridan-2	9/19/73	02:59:57	45.635	67.850	5.2	100 km e of Arkalyk, Turgai Ob.
36	Meridan-2	9/19/73	02:59:57	45.635	67.850	5.2	230 km s of Dzhez-kazgan, Chimkent Ob.
37	Sapphire	9/30/73	04:59:57	51.608	54.582	5.2	40 km w Orenburg, Orenburg Ob.
38	Kama-2	10/26/73	05:59:58	53.656	55.375	4.8	30 km w of Sterlitmak, Bashkir ASSR
39	Kama-1	7/8/74	06:00:02	53.80	55.2	4.6	30 km w of Sterlitimak, Bashkir ASSR

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magni-tude (m_b)	Geographic vicinity
40	Horizon-2	8/14/74	14:59:58	68.913	75.899	5.5	190 km nw of Tazovskiy, Tyumen Ob.
41	Horizon-1	8/29/74	15:00:00	67.233	62.119	5.2	70 km sw of Borkuta, Komi Rep.
42	Crystal	10/2/74	00:59:56	66.1	112.65	4.6	70 km n of Aikhal, Yakutia-Sakha
43	Lazurite	12/7/74	06:00:00	49.92	77.65	4.7	Semipalatisk Test Site, Kaz. ASSR
44	Halite A-2-1	4/25/75	04:59:57	47.50 47.9086	47.50 47.9119	4.9	180 km n of Astrakhan, Gur'yev Ob.[c]
45	Horizon-4	8/12/75	15:00:00	70.76	127.12	5.2	120 km sw of Tiksi, Sakha
46	Horizon-3	9/29/75	10:59:58	69.592	90.396	4.9	90 km ese of Norilsk, Taimyr AO
47	Halite A-3-1	3/29/76	07:00:29	49.6 47.8967	45.0 48.1333	4.4 HFS	180 km n of Astrakhan, Gur'yev Ob.[c]
48	Halite A-4	7/29/76	04:59:58 05:00	47.782	48.120	5.9	180 km n of Astrakhan, Gur'yev Ob.[c]
49	Oka (Neva)	7/26/77	16:59:58	69.532	90.583	4.9	90–120 km ssw of Mirnyy, Yakut, ASSR
50	Meteorite-2	7/26/77	16:59:58	69.532	90.583	4.9	90 km ene of Norilsk, Taimyr AO

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magni-tude (m_b)	Geographic vicinity
51	Meteorite-5	8/10/77	21:59:59 22:00:00.1	50.923 50.9558	110.761 110.9833	5.2	80 km se of Khilok, Chita Ob.[d]
52	Meteorite-3	8/20/77	21:59:59	64.223	99.577	5.0	40 km se of Tura, Evenkii AO
53	Meteorite-4	9/10/77	16:00:03	57.294	106.240	4.8	70 km se of Ust'-Kut, Irkutsk Ob.
54	Halite A-5	9/30/77	06:59:56 06:59:58.4	48.145	47.850	5.1	180 km n of Astrakhan, Gur'yev Ob.[c]
55	Halite A-2-2	10/14/77	07:00:00	— 47.9086	— 47.9119	3.42	180 km n of Astrakhan, Gur'yev Ob.[c]
56	Halite A-2-3	10/30/77		— 47.9086	— 47.9119		180 km n of Astrakhan, Gur'yev Ob.[c]
57	Kraton-4	8/9/78	17:59:58	63.706	125.321	5.6	100 km wsw of Sangar, Yakut ASSR
58	Kraton-3	8/24/78	17:59:57	65.918	112.541	5.1	50 km e of Aykhal, Yakut ASSR[d]
59	Halite A-2-4	9/12/78	05:00:00	— 47.9086	— 47.9119	3.02	180 km n of Astrakhan, Gur'yev Ob.[c]
60	Kraton-2	9/21/78	14:59:58	66.541	86.252	5.2	100 km s of Igarka, Krasnoyarsk Kr.
61	Vyatka (Neva)	10/7/78	23:59:57	61.541	112.883	5.2	90–120 km ssw of Mirnyy, Yakut ASSR

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magni-tude (m_b)	Geographic vicinity
62	Halite A-7	10/17/78	04:59:58	47.818	48.114	5.8	180 km n of Astrakhan, Gur'yev Ob.
63	Kraton-1	10/17/78	13:59:58	63.143	63.392	5.5	400 km ssw of Salekhard, Tumen Ob.
64	Halite A-2-5	11/30/78	08:00:00	— 47.9086	— 47.9119	3.07	180 km n of Astrakhan, Gur'yev Ob.[c]
65	Halite A-9	12/18/78	07:59:56	47.787	48.192	6.0	180 km n of Astrakhan, Gur'yev Ob.
66	Halite A-2-6	1/10/79	08:00:00	— 47.9086	— 47.9119	4.36	180 km n of Astrakhan, Gur'yev Ob.[c]
67	Halite A-8	1/17/79	07:59:57	47.985	48.212	6.0	180 km n of Astrakhan, Gur'yev Ob.
68	Halite A-11	7/14/79	04:59:56	47.835	48.249	5.6	180 km n of Astrakhan, Gur'yev Ob.
69	Kimberlite-4	8/12/79	17:59:59	61.909	122.087	4.9	390 km w of Yakutsk, Yakut ASSR
70	Kimberlite-3	9/6/79	17:59:59	64.126	99.554	4.9	40 km sw of Tura, Evenk AO
71	Cleavage	9/16/79	08:00:00	— 48.29	— 38.29		5 km e of Enakievo, Donets Ob., Ukraine[b]
72	Kimberlite-1	10/4/79	15:59:58	60.650	71.525	5.4	150 km se of Khanty-Mansiysk, Kh.-M. Ob.

