Report

Downsizing Russia's Nuclear Warhead Production Infrastructure

OLEG BUKHARIN

Oleg Bukharin is a Research Staff Member at the Center for Energy and Environmental Studies of Princeton University. His research interests focus on nuclear nonproliferation, arms control, and the safeguards and security of nuclear materials and facilities, with an emphasis on the Russian nuclear complex.

Over a period of 50 years, the Soviet Union built a giant infrastructure dedicated to designing, manufacturing, and maintaining nuclear bombs and warheads for a wide variety of strategic and tactical weapons systems (see Table 1). Under the conditions of the Soviet economic and political system, this nuclear weapons production complex developed into a self-sufficient, vastly redundant, and highly integrated organization, which was managed in an extremely secretive and centralized fashion.

At present, the complex is managed by the Russian Ministry of Atomic Energy (Minatom) and consists of 17 research institutes and manufacturing facilities (Table 2).[1] The complex remains oversized and is still configured to meet Cold War requirements. Downsizing the complex is inevitable. The strategic rationale for maintaining a massive weapons production infrastructure is long gone. Moreover, the Russian economy cannot support it. The technical infrastructure of the complex has already contracted owing to aging and lack of maintenance, while demographic shifts and economic conditions have shrunk its pool of scientific and technical talent.

Russian interests dictate making the nuclear weapons complex smaller, safer, and more efficient. To achieve this goal, Russia must design and implement a strategy of managed downsizing and consolidation of the weapons complex that emphasizes the following elements:

- ensuring the ability of the reduced complex to fulfill its core missions;
- synchronizing the downsizing of the complex with reductions in the Russian nuclear warhead stockpile;
- rapidly demilitarizing (removing classified equipment, materials, etc.) and completing the environmental cleanup of as many facilities as possible to facilitate defense conversion and economic development of the surrounding communities; and
- if complete demilitarization at a particular facility is not possible, physically separating defense from non-defense activities and establishing independent budgets and management structures.

Under current conditions, continuing decay without consolidation remains a very realistic alternative to an orderly transition, however. In this case, Russian national security would be undermined, the possibility of a major accident involving a nuclear weapon or facility would

Table 1: USSR's Nuclear Weapons Production Compex in the Mid-1980s

Facility/ location	Nuclear weapons production functions
Minatom's Nuclear Fuel Cycle Department (formerly Fourth Main Directorate)	
Siberian Chemical Combine/ Seversk (Tomsk-7)	Production of plutonium HEU production Fabrication of HEU and plutonium weapon components
Production Association "Mayak"/ Ozersk (Chelyabinsk-65)	Production of plutonium Production of tritium Fabrication of HEU and plutonium weapon components
Mining and Chemical Combine/ Zheleznogorsk (Krasnoyarsk-26)	Production of plutonium
Urals Electro-Chemical Combine/ Novouralsk (Sverdlovsk-44)	HEU production
Electro-Chemical Plant/ Zelenogorsk (Krasnoyarsk-45)	HEU production
Minatom's Nuclear Weapons Development and Testing Department (formerly Fifth Main Directorate)	
Institute of Experimental Physics, VNIIEF/ Sarov (Arzamas-16)	Nuclear warhead design Stockpile support
Institute of Technical Physics, VNIITF/ Snezhinsk (Chelyabinsk-70)	Nuclear warhead design Stockpile support
Institute of Automatics, VNIIA/ Moscow	Nuclear warhead design and engineering Design of non-nuclear components Nuclear weapons maintenance instrumentation
Institute of Impulse Technologies, VNII IT/ Moscow	Nuclear test diagnostics
Institute of Measurement Systems, NII IS/ Nizhniy Novgorod	Design of non-nuclear components
Design Burea of Road Equipment, KB ATO/ Mytischy, Moscow region	Nuclear warhead transportation and handling equipment
Minatom's Department of Nuclear Weapons Production (formerly Sixth Main Directorate)	
Electrokhimpribor/ Lesnoy (Sverdlovsk-45)	Nuclear warhead assembly/disassembly
Electromechanical Plant "Avangard"/ Sarov (Arzamas-16)	Nuclear warhead assembly/disassembly
Production Association "Start"/ Zarechny (Penza-19)	Nuclear warhead assembly/disassembly
Device-Building Plant/ Trekhgorny (Zlatoust-36)	Nuclear warhead assembly/disassembly
Production Association "Sever"/ Novosibirsk	Production of non-nuclear weapon components
Production Association "Molniya"/ Moscow	Production of non-nuclear weapon components
Urals Electromechanical Plant/ Yekaterinburg	Production of non-nuclear weapon components
Nizhneturinsky Mechanical Plant/ Nizhnyaya Tura	Production of non-nuclear weapon components and support equipment
Kuznetsk Machine-Building Plant/ Kuznetsk	Production of support equipment and non-nuclear weapon components

Table 2: U.S. and Russian Nuclear Weapon Production Complexes

	U.S. DOE weapons complex at present[i]	**Russian weapons complex at present**	**Russian complex in 2005-2010 (aft Phase II)**	**Russian complex in 2010-2015 (after Phase III)**	**Russian complex after deep reductions (after Phase IV)**
Nuclear weapons R&D	LANL LLNL SNL	VNIIEF/A-16 VNIITF/C-70 VNIIA KB ATO NII IS NII IT	VNIIEF/A-16 VNIITF/C-70 VNIIA KB ATO NII IS NII IT	VNIIEF/A-16 VNIITF/C-70 VNIIA	VNIIEF/A-16 and/or VNIITF/C-70
Tritium production and processing	SRS/ stockpile drawdown	C-65 + stockpile drawdown	C-65 + stockpile drawdown	C-65 + stockpile drawdown	VNIIEF/A-16 and/or VNIITF/C-70 + stockpile drawdown
HEU and plutonium component manufacturing	Oak Ridge Y-12 LANL	C-65 T-7[ii]	C-65	C-65	VNIIEF/A-16 and/or VNIITF/C-70
Warhead assembly/ Disassembly	Pantex	Avangard/A-16 P-19 S-45 Z-36	S-45 Z-36	S-45	VNIIEF/A-16 and/or VNIITF/C-70
Production of non-nuclear components	KCP SNL LANL Pantex	Molnia UEMZ Sever N.Tura Plant Avangard/A-16 P-19 S-45 Z-36	UEMZ Avangard/A-16 P-19 S-45 Z-36	S-45 VNIIEF/A-16 VNIITF/C-70 VNIIA	VNIIEF/A-16 and/or VNIITF/C-70
Testing	NTS	NZTS	NZTS	NZTS	NZTS
Weapons program employment[iii]	25,000	75,000	40,000	30,000	15,000-20,000