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magni-tude (m_b)	Geographic vicinity
73	Sheksna (Neva)	10/7/79	20:59:57	61.839	113.059	4.9	90–120 km ssw of Mirnyy, Yakut ASSR
74	Halite A-10	10/24/79	05:59:56	47.769	48.177	5.8	180 km n of Astrakhan, Gur'yev Ob.
75	Butane	6/16/80	06:00	— 53.10	— 55.87		15 km nw of Meleyz, Bashkir, ASSR[b]
76	Butane	6/25/80	06:00	— 53.10	— 55.87		15 km nw of Meleyz, Bashkir, ASSR[b]
77	Vega-1T	10/8/80	05:59:57 06:00:00.3	46.748	48.288	5.2	40 km nne of Astrakhan, Ast. Ob.[c]
78	Batholith-1	11/1/80	12:59:58	60.826	97.537	5.2	120 km se of Baykit, Evenk AO
79	Angara	12/10/80	06:59:57	61.713	67.018	4.6	140 km nw of Khanti-Mansiysk, Kh. Ms. AO
80	Pyrite	5/25/81	04:59:57	68.182	53.689	5.5	50 km ne of Nar'yan Mar, Arkhang. Ob.
81	Helium-1	9/2/81	04:00:04	60.622	55.589	4.5	20 km se of Krasnovishersk, Perm Ob.
82	Vega-4T	9/26/81	04:59:57 05:00:00.3	46.778	48.242	5.2	40 km nne of Astrakhan, Ast. Ob.[c]

Chronological number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magnitude (m_b)	Geographic vicinity
83	Vega-2T	9/26/81	05:03:50 05:03:59.9	46.714	48.240	5.3	40 km nne of Astrakhan, Ast. Ob.[c]
84	Shpat-2	10/22/81	13:59:57	63.755	97.570	4.9	140 km wsw of Tura, Evenk AO
85	Rift-3	7/30/82	21:00:02.3	53.813	104.132	5.1	160 km n of Irkutsk, Buryat AO
86	Rift-1	9/4/82	17:59:58.4	69.206	81.647	5.2	190 km w of Dudinka, Taimyr AO
87	rift-4	9/25/82	17:59:57.1	64.313	91.834	5.1	30 km se of Norilsk, Krasnoyarsk Kr.
88	Neva-1	10/10/82	04:59:57.8	61.555	112.833	5.3	90–120 km ssw of Mirnyy, Yakut ASSR
89	Vega-7T	10/16/82	05:59:57.2 06:00:00.1	46.730	48.197	5.2	40 km nne of Astrakhan, Ast. Ob.[c]
90	Vega-6T	10/16/82	06:04:57.3 06:05:00.1	46.748	48.215	5.2	40 km nne of Astrakhan, Ast. Ob.[c]
91	Vega-5T	10/16/82	06:09:57.10 06:10:00.1	46.754	48.270	5.2	40 km nne of Astrakhan, Ast. Ob.[c]
92	Vega-3T	10/16/82	06:14:57.40 06:15:00.2	46.743	48.213	5.4	40 km nne of Astrakhan, Ast. Ob.[c]
93	Lira-1T	7/10/83	03:59:57.1 04:00:00.0	†1.327 51.3625	53.301 53.3061	5.3	140 km e of Uralsk, Uralsk Ob.[d]

Chronological number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magnitude (m_b)	Geographic vicinity
94	Lira-2T	7/10/83	04:04:57.2 04:04:59.9	51.336 51.3667	53.290 53.3272	5.3	140 km e of Uralsk, Uralsk Ob.[d]
95	Lira-3T	7/10/83	04:09:57.1 04:09:59.9	51.357 51.3800	53.301 53.3397	5.2	140 km e of Uralsk, Uralsk. Ob.[d]
96	Vega-8T	9/24/83	04:59:56.9 05:00:00	46.773 46.7831	48.300 48.3152	5.1	40 km nne of Astrakhan, Ast. Ob.[d]
97	Vega-9T	9/24/83	05:04:56.8 05:05:00.0	46.763 46.7878	48.281 48.2972	5.0	40 km nne of Astrakhan, Ast. Ob.[d]
98	Vega-1T	9/24/83	05:09:57.7 05:10:00.1	46.872 46.7672	48.214 48.3106	4.9	40 km nne of Astrakhan, Ast. Ob.[d]
99	Vega-13T	9/24/83	05:14:56.9 05:14:00.1	46.748 46.7494	48.299 48.3025	5.2	40 km nne of Astrakhan, Ast. Ob.[d]
100	Vega-10T	9/24/83	05:19:57.0 05:19:59.9	46.772 46.7539	48.267 48.2894	5.2	40 km nne of Astrakhan, Ast. Ob.[d]
101	Vega-12T	9/124/83	05:24:56.8 05:25:00.0	46.758 46.7658	48.257 48.2744	5.2	40 km nne of Astrakhan, Ast. Ob.[d]
102	Lira-4T	7/21/84	02:59:57.1 02:59:59.8	51.366 51.3583	53.253 53.3194	5.4	140 km e of Uralsk, Uralsk Ob.[d]
103	Lira-6T	7/21/84	03:04:57.0 03:04:59.7	51.384 51.3905	53.271 53.3514	5.2	140 km e of Uralsk, Uralsk Ob.[d]
104	Lira-5T	7/21/84	03:09:57.1 03:09:59.8	51.366 51.3714	53.276 53.3369	5.3	140 km e of Uralsk, Uralsk Ob.[d]

Chronological number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magnitude (m_b)	Geographic vicinity
105	Quartz-2	8/11/84	18:59:57.4	65.079	55.287	5.3	100 w of Pechora, Komi R.
106	Quartz-3	8/25/84	18:59:58.5	61.876	72.092	5.4	100 km w of Surgut, KhantiMansiick.AO
107	Dnepr-2	8/27/84	05:59:57.0	66.770	33.680	4.5	20 km n of Kirovsk, Murmansk Ob.
108	Helium-2	8/28/84	02:59:55.5	60.826	57.472	4.4	20 km se of Krasno-vishersk, Perm Ob.
109	Helium-2	8/28/84	03:04:59	60.791	57.544	4.3	20 km se of Krasno-vishersk, Perm Ob.
110	Quartz-4	9/17/84	20:59:57.4 17.09.84.0	55.835 55.8342	87.408 87.5261	4.9	50 km ssw of Marinsk, Kemerovo Ob.[d]
111	Vega-14	10/27/84	05:59:58.6	47.044	47.919	5.0	40 km nne of Astra-khan, Ast. Ob.
112	Vega-15	10/27/84	06:04:57.1	46.843	48.023	5.0	40 km nne of Astra-khan, Ast. Ob.
113	Benzene	6/18/85	03:59:58.3	60.17	72.50		60 km s of Nefte-yugansk, Kh. Ma. AO[d]
114	Agate (Quartz-1)	7/18/85	21:14:57.5 21:15:00.3	65.965 65.9939	40.754 41.0381	5.0	150 km w of Mezen Arkangelsk Ob.[d]

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Time (GMT)	Latitude (°N)	Longitude (°E)	Seismic magni-tude (m_b)	Geographic vicinity
115	Helium-3	4/19/87	03:59:57.2	60.250	57.083	4.5	20 km se of Krasno-vishersk, Perm Ob.
116	Helium-3	4/19/87	04:05:55.7	60.813	57.548	4.4	20 km se of Krasno-vishersk, Perm Ob.
117	Neva-2	7/6/87	23:59:56.7	61.501	112.803	5.1	90–120 km ssw of Mirnyy, Yakut ASSR
118	Neva-3	7/24/87	01:59:56.8	61.478	112.753	5.1	90–120 km ssw of Mirnyy, Yakut ASSR
119	Neva-4	8/12/87	01:29:56.8	61.455	112.760	5.0	90–120 km ssw of Mirnyy, Yakut ASSR
120	Batholith-2	10/3/87	15:14:57.4	47.605	56.227	5.2	320 km ssw of Aktyubinsk, Ak. Ob.
121	Ruby-2	8/22/88	16:19:58.2	66.316	78.548	5.3	40 km ne of Urengoy, Yamalo-Nenetsk AO
122	Ruby-1	9/6/88	16:19:58.6	61.331	47.955	4.8	80 km ene of Kotlas, Arkhangelsk Ob.

a. Actual timeand location based on V.S. Bocharov, S.A. Zelentsev, and B.I. Mikhailov, "Characteristics of 96 Underground Nuclear Explosions at the Semipalatinsk Experimental Test Site," *Atomnaya Energiya*, Vol. 67, No. 3, September 1989.

b. Actual location based on geographical description of site.

c. Actual time and/or location based on V.V. Adushkin, et. al., *Characteristics of Seismic Waves from Soviet Peaceful Nuclear Explosions in Salt*, ciences, Russian Federation, Institutr Dynamics of the Geosphere, UCRL-CR-120929, April 1995.

d. Actual time and/or location based on D.D. Sultanov, *Instigation of SeismicEfficiency of Soviet Peaceful Nuclear Explosions Conducted in Various Geological Conditions, Part 1*, Acad, Russian, Institute for Dynamics of the Geosphere, July 28, 1993.

APPENDIX B: PEACEFUL NUCLEAR EXPLOSIONS IN THE SOVIET UNION (BY PURPOSE)

A. Development of Nuclear Excavation Technologies of Interest

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
A.1. Water reservoir development								
1	Chagan	1/15/65	Semipalatinsk Test Site, Kaz. ASSR	140	178	Sandstone	Crater in bed of Shagan River	MMB[a]
4	Sary-Uzen'	10/14/65	Same as above	1.1	48	Aleurolite, Siltstone	Also called "1003"	MMB
15	Hole 2T	12/6/69	100–115 km sse of Sai-Utes, Mangyshlak Ob.	31	407	Chalk	Possible new test site[b]	MMB
17	Hole 5T	12/12/70	Same as above	84	497	Chalk	Same as above	MMB
18	Hole 1T	12/23/70	Same as above	75	740	Chalk	Same as above	MMB
A.2. Experimental development work on constructing canals								
10	Tel'kem-1	10/21/68	Semipalatinsk Test Site, Kaz. ASSR	0.24	30.5	Siltstone/ Sandstone	Also called "T-1"; in Hole 2308	MMB[a]
11	Tel'kem-2	11/12/68	Same as above	3×0.24	30.5	Siltstone/ Sandstone	Also called "T-2"; in Holes 2305, 2306 and 2307	MMB
19	Taiga	3/23/71	100 km nnw of Krasnovishersk, Perm Ob.	3×15	128	Alluvium/ Sandstone	Explosion on Kama-Pechora Canal[c]	Reclaim. & water min.

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
A.3. Experimental development work on constructing a dams with deeply-buried cratering explosions								
42	Crystal	10/2/74	70 km ne of Aikhal, Yakutia-Sakha	1.7	98	Limestone	Also called "Pipe"[d]	Non-ferrous metals min.
43	Lazurite	12/7/74	Semipalatinsk Test Site, Kaz. ASSR	1.7	75	Quartzite/ Cherty slate	Hole P-1	MMB[a]
B. Contained Applications								
B.1. Stimulation of oil production and increasing the efficiency of oil recovery								
2	Butane	3/30/65	15 km nw of Meleyz Bashkir, ASSR	2× 2.3	1341 & 1375	Limestone	"Grachevka 1"; Holes 617 and 618	Oil prod. ministry
3	Butane	6/10/65	Same as above	7.6	1350	Limestone	"Grachevka 2"; Hole 622	Oil prod. ministry
12	Grifon	9/2/69	10 km s from Osa, Perm Ob.	7.6	1212	Limestone	Osa oil field; Hole 1001	Oil prod. ministry
13	Grifon	9/8/69	Same as above	7.6	1208	Limestone	Osa oil field; Hole 1002	Oil prod. ministry
14	Stavropol'	9/26/69	100 km nne of Stavropol', Stav. Kr.	10	712	Clay	Takhta-Kagulta gas field	Gas prod. ministry

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
49	Oka (Neva)	11/5/76	90–120 km ssw of Mirnyy, Yakut ASSR	15	1522	Dolomite	Also listed as DSS by Benz[e]	Geology ministry
61	Vyatka (Neva)	10/7/78	90–120 km ssw of Mirnyy, Yakut ASSR	13	1530	Dolomite		Geology ministry
73	Sheksna (Neva)	10/7/79	Same as above	15	1545	Dolomite	Hole 47	Geology ministry
75	Butane	6/16/80	15 km nw of Meleyz, Bashkir, ASSR	3.0	1400	Limestone		Oil prod. ministry
76	Butane	6/25/80	Same as above	3.0	1390	Limestone		Oil prod. ministry
79	Angara	12/10/80	140 km nw of Khanti-Mansiysk, Kh. Ms.AO.	15	2485	Sandstone		Geology ministry
81	Helium-1	9/2/81	20 km se of Krasnovishersk, Perm Ob.	3.2	2088	Limestone	Hole 401	Oil prod. ministry
88	Neva-1	10/10/82	90–120 km ssw of Mirnyy, Yakut ASSR	16	1502	Dolomite	Hole 66	Geology ministry
108	Helium-2	8/28/84	20 km se of Krasnovishersk, Perm Ob.	3.2	2065	Limestone	Hole 402	Oil prod. ministry