[i] Abbreviations for U.S. facilities: LANL (Los Alamos National Laboratory); LLNL (Lawrence Livermore National Laboratory); SNL (Sandia National Laboratory); KCP (Kansas City Plant); SRS (Savannah River Site); NTS (Nevada Test Site).

[ii] Officially, Krasnoyarsk-26 also remains a part of the weapons complex. Presumably, its weapons mission is the management of strategic stocks of plutonium. It is, however, possible that the continuing operation of plutonium production reactors and reprocessing plants in Krasnoyarsk-26 and Tomsk-7 is qualified by Minatom as defense-related work even if no new plutonium is used in nuclear weapons.

[iii] Weapons program employment levels for the Russian complex after Phase III and Phase IV reductions are based on estimates for 2005 facility employment levels.

increase, and the prospects for economic development of the surrounding communities would dim.

The future trajectory of the Russian warhead production complex matters not only for Russia; it is also of critical importance to the United States and other Western nations for a number of reasons:

- From the perspective of arms control and strategic stability, an over-sized Russian warhead production complex perpetuates the risk that Russia could quickly rebuild its huge nuclear stockpile if political and economic circumstances change.
- Continuing decay of the massive complex undermines ongoing efforts to secure hundreds of tons of highly enriched uranium (HEU) and plutonium and increases the risk of proliferation of nuclear weapons technologies and expertise.
- A lack of consolidation will have a major impact on U.S.-Russian cooperative programs. In particular, business development and nonproliferation cooperation with the closed nuclear cities and associated nuclear facilities remain inhibited because of restricted access and investment limitations.

The optimal configuration of the complex will have to be determined by the Russian government on the basis of a comprehensive review of the technical capabilities of the existing facilities, the size and composition of the projected nuclear weapons stockpile, and other factors. The Russian government has reportedly developed a complex restructuring program.[2] The implementation of this program is an important and urgent task. It is likely, however, that the current plan is based on conservative assumptions regarding the size of stockpile (it most likely envisions a stockpile based on START I or START II limits) and corresponding levels of funding. In reality, however, Russian strategic nuclear weapons are projected to decline to much lower levels by 2005-2010, and funding is likely to remain scarce. It is therefore important to start considering correspondingly deeper reductions of Russia's weapons production infrastructure.

Based on open source information about the Russian nuclear weapons complex, this report discusses its core missions and associated infrastructure requirements, reviews recent developments in the complex, and outlines a long-term strategy for restructuring and consolidating the Russian nuclear warhead production infrastructure (see Figure 1). Although this report does not address in detail problems related to excess nuclear workers, conversion of nuclear facilities, and social stability in the closed nuclear cities, dealing with these factors is clearly a precondition to implementing any downsizing strategy for the Russian nuclear weapons complex.[3]