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
109	Helium-2	8/28/84	Same as above	3.2	2075	Limestone	Hole 403	Oil prod. ministry
113	Benzene	6/18/85	60 km s of Nefteyugansk, Kh. Ma. AO.	2.5	2859	Argillite		Oil prod. ministry
115	Helium-3	4/19/87	20 km se of Krasnovishersk, Perm Ob.	3.2	2015	Limestone	Hole 404	Oil prod. ministry
116	Helium-3	4/19/87	Same as above	3.2	2056	Limestone	Hole 405	Oil prod. ministry
117	Neva-2	7/6/87	90–120 km ssw of Mirnyy, Yakut ASSR	13	1527	Solomite	Hole 61	Geology ministry
118	Neva-3	7/24/87	Same as above	13	1515	Dolomite	Hole 68	Geology ministry
119	Neva-4	8/12/87	Same as above	3.2	815	Salt	Hole 101	Geology ministry
8.2. Experimental-industrial studies for the development of constructing underground cavities in salt								
5	Halite A-1	4/22/66	180 km n of Astrakhan, Gur'yev Ob.	1.1	161	Salt		MMB[a]
9	Halite A-2	7/1/68	Same as above	27	597	Salt		MMB
25	Halite A-3	12/22/71	Same as above	64	986	Salt		MMB

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
B.3. Elimination of runaway gas wells								
6	Urta-Bulak	9/30/66	80 km s of Bukhara, Bukhara Ob.	30	1532	Clay	Urtabulak gas field	Geology ministry
8	Pamuk	5/21/68	70 km w of Karshi, Kashkadar'in Ob.	47	2440	Salt	Pamuk gas field	Geology ministry
26	Crater	4/11/72	3se of Mary, Mary Ob., Turkmen	14	120	Argillite	Mary gas field	Geology ministry
27	Fakel	7/9/72	20 km n of Krasnograd, Kharkov Ob.	3.8	2483	Salt	Krestishevo gas field	Geology ministry
80	Pyrite	5/25/81	50 km ne of Nar'yan Mar, Arkhang. Ob.	37.6	1511	Clay	Kumzhinskoe gas field	5/25/81
B.4. Experimental-industrial work on the construction of underground cavities								
7	Tavda	10/6/67	70 km nne of Tyumen, Tyumen Ob.	0.3	172		Seismic source[f]	Gas prod. ministry
16	Magistral'	6/25/70	70 km ne of Orenburg, Orenburg Ob.	2.3	702			Gas prod. ministry
24	Sapphire	10/22/71	40 km wsw of Orenburg, Orenburg OB.	15	1142	Salt	Hole E-2; also called "Dedurovka-1"	Gas prod. ministry
37	Sapphire	9/30/73	40 km wsw of Orenburg, Orenburg Ob.	10	1145	Salt	Hole E-3; also called "Dedurovka-2"	Gas prod. ministry

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
77	Vega-1T	10/8/80	40 km nne of Astrakhan, Ast. Ob.	8.5	1050	Salt dome		Gas prod. ministry
82	Vega-4T	9/26/81	Same as above	8.5	1050	Salt dome		Gas prod. ministry
83	Vega-2T	9/26/81	Same as above	8.5	1050	Salt dome		Gas prod. ministry
89	Vega-7T	10/16/82	Same as above	8.5	974	Salt dome		Gas prod. ministry
90	Vega-6T	10/16/82	Same as above	8.5	991	Salt dome		Gas prod. ministry
91	Vega-5T	10/16/82	Same as above	8.5	1100	Salt dome		Gas prod. ministry
92	Vega-3T	10/16/82	Same as above	13.5	1057	Salt dome		Gas prod. ministry
93	Lira-1T	7/10/83	140 km e of Uralsk, Uralsk Ob.	13.5	917	Salt dome		Gas prod. ministry
94	Lira-2T	7/10/83	Same as above	13.5	917	Salt dome		Gas prod. ministry
95	Lira-3T	7/10/83	Same as above	13.5	841	Salt dome		Gas prod. ministry
96	Vega-8T	9/24/83	40 km nne of Astrakhan, Ast. Ob.	8.5	1050	Salt dome		Gas prod. ministry

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
97	Vega-9T	9/24/83	Same as above	8.5	1050	Salt dome		Gas prod. ministry
98	Vega-1T	9/24/83	Same as above	8.5	920	Salt dome		Gas prod. ministry
99	Vega-13T	9/24/83	Same as above	8.5	1100	Salt dome		Gas prod. ministry
100	Vega-10T	9/24/83	Same as above	8.5	950	Salt dome		Gas prod. ministry
101	Vega-12T	9/24/83	Same as above	8.5	1100	Salt dome		Gas prod. ministry
102	Lira-4T	7/21/84	140 km e of Uralsk, Uralsk Ob.	13.5	846	Salt dome		Gas prod. ministry
103	Lira-6T	7/21/84	Same as above	13.5	955	Salt dome		Gas prod. ministry
104	Lira-5T	7/21/84	Same as above	13.5	844	Salt dome		Gas prod. ministry
111	Vega-14T	10/27/84	40 km nne of Astrakhan, Ast. Ob.	3.2	1000	Slt dome		Gas prod. ministry
112	Vega-15T	10/27/84	Same as above	3.2	1000	Salt dome		Gas prod. ministry

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
B.5. Deep seismic sounding of the earth's crustures favorable for resource development								
20	Globus-4	7/2/71	30 km sw of Vorkuta, Komi Rep.	2.3	542	Sandstone	Kineshma-Vorkuta Line-1	Geology ministry
21	Globus-3	7/10/71	140 km sw of Pechora, Komi Rep.	2.3	465	Clay	Same as above	Geology ministry
22	Globus-1	9/19/71	30 km ene of Kineshma, Ivanovsk Ob.	2.3	610	Limestone	Same as above	Geology ministry
23	Globus-2	10/4/71	80 km ene of Kotlas, Arkh. Ob.	2.3	595	Aleurite	Same as above	Geology ministry
28	Region-3	8/20/72	310 km sw of Uralsk, Uralsk Ob.	6.6	489	Clay	Elista-Buzuluk Line-2	Geology ministry
30	Region-1	9/21/72	80 km ssw of Buzuluk, Orenburg Ob.	2.3	485	(Salt)?	Same as above	Geology ministry
31	Region-4	10/3/72	80 km ne of Elista, Kalmyk Rep.	6.6	485	Clay	Same as above	Geology ministry
32	Region-2	11/24/72	90 km ssw of Buzuluk, Orenburg Ob.	2.3	675	(Salt)?	Buzuluk-Kushmurun Line-3	Geology ministry
33	Region-5	11/24/72	160 km sse of Kustanay, Kust. Ob.	6.6	489	Limestone	Same as above	Geology ministry
34	Meridan-3	8/15/73	90 km sw of Turkestan, Chimkent Ob.	6.3	600	Clay	Karatau-Tengiz Line-4	Geology ministry

Chronological number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
35	Meridan-1	8/28/73	100 km e of Arkalyk, Turgai Ob.	6.3	395	Arg. Aleur	Same as above	Geology ministry
36	Meridan-2	9/19/73	230 km s of Dzhezkazgan, Chimkent Ob.	6.3	600	Arg. Aleur	Same as above	Geology ministry
40	Horizon-2	8/14/74	190 km nw of Tazovskiy, Tyumen Ob.	7.6	534	Clay	Vorkuta-Tiksi Line-5	Geology ministry
41	Horizon-1	8/29/74	70 km sw of Vorkuta, Komi Rep.	7.6	583	Sandstone	Same as above	Geology ministry
45	Horizon-4	8/12/75	120 km sw of Tiksi, Sakha	7.6	496		Same as above	Geology ministry
46	Horizon-3	9/29/75	90 km ese of Norilsk, Taimyr AO	7.6	834	Salt	Same as above	Geology ministry
50	Meteorite-2	7/26/77	90 km ene of Norilsk, Taimyr AO	13	850	Salt	Dikson-Khilok Line-6	Geology ministry
51	Meteorite-5	8/10/77	80 km se of Khilok, Chita Ob.	8.5	494	Granite	Same as above	Geology ministry
52	Meteorite-3	8/20/77	40 km se of Tura, Evenkii AO	8.5	600	Tuff	Same as above	Geology ministry
53	Meteorite-4	9/10/77	70 km se of Ust'-Kut, Irkutsk Ob.	7.0	550	Aleur-Marl	Same as above	Geology ministry
57	Kraton-4	8/9/78	100 km wsw of Sangar, Yakut ASSR	22	567	Arg, Aleur, Sandstone	Berezovo-Ust Maya Line-7	Geology ministry

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
58	Kraton-3	8/24/78	50 km e of Aykhal, Yakut ASSR	19	577	Limestone	Same as above	Geology ministry
60	Kraton-2	9/21/78	100 km s of Igarka, Krasnoyarsk Kr.	16	886	Aleu., Ss.	Same as above	Geology ministry
63	Kraton-1	10/17/78	400 km ssw of Salekhard, Tyumen Ob.	2.3	593	Al eu., Ss.	Same as above	Geology ministry
69	Kimberlite-4	8/12/79	390 km w of Yakutsk, Yakut ASSR	6.5	962	(Salt)?	Khanti Mansisk-Lena Line-8	Geology ministry
70	Kimberlite-3	9/6/79	40 km sw of Tura, Evenk AO	6.5	5	Tuff	Same as above	Geology ministry
72	Kimberlite-1	10/4/79	150 km se of Khanty-Mansiysk, Kh.-M. Ob.	21	837	Clay	Same as above	Geology ministry
78	Batholith-1	11/1/80	120 km se of Baykit, Evenk AO	8	720	Dolomite	Emba R.-Kolpashev-Olekminsk Line-9	Geology ministry
84	Shpat-2	10/22/81	140 km wsw of Tura, Evenk AO	8.5	581	Dolomite	Kyet R.-Tiksi Line-10	Geology ministry
85	Rift-3	7/30/82	160 km n of Irkutsk, Buryat AO	8.5	854	Dolomite	Yamal Pen.-Kyakhta Line-11	Geology ministry
86	Rift-1	9/4/82	190 km w of Dudinka, Taimyr AO	16	960	Sandstone	Same as above	Geology ministry
87	Rift-4	9/25/82	30 km se of Norilsk, Krasnoyarsk Kr.	8.5	554	Gabbro-Dolomite	Same as above	Geology ministry

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
105	Quartz-2	8/11/84	100 km w of Pechora, Komi R.	9.5	759	Clay	Murmansk-Kizil Line-12	Geology ministry
106	Quartz-3	8/25/84	100 km nw of Surgut, K.M. AO	8.5	726	Clay	Same as above	Geology ministry
110	Quartz-4	9/17/84	50 km ssw of Marinsk, Kemerovo Ob.	10	557	Granite	Same as above	Geology ministry
114	Agate	7/18/85	150 km w of Mezen', Arkangelsk Ob.	8.5	772	Granite	Same as above	Geology ministry
120	Batholith-2	10/3/87	320 km ssw of Aktyubinsk, Ak. Ob.	8.5	1002	Salt dome	Emba R.-Kolpashevo-Olekminsk Line-9	Geology ministry
121	Ruby-2	8/22/88	40 km ne of Urengoy, Yamalo-Nenetsk AO	16	829	Clay	Kostomushka-Urengoi Line-13	Geology ministry
122	Ruby-1	9/6/88	80 km ene of Kotlas, Arkhangelsk Ob.	7.5	820	Anhydrite, Dolomite	Kostomuksha-Semipalatinsk Lines-14&13	Geology ministry
B.6. Experimental-industrial work on the breakage of ore								
29	Dnepr-1	9/4/72	20 km n of Kirovsk, Murmansk Ob.	2.1	131	Apatite Ore	"Apatiti-1"	Fertilizer min.
107	Dnepr-2	8/27/84	Same as above	2×1.8	175	Apatite Ore	"Apatiti-2"	Fertilizer min.

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
B.7. Burial of biologically dangerous oil field wastes in deep geologic formations								
38	Kama-2	10/26/73	30 km w of Sterlitmak, Bashkir ASSR	10	2026	Dolomite		Oil ref. & chem. min.
39	Kama-1	7/8/74	Same as above	10	2123	Dolomite		Same
B.8. Transplutonic element production								
44	Halite A-2-1	4/25/75	180 km n of Astrakhan, Gur'yev Ob.	0.35	583	Salt cavity	Exp. in water-filled A-2 cavity	MMB[a]
48	Halite A-4	7/29/76	Same as above	58	1000	Salt		MMB[a]
54	Halite A-5	9/30/77	Same as above	9.3	1503	Salt		MMB[a]
55	Halite A-2-2	10/14/77	Same as above	0.10	582	Salt cavity	Exp. in water-filled A-2 cavity	MMB[a]
56	Halite A-2-3	10/30/77	Same as above	0.01	582	Salt cavity	Exp. in water-filled A-2 cavity	MMB[a]
59	Halite A-2-4	9/12/78	Same as above	0.08	584	Salt cavity	Exp. in water-filled A-2 cavity	MMB[a]
62	Halite A-7	10/17/78	Same as above	73	971	Salt dome	Two explosions in same hole[g]	MMB[a]
64	Halite A-2-5	11/30/78	Same as above	0.06	585	Salt cavity	Exp. in water-filled A-2 cavity	MMB[a]
65	Halite A-9	12/18/78	Same as above	103	630	Salt dome		MMB[a]