THE RISE AND FALL OF THE SOVIET NUCLEAR WEAPONS COMPLEX

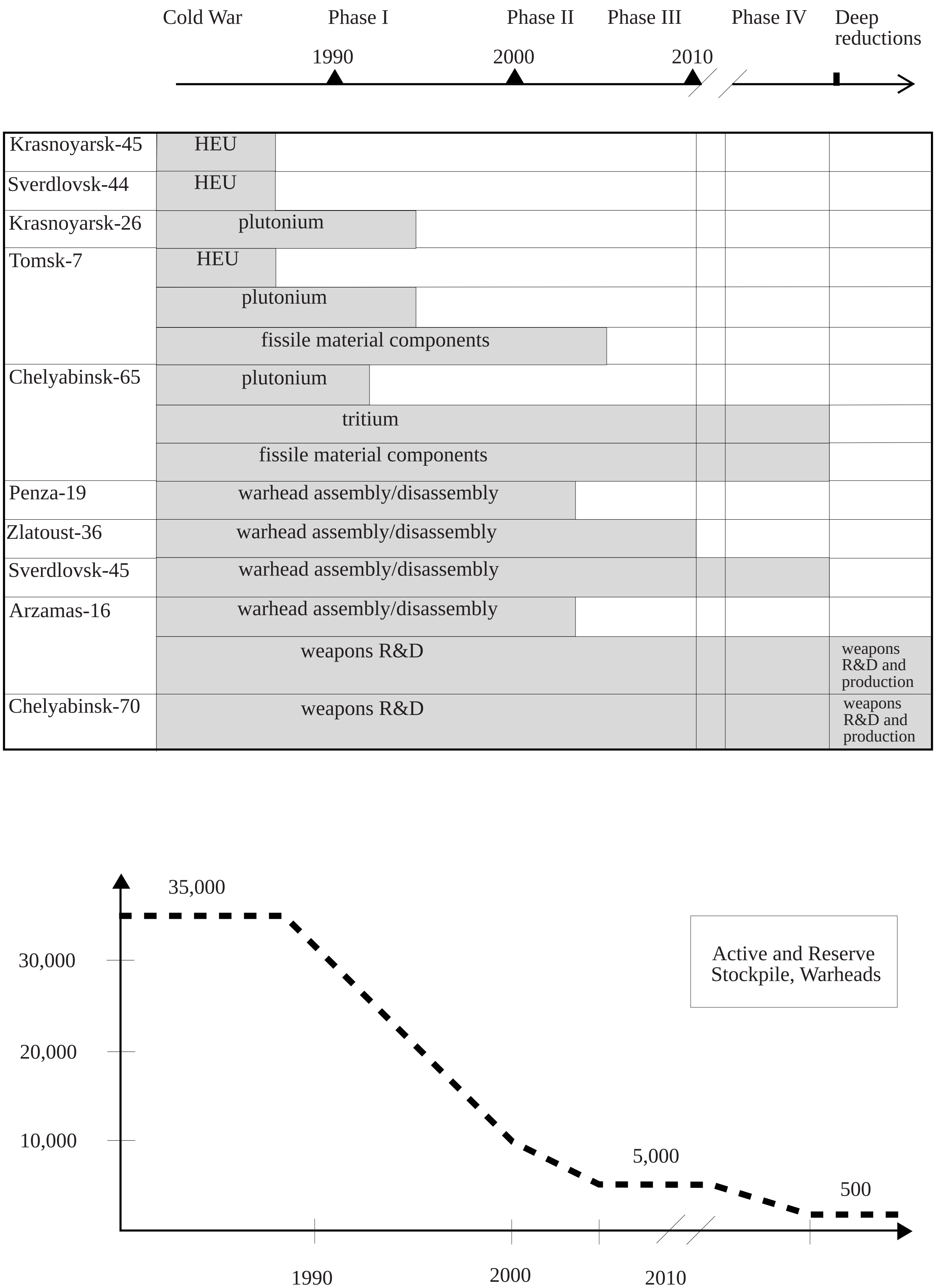
The Growth Phase: 1945 to Mid-1980s

The Soviet nuclear program began in August 1945 as a crash effort in response to the atomic bombardment of Japan by the United States.[4] In less then five years, the program met its original goal–the development and production of an aircraft-deliverable nuclear bomb. Even before the first nuclear test on August 29, 1949, however, the Soviet government started to plan a massive effort to develop the infrastructure required to design, test, and mass-produce more advanced nuclear weapons. The driving policy objective was to catch up with the United States, which at that time had a diverse and rapidly growing stockpile. The increasing number and diversity of nuclear weapons-delivery systems and qualitative improvements in nuclear weapons drove the subsequent expansion of the Soviet nuclear weapons complex.

During the 1950s and 1960s, the "pioneering" period of the weapons program, the focus was on the development and mass-production of thermonuclear and more efficient fission explosives for an increasing variety of delivery systems, including warheads for medium-range and intercontinental-range ballistic missiles, and various tactical systems.[5] The transfer of custodianship of nuclear weapons to the military in the late 1950s led to the introduction of new safety and user-control features to Soviet warhead designs, and also prompted the development of a warhead management infrastructure for deployed weapons.

The increasing complexity of nuclear weapons and operations, and the expansion of the nuclear stockpile were paralleled and facilitated by the expansion of the weapons research and development (R&D) and industrial production infrastructure. During the 1950s and 1960s, this expansion was primarily due to the construction of new major facilities, most of them in closed nuclear cities. In addition, research institutes and manufacturing facilities were transferred to the weapons program from other

Figure 1: Closed City Demilitarization Timeline



industries. By the late 1960s, the Soviet Union had a thoroughly integrated and redundant weapons complex, which consisted of over 20 research institutes and design bureaus, fissile material production centers, and serial warhead production facilities.

During the 1970s, the "golden age" of the program, the focus was on warhead miniaturization and hardening against nuclear-armed anti-missile missiles.[6] During that period, the warheads for many types of currently deployed submarine-launched ballistic missiles (SLBMs) and land-based inter-continental ballistic missiles (ICBMs) were designed and major advances in the development of tactical nuclear weapons were made. Stockpile diversity also increased as the military demanded that an increasingly large number of weapons systems be nuclear-capable. In the 1980s, the complex continued to develop and field new warhead designs, including those of third-generation weapons.[7] Progress was also made in the area of warhead safety and security.

During the 1970s and 1980s, the production infrastructure continued to grow rapidly. In 1969, the Soviet government resolved to increase the warhead production capacity by a factor of 2.5 to three.[8] By the early 1980s, "Minsredmash [Minatom's predecessor] had overtaken the United States in both quantities and quality of nuclear weapons."[9] It is believed that by the mid-1980s, the stockpile had reached its peak size of approximately 35,000 warheads.[10]

This last phase of infrastructure growth mainly involved the modernization and expansion of existing facilities and was driven by improvements in nuclear weapons technology. At serial production facilities, for example, the transition to conveyor methods of assembly of nuclear warheads in the late 1960s to early 1970s led to the construction of new warhead assembly buildings.[11] Also in the 1970s, in response to warhead miniaturization requirements, new production shops and buildings were built to accommodate microelectronics and precision-mechanical systems production capabilities.

The Decline of the Complex: Late 1980s to 1990s

The situation began to change in the late 1980s as the Soviet government initiated a program of "defense conversion" and began the process of gradually phasing out the production of fissile materials for nuclear weapons and started the dismantlement of obsolete nuclear warheads.

The production of HEU for weapons ceased in 1988. The production of plutonium dropped several-fold from its Cold War levels as 10 out of 13 plutonium-production reactors were shut down between 1987 and 1992. (The three reactors still in operation produce heat and electricity for the local populations and cannot be shut down until replacement energy sources become available.) In October 1994, the Russian government declared that freshly produced plutonium would be placed in storage and would no longer be used in nuclear weapons.

Post-Soviet economic and social dislocations have weakened the remainder of the complex—its weapons R&D institutes and industrial warhead production facilities. The level of weapons R&D has declined sharply because of funding shortfalls and the constraints on nuclear testing imposed by the Comprehensive Test Ban Treaty (CTBT). No test site activities took place at Novaya Zemlya for five years between 1990 and 1995. Defense orders at serial production facilities have also plummeted as a result of stockpile reductions and funding shortages. The production of warheads has declined to one-twelfth of its Cold War levels.[12] The Molnia plant in Moscow, for example, a manufacturer of warhead electronic and automatic components, completely lost its defense orders in the early 1990s.[13] (Molnia succeeded in recapturing some nuclear weapons work in 1997-98.[14])

In the absence of work and without sufficient maintenance, the R&D and production base of the complex has deteriorated. The complex has also lost a substantial fraction of its qualified personnel. Weapons institutes and facilities in open cities have lost up to two-thirds of their staff to the commercial sector. (For example, the number of workers at the Molnia plant in Moscow declined from 6,700 in the late 1980s to 2,500 in 1995.[15])

Weapons facilities in closed cities have also suffered personnel losses, although not as dramatic. According to the local newspaper in Chelyabinsk-70,[16] for example, "[the warhead R&D institute] VNIITF is experiencing significant difficulties because of the outflow of personnel, in particular, of qualified workers. Massive resignations could render the institute incapable of fulfilling state defense orders."[17] Perhaps more significantly, a large percentage of workers in the closed cities are underemployed and the already limited funds provided to fulfill defense orders are disbursed among many people who are not directly involved in weapons production. Analysts have also suggested that even if funding were to be restored to adequate levels, it would take years to bring the proficiency and dedication of nuclear workers up to previous standards.

In 1999-2000, the Russian government took steps that somewhat stabilized the complex. As of the fall 1999, salaries, although low, were paid on time and the warhead design centers in Arzamas-16 and Chelyabinsk-70 received limited funds to procure equipment and materials in support of their stockpile stewardship work. As a consequence, morale has improved. Furthermore, the Russian government has recently reaffirmed Russia's reliance on nuclear weapons to ensure its military security, while the April 1999 meeting of the Russian National Security Council addressed the needs of the warhead production complex. Nevertheless, pressure to restructure and downsize the complex remains.

OPERATIONAL ENVIRONMENT, MISSIONS, AND CRITICAL INFRASTRUCTURE REQUIREMENTS

Changes in the Operational Environment

During the Cold War, the principal task of the warhead research and design institutes was to advance nuclear weapons science, to design and test new warheads, and to provide scientific oversight of the handling of nuclear warheads throughout their life-cycle. The serial production facilities worked to dismantle obsolete warheads, to modernize and refurbish warheads in the stockpile, and to put into production and mass-produce warheads of more advanced types. Because of the high pace of technological innovation, nuclear warheads were often replaced before the end of their designed service life.[18]

Funding shortages, the end of nuclear testing, and stockpile reductions have dramatically changed the direction of nuclear weapons activities.[19] At present, there is no money to support any major weapons-development program. The level of stockpile support work, such as warhead remanufacturing, has declined and sometimes is well below technical and operational requirements. The complex now must prioritize its tasks and missions and concentrate on the least costly and most cost-effective alternatives. It is also no longer possible to maintain redundant programs and facilities, a standard practice during the Cold War.

The end of nuclear testing in 1990 and Russia's ratification of the CTBT in 2000 have changed the nature of warhead R&D activities. The development of more advanced warhead designs has lost priority. Activities are largely limited to maintaining nuclear warhead design skills and preventing surprise breakthroughs in nuclear weapons technology by foreign countries. As of March 2000, for example, no work on new warhead designs was taking place at Chelyabinsk-70.[20]

Stockpile reductions have changed the activities and missions of the Russian nuclear weapons complex. As a result of the Intermediate Range Nuclear Forces (INF) and START I treaties, the Bush-Gorbachev tactical weapons initiatives of 1991, decommissioning of naval ships, aircraft, and other delivery systems, and the retirement of unsafe and obsolete weapons, the Russian stockpile is estimated to have declined from approximately 35,000 warheads in the mid-1980s to approximately 10,000 operational and reserve warheads in 2000.[21] Additional strategic weapons cuts could occur as a result of the START II and START III treaties. With or without arms control agreements, the stockpile is projected to shrink to 5,000 warheads by 2005-2010.[22]

Stockpile reductions have presumably allowed Russia to keep newer warheads thereby temporarily scaling down warhead remanufacturing activities. The priority of stockpile surveillance and warhead life extension has correspondingly increased. Stockpile reductions have also resulted in a large-scale warhead dismantlement effort.

Missions and Critical Infrastructure Requirements

The missions of the Russian warhead production complex after the Cold War can be summarized as follows:[23]

- stockpile surveillance and refurbishment;
- warhead life extension;
- dismantlement of retired warheads;
- weapons R&D to prevent surprise nuclear weapons science breakthroughs in foreign countries; and
- support to arms control and nonproliferation initiatives.

The complex will not be able to execute its missions without specialized facilities providing for nuclear weapons R&D and non-nuclear testing, tritium production and processing, fissile material component manufacturing, and warhead assembly and disassembly.[24] These critical infrastructure requirements and Russia's existing capabilities are the main factors in planning the size and configuration of the future weapons complex. In most cases this infrastructure is still oversized and redundant.

Nuclear Weapons R&D and Non-Nuclear Testing

Surveillance of existing warheads to ensure their safety, security, and reliability has become one of complex's primary tasks. Because of a desire to achieve at least partial parity with the U.S. Department of Energy (DOE) Science-Based Stockpile Stewardship Program, Russian specialists are under pressure to strengthen computational and experimental capabilities to improve their understanding of nuclear weapons physics and the effects of aging on nuclear weapons. Russia, however, may be less dependent on advanced scientific capabilities than the United States because of the relative simplicity of its warhead designs and traditional stockpile management practices.[25] U.S. Department of Defense officials have argued:

> [W]hether the Russians depended on nuclear testing to maintain confidence in their stockpile to the same extent as the United States is difficult to say. There is a reason to believe that they did not. We think that the Russians ensured stockpile reliability through conservative warhead designs that included lavish use of fissile material and high-explosives and by re-manufacturing nuclear weapons before age-related problems appeared.[26]

In the future, Russia will likely adopt a balanced, minimal-cost approach to stockpile stewardship that combines stockpile surveillance and warhead remanufacturing activities.