Chrono-logical number	Ministry of atomic energy (MAE) name	Date	Geographic vicinity	MAE yield (kt)	MAE depth of burial (m)	Geology	Name/Comments	Sponsor of test
66	Halite A-2-6	1/10/79	Same as above	0.5	581	Salt cavity	Exp. in water-filled A-2 cavity	MMB[a]
67	Halite A-8	1/17/79	Same as above	65	995	Salt dome	Two explosions in same hole[g]	MMB[a]
68	Halite A-11	7/14/79	Same as above	21	982	Salt dome	Three explosions in same hole[g]	MMB[a]
74	Halite A-10	10/24/79	Same as above	33	982	Salt dome	Two explosions in same hole[g]	MMB[a]
B.9. Decoupling experiment								
47	Halite A-3-1	3/29/76	180 km n of Astrakhan, Gur'yev Ob.	10	990	Salt cavity	Decoupled shot in A-3 cavity	MMB[a]
B.10. Experimental-industrial work on preventing sudden blow-out of coal dust and methane								
71	Cleavage	9/16/79	5 km e of Enakievo, Donets Ob., Ukraine	0.3	903	Sandstone	Ref. 1 gives time as 0900 GMT	Coal prod. ministry

a. Ministry of Medium Machine Building, the Soviet Ministry responsible for the nuclear weapons program and the predecessor to MinAtom.
b. Oleg Stefashin, "Unknown New Test Site," *Ivestiya*, January 23, 1991, p. 2; from JPRS-TAC-91-004, p. 33.
c. Kireev, V.V. et. al., "Group Excavation by Nuclear Explosions in Allevial Media," IAEA-TC-1-4/14, in *Peaceful Nuclear Explosions IV*, AEA Panel, pp. 399–419, 1995.
d. Sultanov, D.D., et. al., *Inigation of Seismic Eciency of Soviet Peaceful Nuclear Explosions Conducted UndVarious Geological Conditions*, ences, Institute for ynamics of the Geo-sphere, July 28, 1993.
e. Benz, H.M., et. al., "Deep Seismic Sounding in Northern Eurasia," *EOS*, Vol. 7y 14, 1992, pp. 297–300.
f. Litvinov, Boris, private communication, May 1994.
g. USSR Nuclear Weapons ?Tests and Peaceful Nuclear Explosions, 1949 through 1990, RFCN-VNIIEF, Sarov, ISBN 5-851650-062-1, 1996.

APPENDIX C: THE SOVIET PROGRAM TO DEVELOP NUCLEAR EXPLOSIVES FOR PEACEFUL USES

The Russian Ministry of Atomic Energy (MinAtom) recently released a comprehensive list of all nuclear explosions conducted by the Soviet Union.[1] Included is a list of the date, test-site area location, emplacement hole, or tunnel designation for each explosion. In addition, for each explosion, the list includes the general purpose and yield or yield range of the test. If the explosion involved multiple devices fired simultaneously, the purpose and yield range of each device test is given. This list reveals that during the life of the Program for the Use of Nuclear Explosions in the National Economy, the Soviet Union carried out 40 device-development tests at its nuclear weapons test sites to develop special nuclear explosives or emplacement techniques for such applications. Table C.1 is a list of the PNE device-development explosions carried out for the development of such explosives.

All but two of these PNE device-development tests were at the Degelen, Sary-Uzen, or Balapan areas of the Semipalatinsk Test Site (STS). The other two were at the Novaya Zemlya Test Site. As noted in table C.1, three of these explosions, on 5/28/67, 10/17/67, and 9/11/69, consisted of two PNE device-development tests fired simultaneously in the same tunnel complex. Another five PNE device-development tests were fired simultaneously along with one or more nuclear weapons tests.

Also shown in table C.1 is the seismic body wave magnitude for 37 of these explosions as reported by the International Seismic Center (ISC). Three were presumably of sufficiently low yield that they were not detected and identified as events by the ISC.

Supplemental data on the yield and/or depth of burial (DoB) of some of these events were reported earlier by two other Russian sources,[2,3] both associated with MinAtom. Endnote 2 provided a list of the date, location, and geology of some 96 underground explosions at STS from 1961 through 1972. Exact yields were provided for 22, with only a yield range for the remainder. Yields given for the same events as in endnote 1 were, with one exception, the same.[4] Endnote 3 provided a comprehensive list of all the underground explosions fired at STS from 1961 through 1989, including the 96 that were listed in endnote 2. Yields and yield ranges were given for all other events, which also agreed with endnotes 1 and 2 with a few exceptions.[5]

Table C.1 PNE device development explosions in the Soviet Union.

Date	Test site area	Tunnel or hole number	ISC mag.	Yield (kt) from endnote 1	Seismic yield (kt)	DoB (m) from endnote 2	Calculated DoB_s[a]	Comments
10/25/64	N. Zemlya	B	a	.001-20				
11/16/64	Degelen	Z-5	5.6	20-150	30		69[b]	Test of explosive for Chagan crater?
6/17/65	Degelen	Zh-1	5.2	.001-20	8	152	76	Excavation explosive test?
12/24/65	Degelen	Z-3	5.0	.001-20	4	213	134	
12/13/66	Degelen	E-1	6.1	125	152	297	59[c]	High yield excavation explosive test?
4/21/66	Degelen	A-4P	5.3	.001-20	11	178	80	
5/7/66	Degelen	No. 25	4.8	4	2	274	173[c]	
6/29/66	Degelen	Z-6	5.6	20-150	30			Test of Urtabulak explosive?
8/19/66	Degelen	Z-1P	5.1	.001-20	6	134	74	Excavation explosive test?
12/3/66	Degelen	No. 14[d]	4.8	.001-20	2	153	121	
12/18/66	Sary-Uzen	Hole 101	5.8	20-150	58	427	53[b]	Excavation explosive test?
4/20/67	Degelen	No. 25P	5.5	20-150	22	225	80	Excavation explosive test?
5/28/67	Degelen	No. 11P[e]	5.4	.001-20	16	262	104	Oil stimulation explosives?
7/15/67	Degelen	506	5.4	.001-20	16	161	64	Oil stimulation explosives?
10/17/67	Degelen	B[e]	5.6	.001-20	30	181	58	Test of "Pamuk" explosive?

Table C.1 (Continued) PNE device development explosions in the Soviet Union.