As in the past, future stockpile surveillance activities will rely to a significant extent on diagnostics and functionality testing of warhead electronics in the field, random sampling of deployed weapons for return to their parent warhead design institutes for disassembly and in-depth component evaluation and testing, and testing of a statistically significant number of components from production lots. Environmental testing of warheads and flight-testing of inert warheads will provide for an integrated assessment of life-cycle warhead performance and weapon use (minus nuclear detonation). Since the CTBT prohibits nuclear explosive testing, Russia therefore will also have to rely on computer simulations, hydrodynamic and subcritical testing, and other R&D tools to validate expected warhead performance.[27]

Many experimental facilities that are critical to Russia's stockpile surveillance mission are located at the warhead design centers in Arzamas-16 (Institute of Experimental Physics, VNIIEF) and Chelyabinsk-70 (Institute of Technical Physics, VNIITF). In particular, both centers have advanced high-explosive firing sites and flash X-ray facilities, computer centers capable of writing and running large hydrodynamic weapon codes, research reactor facilities designed to study problems of radiation hardening, material science research facilities, and experimental complexes to simulate environmental and aging effects on nuclear warheads. Component testing, flight-testing of inert warheads, and some other important stockpile surveillance functions are also performed by Minatom's production facilities. Subcritical experiments are carried out at a rate of approximately five experiments a year (some of them associated with warhead safety activities) at the Novaya Zemlya test site by technical teams from Arzamas-16 and Chelyabinsk-70.[28]

Non-nuclear testing, hydrodynamic and subcritical tests, and timely re-manufacturing of nuclear warheads to specifications would provide adequate assurances of safety, security, and reliability of Russia's nuclear stockpile. The success of the Russian stockpile stewardship program will likely be determined by Russia's ability to maintain a minimal set of experimental facilities and competence in the key specialties in the areas of nuclear weapons and fissile materials.

Tritium Production and Processing

Most modern nuclear weapons use tritium to boost the yield of the fission primary to make possible ignition of the thermonuclear secondary. Tritium, a relatively short-lived isotope, decays to helium at a rate of approximately 5.5 percent per year. This property of tritium dictates the need for a capability to purify tritium stocks and produce new tritium.

In Russia, the production and processing of tritium takes place at Chelyabinsk-65. Tritium is produced in two reactors by neutron irradiation of lithium-6 targets. The reactors are relatively modern (1979 and 1980 start-up) and appear more than adequate to support the projected tritium requirements in the future.[29]

Recovery and recycling of tritium from dismantled warheads may, however, obviate the need for new production for many years. Indeed, a tritium inventory for the operational stockpile of 35,000 warheads in 1985 would be sufficient to support a 5,000-warhead stockpile almost until 2030.

Re-manufacturing of Nuclear Warheads

Remanufacturing of nuclear warheads is partly required to replace warheads withdrawn from the operational stockpile for disassembly and evaluation. The bulk of remanufacturing, however, is necessary to replace components with limited service lives or to modernize weapons to enhance their safety and security.

Russia has a limited ability to mount an analog to the U.S. science-based stockpile surveillance and stewardship program designed to predict and assess effects of warhead aging. Thus, warhead remanufacturing will remain a central element of warhead management practices in Russia. Of particular significance to the warhead remanufacturing mission are fissile material component manufacturing and warhead assembly and disassembly facilities.

Manufacturing of HEU and plutonium components. Fabrication of fissile material components for nuclear warheads involves many operations and requires dedicated safe and secure facilities. Future Russian production capacity will be largely devoted to rebuilding aging plutonium pits. Aging of plutonium occurs as a result of accumulation of helium-4 (from plutonium alpha-decays) and gamma-emitting americium-241 (a decay product of plutonium-241), and unwanted chemical reactions (for example, corrosion due to defective pit welds).[30] The remanufacturing operation involves a disassembly of an old pit, purification of plutonium, and manufacture of a new pit.[31]

In Russia, chemical and metallurgical plants, designed to process HEU and plutonium and to fabricate warhead components, are located at Chelyabinsk-65 and Tomsk-7.[32] (Uranium processing operations also take place at some serial warhead assembly plants.) During the Cold War the two facilities produced HEU and plutonium components for an estimated 2,500 to 4,000 warheads per year (assuming a pit life of seven to 15 years). Minatom specialists are reportedly working to improve pit and warhead manufacturing technologies to increase warhead life to 25 years. Assuming a stockpile of 5,000 warheads, annual production requirements would eventually drop to approximately 200 pits.[33]

It should be noted, however, that in the past the concentration of americium in remanufactured pits was probably kept below a certain limit by mixing plutonium from dismantled warheads with freshly produced plutonium. As Russia no longer produces plutonium for weapons, this approach will not work in the future and a plutonium purification facility will be necessary. Whether such a facility exists at present and, if so, where are not publicly known.

Warhead Assembly, Disassembly, and Dismantlement. The operations of warhead disassembly and assembly to replace aging high-explosive and fissile material components, or to dismantle retired warheads require highly secure facilities. These facilities must be capable of handling, processing, and storing fissile and high-explosive materials, as well as warhead subassemblies and intact warheads. Russia has four such assembly-disassembly ("serial production") complexes at Arzamas-16, Sverdlovsk-45, Zlatoust-36, and Penza-19. Each of these plants probably has an area of specialization. For example, it has been reported that only the Arzamas-16 and Sverdlovsk-45 plants manufacture, refurbish, and dismantle warhead physics packages.[34] The Zlatoust-36 facility builds physics packages into ICBM/SLBM reentry vehicles. And the Penza-19 complex produces automatic and electronic components and subassemblies. The plants also presumably specialize with respect to the types of warheads produced. For example, the Avangard plant in the recent years has worked primarily on warheads designed by the Institute of Automatics (VNIIA, Moscow) for the navy and air force.[35] It is likely that the Sverdlovsk-45 complex specializes in warheads for strategic missiles and certain tactical weapons systems.