Date	Test site area	Tunnel or hole number	ISC mag.	Yield (kt) from endnote 1	Seismic yield (kt)	DoB (m) from endnote 2	Calculated DoB$_s$[a]	Comments
1/7/68	Degelen	810	5.1	.001-20	6	237	130	Excavation explosive test?
11/9/68	Degelen	606	4.9	.001-20	3			
12/18/68	Degelen	508	5.0	.001-20	4	194	122	
4/13/69	Degelen	No. 24P	a	.001-20				
7/4/69	Degelen	710[d]	5.2	.001-20	8	219	110	
9/11/69	Degelen	503[e]	5.0	.001-20	4	190	120	
11/27/69	Degelen	511	a	.001-20				
12/29/69	Degelen	Sh-1	5.1	.001-20	6	86	47	Excavation explosive test?
3/27/70	Degelen	610	5.0	.001-20	4	138	87	Excavation explosive test?
6/28/70	Degelen	705	5.7	20-150	42	332	96	Excavation explosive test?
9/6/70	Degelen	502	5.4	.001-20	16	212	84	Excavation explosive test?
11/4/70	Sary-Uzen	Hole 125	5.4	.001-20	16	249	57[b]	Proof test of explosives for "Taiga"; formed collapse crater
3/22/71	Degelen	510P	5.7	20-150	42	283	81	Excavation explosive test?
4/9/71	Degelen	148/1	a	0.23				Ejection technique for "Dnepr 1"
3/28/72	Degelen	191[d]	5.1	.001-20	6	124	68	

Table C.1 (Continued) PNE device development explosions in the Soviet Union.

Date	Test site area	Tunnel or hole number	ISC mag.	Yield (kt) from endnote 1	Seismic yield (kt)	DoB (m) from endnote 2	Calculated DoB_s[a]	Comments
12/10/72	Balapan	Hole 1204	6.0	140	110	478	72[b]	Excavation explosive test?; formed collapse crater
7/23/73	Balapan	Hole 1066	6.1	150-1500	152	465[f]	84[b]	High yield test of excavation explosive test?; formed collapse crater
5/31/74	Balapan	Hole 1207	5.9	20-150	80		92[b]	High yield test of excavation explosive test?; formed collapse crater
12/16/74	Degelen	148/5	4.8	3.8	2			Ejection technique for "Dnepr-2"
6/8/75	Degelen	165	5.5	.001-20	22			
8/18/83	N. Zemlya	A-40[d]	5.9	.001-20	b			
12/28/84	Balapan	Hole 1353[d]	6.0	.001-20	110			

a. Calculated using seismic yield and DoB from endnote 2 except in those cases where actual yields were known. DoB from endnote 7 we used for the tests where those values appeared more reasonable.
b. Scaled depth of burial from endnote 7.
c. Scaled depth of burial calculated using reported yield.
d. A PNE device-development test was fired simultaneously in the same tunnel complex with one or more weapons development, effects, or safety tests.
e. Two PNE device-development tests were carried out simultaneously in the same tunnel.
f. Depth of burial and yield shown are from endnote 7. This yield of 150 kt compares well with the seismic yield of 152 kt. However, endnote 7 gives the scaled depth of burial as 83.9 $m/kt^{1/3}$ even though the depth of burial and yield calculate a scaled depth of burial of 87.5 $m/kt^{1/3}$.

Using the yields from 19 explosions in endnote 2, all but four of which were weapons-development or effects tests, and their ISC seismic magnitudes, Vergino[6] calculated the following general yield–magnitude relation for explosions in any of the three areas of the STS:

$$m_b = 4.41 + 0.71 \log W,$$

where

$$m_b = \text{seismic magnitude},$$

and

$$W = \text{explosion yield (kt)},$$

which has a two-sigma error of about $\pm 1.7\times$. The seismic yields shown in the sixth column of table C.1 for the 32 PNE device-development explosions at STS with ISC magnitudes were calculated using this equation.

Endnote 2 provided a depth of burial for many of the PNE device-development tests listed in table C.1, which are shown in column seven. Using the seismic yield (or actual yields if known), the cube-root scaled depths of burial were calculated as shown in column eight, subject to the exceptions noted in the table, which arose from a recent publication by Adushkin and Spivak of the Russian Institute for Dynamics of the Geosphere.[7] This report provides data on a large number of Russian nuclear explosions that were buried at depths that resulted in cratering or other disruption of the earth's surface. In addition to those PNE cratering explosions discussed in Section III of the main report, Adushkin and Spivak also include data on many such explosions at the STS, including seven of the PNE device-development tests listed in table C.1. In some cases, their numbers are consistent with those provided by endnotes 1–3, but in others, they are significantly different. Of particular note are the following data:

- For the 12-18-66 Hole 101 event in the Sary-Uzen Area of STS, Adushkin and Spivak give the yield as ~80 kt, which is consistent with the seismic yield, but they give the depth of burial as 228 m, significantly smaller than the 427 m in endnote 2. They also describe the geology as sandstone overlain by a clay layer 40 m thick and sandy loam 7 m thick, rather than prophyrite as given in endnote 2. Adushkin and Spivak's numbers indicate a scaled depth of burial of only 59 m/kt$^{1/3}$, which is consistent with the cratering action and venting of the explosion described by them. Endnote 3 also indicates that this explosion dynamically vented. The crater produced by the explosion had a radius of 145 m and a depth of about 15 m, but with a 10-m-high mound in the center.

- For the 11-04-70 Hole 125 event also in the Sary-Uzen Area of STS, Adushkin and Spivak give the yield as 19 kt, which is consistent with the seismic yield, but they give the depth of burial as 151.3 m, significantly smaller than the 249 m in endnote 2. They describe the geology as a porphyritic massif overlain by sandy gravel and loam deposits 10–27 m thick, which is consistent with endnote 2. Adushkin and Spivak's numbers indicate a scaled depth of burial of only 57 $m/kt^{1/3}$, which is consistent with the cratering action and venting of the explosion described by them. Endnote 3 also indicates that this explosion vented. The crater produced by the explosion had a radius of 95–105 m and a depth of about 17.5 m, but with an 8-m-high mound in the center. As indicated in the main report, this explosion was the final test of the explosives used for the Taiga row-cratering explosion on the alignment of the Pechora-Kama Canal.

- For the 12-10-72 Hole 1204 event in the Balapan Area of STS, Adushkin and Spivak give the yield as "about 150 kt," which is consistent with the yield of 140 kt given by endnote 1, but they give the depth of burial as 378 m, significantly smaller than the 478 m in endnote 2. The geology is described as a sand-tuff formation, overlain by 20 m of alluvium. The explosion produced a dome that rose to 32 m and then collapsed, resulting in an early dynamic vent of radioactive gases and a collapse crater with a radius of 72 m and a depth of 26 m.

- For the 07-23-73 Hole 1066 event in the Balapan Area of STS, Adushkin and Spivak give the yield as 150 kt and the depth of burial as 465 m. The explosion was fired in a granite massif overlain by alluvial clay and sandy loam 13 m thick. The explosion in the hard rock produced a dome that rose to a height of 19 m before collapsing, but there was no prompt vent. It resulted in a collapse crater with a radius of 110 m and a depth of 14 m.