Russia's warhead remanufacturing capacity is strongly affected by the tempo of dismantlement operations. The dismantlement process retraces the principal steps of warhead production and utilizes many of the same technical capabilities, personnel, and infrastructure. Warheads are dismantled at the facilities where they were assembled.

Warhead dismantlement is comparatively more time-consuming and labor intensive than assembly. It also requires large-scale storage and transportation of intact warheads prior to dismantlement, and generates large streams of fissile materials, electronic and mechanical components, and high-explosives that require storage, processing, and disposition.

Large-scale stockpile reductions began in the late 1980s. By 1998, an estimated 10,000 to 11,000 warheads had been taken apart and 4,000 to 5,000 were in line for dismantlement.[36] Assuming a dismantlement rate of 1,500 warheads per year, the elimination of the backlog of obsolete and retired warheads to reduce the stockpile to 5,000 warheads will continue until 2008.

FOUR PHASES OF DOWNSIZING THE RUSSIAN NUCLEAR COMPLEX

This report divides the process of downsizing into four phases (see Figure 1): an initial phase of contraction, which is already largely over; the current phase, corresponding to Minatom's ongoing efforts to downsize the complex; and two hypothetical future phases associated with further stockpile reductions to 5,000 and 500 warheads respectively. The objective of the two future phases of complex reductions would be not only to optimize the complex for reduced warhead arsenals but also to facilitate rapid demilitarization of as many facilities and locations as possible to make them available for international cooperation, defense conversion, and business development.[37]

Phase I (late 1980s–late 1990s): Contraction of the Complex

The initial phase of downsizing encompassed approximately 10 years and can be characterized by the following three developments: the termination of HEU and plutonium production for weapons, defense conversion without complex restructuring, and spontaneous contraction of weapons production capabilities.

The termination of defense orders for new fissile materials effectively excluded the uranium enrichment and plutonium production plants from the weapons program.[38] As a result, no nuclear weapons activities presently take place in three closed nuclear cities: Sverdlovsk-44, Krasnoyarsk-45, and Krasnoyarsk-26. They, however, remain critical to the mission of storing and managing hundreds of tons of fissile materials, some of which could be a part of Russia's strategic reserves. (According to Minatom officials, the Krasnoyarsk-26 plutonium complex remains officially a part of the weapons complex.)

By the late 1980s, the Soviet government had become aware of the need to scale down the nuclear weapons program. It appears, however, that the initial plan was to downsize but not restructure the complex. In other words, defense activities were to continue at every facility of the complex but at a reduced level. Defense conversion programs were developed to redirect excess workers and equipment to civilian work. Most defense conversion efforts, however, have failed because of insufficient investments, the collapse of Russia's domestic markets, lack of entrepreneurial and market skills, secrecy, inflexible institutional bureaucracies, and high production costs.

As a result, the reductions have been largely spontaneous. Although infrastructure deterioration and personnel attrition have already made the complex much less capable, it remains oversized and, with the exception of the separation of the HEU and plutonium production facilities, it has not changed structurally.

Phase II (late 1998 to 2005): Minatom's 1998 Program

It was not until after the mid-1990s that Minatom and its facility managers accepted weapons program cutbacks as irreversible and concluded that a serious restructuring and downsizing effort was needed for the complex to survive in the new environment. Such an effort was launched. It appears that its main objective is to focus defense order funds by reducing facility duplication and separating the defense part of the complex from the part excess to defense requirements. A second, related objective is to create civilian jobs for excess personnel.

Minatom's plans were formalized in the program "On Restructuring and Conversion of the Nuclear Weapons Complex in 1998-2000," adopted by the Russian government in June 1998 as a part of a broader plan to restructure Russia's defense industries. The program and other planning documents call on Minatom to:

- stop warhead assembly at the Arzamas-16 and Penza-19 serial production facilities by 2000;
- stop warhead dismantlement in Arzamas-16 and Penza-19 in 2003;
- transfer the production of certain non-nuclear warhead components and assemblies to the pilot production plants of the warhead R&D institutes by 2000;

- consolidate weapons work at the remaining non-nuclear component manufacturing facilities by 2000;
- phase out nuclear weapons work at one of the two fissile material processing plants in 2003;
- cut the number of defense program personnel from 75,000 to 40,000 by 2005;[39] and
- cut the number of personnel at the serial production plants from 78,000 during the Cold War to approximately 11,000 in the next few years.

Downsizing is also planned for individual facilities and would involve defense personnel reductions and consolidation of weapons activities in fewer buildings and production areas. For example, the number of defense program personnel at the warhead assembly facility in Zlatoust-36 is expected to decrease from 5,766 in 1997 to 2,800 in 2001.[40] At the Urals Electro-Mechanical Plant in Yekaterinburg, which produces nuclear warhead electronic components, the plan is to split the facility into two separate entities.[41] The weapons part would be located in a single building and would retain about one-third of the equipment and infrastructure. It would be supported exclusively by funds from defense orders. The remainder of the plant would have to support itself by producing and selling commercial products on the open market. The weapons program employment would decline from the Cold War level of 12,000 to 1,500.

Certain steps to implement this program have already been taken. In April 1999, Minatom formed the Department for Conversion of Nuclear Industry, which has responsibility for defense conversion and complex restructuring.[42] All research institutes and production plants of the weapons complex have developed and are working to implement facility-level restructuring programs. Essentially no weapons work is taking place at the Molnia plant in Moscow. The production association Sever in Novosibirsk, a nuclear warhead electronic components and subassemblies production facility, has already consolidated all weapons work in a single technical area and reduced defense program staff.[43] This facility is projected to lose its weapons function by 2005-2007. Warhead assembly work was terminated at the Avangard plant in Arzamas-16, and now its primary weapons function is warhead dismantlement.[44] The Penza-19 facility reportedly has no defense orders and the closed city is on the verge of being opened.[45] Tomsk-7 has also essentially become a civilian nuclear technology center. Already, the bulk of the workload at the chemical and metallurgical plant in Tomsk-7 is non-military and related to HEU downblending under the U.S.-Russian HEU agreement.

If successful, the implementation of Minatom's program would be a major step in the right direction. Nuclear weapons work would be concentrated in five closed cities: Arzamas-16, Chelyabinsk-70, Sverdlovsk-45, Zlatoust-36, and Chelyabinsk-65. The complex, however, would likely remain oversized relative to the projected 2005-2010 arsenal of 5,000 warheads. Also, compared to the United States, it would employ considerably more people and include twice as many sites (see Table 2). On the last point, it should be noted, however, that there are significant differences in technical approaches and stockpile surveillance and management practices in the two countries (see Table 3). These differences do not permit a direct comparison of the two complexes. Generally, the Russian complex is likely to require more people and infrastructure to support a comparable-size stockpile.

Phase III (2005–2010): "Complex 2010"

The objective of the third phase of consolidation is to create a "Complex 2010" that is optimized for supporting a stockpile of 5,000 warheads. Assuming a warhead life of 25 years, the complex would have a capacity to remanufacture approximately 200 warheads per year. Phase III would begin immediately after the current effort is completed by 2005-2010 and would likely require five to ten years to implement. A possible approach to Phase III reductions is to:

- consolidate warhead assembly and disassembly operations at one facility (most likely Sverdlovsk-45, Minatom's leading serial production facility); and
- transfer the production of electronic, mechanical, and other non-nuclear components and equipment to Sverdlovsk-45, as well as to the Institute of Automatics in Moscow and the federal weapons research centers in Arzamas-16 and Chelyabinsk-70.

Given its tight budget and reductions in the number of types of warheads in the stockpile (due to retirement of certain classes of delivery systems), the Russian government will likely remain under pressure to consolidate weapons activities that are taking place in the R&D centers in Arzamas-16 and Chelyabinsk-70. Indeed, proposals to phase out defense work in Chelyabinsk-70 have already been made.

Table 3: Some Differences Between the U.S. and Russian Nuclear Weapons Complexes

Area of differences	**United States**	**Russia**
Technology	- warheads are more sophisticated; - pit and warhead lives are relatively long (possibly 50 and 25 yrs respectively)	- warhead designs are less complex and more conservative (more fissile materials? and explosives); - warheads are less robust and more maintenance-intensive; - pit and warhead lives are relatively short (10-15 yrs)
Stockpile management	Emphasis on surveillance, replacement of components as they age	Emphasis on complete periodic remanufacturing of nuclear warheads before problems of aging occur
Use of commercial off-the-shelf technologies	Significant for non-nuclear components (electronics, mechanical, materials)	Virtually 100 percent production of non-nuclear components and manufacturing equipment internally
Commercial vs. defense programs	Separated	Integrated
Structure of principal R&D facilities	DOE national laboratories are primarily R&D centers with little production personnel and capacities	VNIIEF (Arzamas-16), VNIITF (Chelyabinsk-70), and VNIIA (Moscow) have pilot production plants that employ thousands of workers
Technology vs. labor	Reliance on computing and advanced technologies	Reliance on labor-intensive processes (e.g., greater role of analytical models) and large manpower

Closing down one of the two research centers, however, could be counterproductive. Each institute has unique facilities and will remain responsible for specific types of warheads (for example, gravity bombs and all SLBM warheads for Chelyabinsk-70, and SS-25 and SS-27 ICBM warheads for Arzamas-16). Moreover, the downsizing of the complex will likely increase the relative significance of the warhead design centers in the Russian nuclear weapons program. In particular, their existence would be more justified if the small-lot production of warhead components was transferred from industrial facilities to the pilot production plants associated with the two institutes. The two federal centers could also assume the responsibility for the weapons work that is currently performed at smaller R&D institutes in Moscow and other open cities.

Minatom should, however, work to increase cooperation between Chelyabinsk-70 and Arzamas-16 and to reduce the duplication of experimental and research facilities. Minatom officials have already stated that most new facilities would be constructed in Arzmas-16 and would not be duplicated in Chelyabinsk-70.[46]

If Phase II of complex downsizing is primarily intended to reduce the extent of duplication by shutting down excess facilities, Phase III would consolidate weapons activities at fewer core facilities by relocating certain weapons functions to these facilities and demilitarizing the remaining facilities. As a result of Phase III reductions, nuclear weapons activities would remain in four closed cities and at few facilities in open cities. The Russian weapons complex would become roughly comparable in size to the DOE weapons complex in the United States (see Table 2).

Phase IV: Deep Reductions

Phase IV consolidation of the weapons infrastructure would occur some time in the future in response to stockpile reductions to 500 warheads. Such deep reductions would not be possible without an international arms control agreement between all nuclear weapons states that would require parallel and verifiable reductions of U.S. and Russian nuclear arsenals and the corresponding production infrastructure.

In Russia, Phase IV reductions could be implemented by consolidating critical stockpile activities in the federal centers in Arzamas-16 and/or Chelyabinsk-70. (It might be necessary to maintain the tritium production capability in Chelyabinsk-65, but the need for new production could be delayed almost indefinitely.) Both institutes are well equipped for the mission. Chelyabinsk-70, for example, has a tritium processing line and fissile materials processing capabilities.[47] Its two pilot production plants are capable of producing high-explosives, beryllium, and various electronic and mechanical components, as well as assembling physics packages and warheads. Comparable capabilities presumably exist in Arzamas-16 as well. The serial production facility in Sverdlovsk-45 would in this case focus on the task of eliminating excess warheads and, after that, would be demilitarized and converted to civilian uses.