- For the 05-31-74 Hole 1207 event in the Balapan Area of STS, Adushkin and Spivak give only a scaled depth of burial of 92 $m/kt^{1/3}$ and indicate that the explosion was fired in a schist-type rock medium. Endnote 3 reports that the explosion was completely contained, as was Hole 1066, but it also produced a collapse crater with a radius of 98 m and a depth of 4.5 m.

It is of significance to note that many of the PNE device-development tests in table C.1 were carried out at scaled depths of burial much less than that required for complete containment of the dynamic effects of the explosion and to prevent prompt venting of the radioactive gases from the nuclear explosion. Although the U.S. has essentially no experience with nuclear explosions at

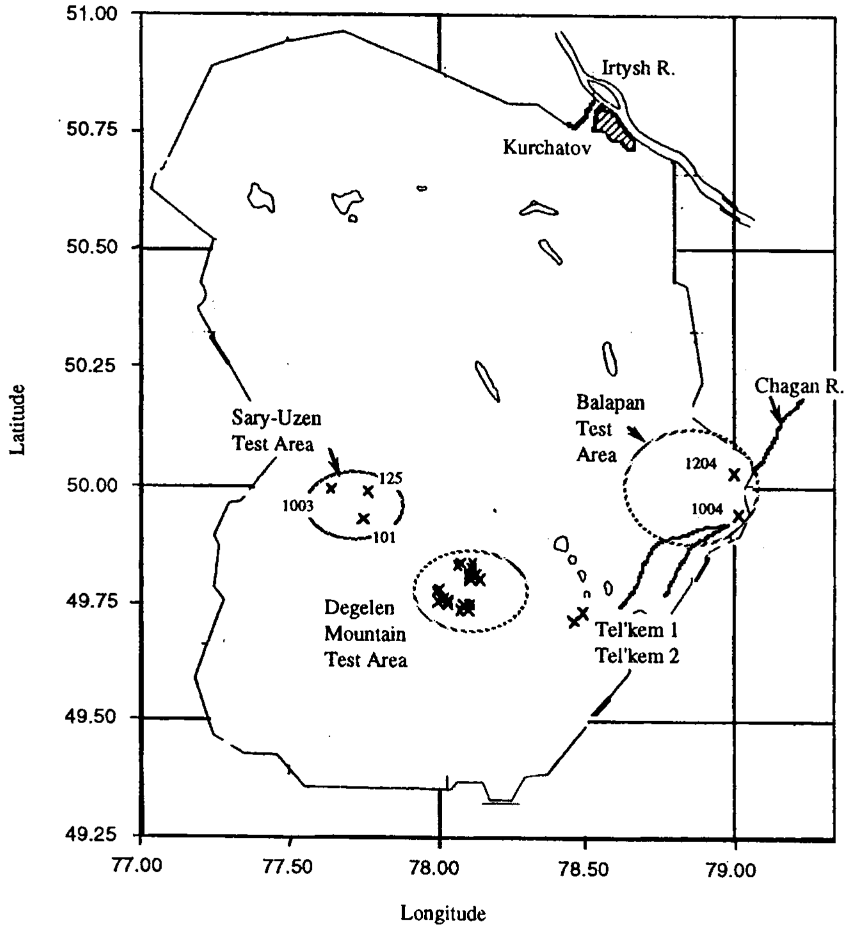

Figure C.1: Map of the Semipalatinsk Test Site (STS) showing the three major areas and the location of the PNE device-development explosions as well as the cratering explosions carried out at STS as part of the nuclear excavation technology development program discussed in the main report.

scaled depths of burial between 60 and 90 m/kt$^{1/3}$, it is expected that nuclear explosions in this range would result in the creation of a dome, prompt venting of radioactive gases, and a major disruption of the earth's surface, much as Adushkin and Spivak have described. The use of such shallow scaled depths of burial with their high probability of releasing all the radioactive gases from the nuclear explosion would suggest that these explosions may well have been associated with the development of new families of low-fission excavation explosives.

As discussed in the main report, the Soviet PNE Program developed special nuclear explosives or emplacement techniques for four general purposes: low-fission explosives for excavation projects; small-diameter, high pressure and temperature explosives for closure of gas well fires; small-diameter, low-tritium explosives for hydrocarbon stimulation applications; and techniques for ejection of fission products far from the explosion site.

With these comments and the schedule of PNEs projects discussed in the main report in mind, the last column in table C.1 presents comments on some of these PNE device-development tests and speculation on their possible purposes.

Figure C.1 is a map of the Semipalatinsk Test Site showing the location of the three major testing areas—Degelen Mountains, Balapan, and Sary-Uzen—as well as the locations as given in endnote 3 of most of the PNE device-development tests listed in table C.1. Also shown in figure C.1 are the locations of the four nuclear cratering explosions at STS that were described in the main report: the "1004" Chagan crater, the "1003" Sary-Uzen crater, Tel'kems 1, and Tel'kems 2.

NOTES AND REFERENCES

1. USSR Nuclear Weapons Tests and Peaceful Nuclear Explosions—1949 through 1990, RFCN-VNIIEF, Sarov, 1996; ISBN 5-85165-062-1.

2. Bocharov, V. S., S. A. Zelentsev, and B. I. Mikhailov, "Characteristics of 96 Underground Nuclear Explosions at the Semipalatinsk Experimental Test Site," Atomnaya Energiya, Vol. 67, No. 3, (1989), pp. 210–214.

3. Gorin, V. V., et. al., "The Semipalatinsk Test Site: Chronology of Underground Nuclear Explosions and Their Primary Radiation Effects," Bulletin of the Center for Public Information on Atomic Energy, No. 9, (1993), pp. 21–32.

4. Endnote 1 gave the yield of the PNE test on 3/28/72 as being in the range of 0.001-20 kt whereas endnotes 2 and 3 give it as 6 kt. It may be significant that the PNE test was fired simultaneously with two weapons-related tests, and the 6 kt is the total yield.

5. Endnote 3 only gives a yield range of <20 kt for the PNE event of 12/16/74 whereas endnote 1 gives the yield as 3.8 kt.

6. Vergino, E. S., "Soviet Test Yields," EOS, Vol. 70, No. 48, (November 28, 1989).

7. Adushkin, V. V. and A. A. Spivak, Geologic Characterization and Mechanics of Underground Nuclear Explosions, Defense Nuclear Agency Contract No. DNA 001-93-0026, (June 1994).