DOWNSIZING THE COMPLEX

A rational approach to optimizing the weapons complex would be to consolidate weapons work at the smallest number of facilities possible and would be based on a cost-benefit analysis of the existing infrastructure, future missions, and stockpile and funding projections. In reality, however, there are many other factors that could influence Minatom's ability to plan and execute the downsizing and restructuring of the complex:

- **Redirection of excess workers.** The most significant near-term problem, especially in the closed nuclear cities, is the redirection of excess workers to productive non-weapons work.[48] The crisis of the Russian economy and insufficient foreign investment will continue to inhibit defense conversion at Minatom facilities and economic development of the surrounding communities. In fact, social and economic conditions in the closed nuclear cities could become worse as a result of the Russian government's taking away or cutting back tax privileges that closed cities could provide to commercial companies before 2000.[49] Workforce reductions resulting from retirement, personnel losses to the commercial sector, and minimal new hiring will likely relieve this pressure in about 10 years. Massive retirement, however, would increase the need for social protection of and better pensions for nuclear veterans.
- **Funding shortages.** Defense conversion and redirection of excess workers, social protection of retirees, and consolidation of weapons activities at fewer facilities would all require considerable funding. Minatom estimates that it needs approximately $1 billion to implement its current complex restructuring plans. Until the national economy recovers, the Russian government will not be able to finance complex downsizing activities on a sufficient scale.
- **Domestic political issues.** A decision to terminate defense orders at a large production facility, especially in a closed city, would be politically unpopular (unless attractive non-military jobs are created) and would encounter opposition from facility workers, surrounding communities, regional political authorities, and in the Russian Duma. Pressure from these special interest groups, compounded by creeping anti-Western sentiment and nationalism, will likely impede the downsizing process.
- **Arms control uncertainties**. Conditions imposed by the Duma on START II implementation, the uncertain future of START III, and the rejection by the U.S. Senate of the CTBT create considerable uncertainties about future stockpile reductions and complicate the planning of complex downsizing. In the absence of binding arms control agreements, the Russian government would be hard pressed to maintain a "national emergency" option (and the corresponding warhead production infrastructure) of building up its nuclear stockpile and of resuming massive warhead R&D effort. For example, there have already been proposals to develop and mass-produce new tactical weapons in response to the North Atlantic Treaty Organization expansion, and to initiate a weapons R&D effort aimed at countering the potential deployment of a strategic missile defense system in the United States.

These difficulties are serious, and unless the Russian government provides strong political support, leadership, and sufficient funding, the continuation of the steady erosion of the complex without restructuring cannot be ruled out.

High-level discussions and technical cooperation with the United States in the areas of complex restructuring and stockpile stewardship must also become an integral element of the effort to reconfigure the Russian nuclear weapons complex. Indeed, the U.S.-Russian nuclear relationship is a major variable in reshaping Russia's warhead production complex. Greater transparency of nuclear operations in both countries and expanded cooperation are thus critical for developing rational, post-Cold War nuclear policies.

[1] The facilities of the nuclear weapons complex are managed by three Minatom departments: the Nuclear Fuel Cycle Department (formerly the Fourth Main Directorate), the Nuclear Weapons Development and Testing Department (formerly the Fifth Main Directorate), and Department of Nuclear Weapons Production (formerly the Sixth Main Directorate). Another facility of the complex—the Novaya Zemlya Test Site—is managed by the Ministry of Defense.

[2] The future of the nuclear weapons complex is discussed in several Russian government documents, including the program of armaments (which discusses Minatom's responsibilities to 2005), the federal program of increasing safety of nuclear weapons, and the programs of development and restructuring of the nuclear weapons complex and defense conversion. See, "We Must Save the Best (Press-Conference with L. Ryabev)," *Gorodskoy kuryer* (Sarov), March 5, 1998. In this and all subsequent references, the titles of Russian-language sources are given in English translation. As of fall 2000, the government was also considering a program, "On Reforming Facilities of the Nuclear Weapons Complex in 2001-2005 and to 2010."

[3] For an in-depth discussion of the social and economic situation in Russian closed nuclear cities, as well as Russian internal and international cooperative efforts to convert nuclear weapons facilities and create jobs for excess workers, see: Oleg Bukharin, Harold Feiveson, Frank von Hippel, Sharon Weiner, Matthew Bunn, William Hoehn III, and Kenneth Luongo, *Helping Russia Downsize Its Nuclear Complex: A Focus on the Closed Nuclear Cities*, Report of an International Conference held at Princeton University, March 14-15, 2000, PNPA/Princeton University, June 2000; and Oleg Bukharin, Frank von Hippel, and Sharon Weiner, *Conversion and Job Creation in Russia's Closed Nuclear Cities*, (PNPA/Princeton University, November 2000).

[4] Officially, the Soviet nuclear research and development program began on February 11, 1943. Its scale, however, remained limited until the United States used atomic weapons against Hiroshima and Nagasaki on August 6 and 9, 1945. For details, see, for example, Victor N. Mikhailov, A.M. Petrosyants et al., eds., *The Creation of the First Soviet Nuclear Bomb* (Moscow: EnergoIzdat, 1995).

[5] See, for example, Stanislav Voronin, "The Echo of the First Explosion at the End of the Century," *Atompressa* (Elektrostal), No. 29 (360), August 1999, pp. 3-4.

[6] Boris Litvinov, "Today, This Can Be Told ," *Atompressa* (Elektrostal), No. 26 (357), July 1999, p. 1.

[7] Third-generation nuclear weapons are designed to emphasize a particular effect of a nuclear explosion, such as high neutron radiation for a neutron bomb.

[8] L. Petukhov, "The Balance of Power Provided for Peace on Our Planet," *Atompressa* (Elektrostal), No. 43 (374), December 1999, p. 1.

[9] Ibid.

[10] Anatoliy Dyakov, presentation at the workshop "The Future of U.S.-Russian Nuclear Arms Control," Boston, Massachusetts, February 2-6, 1998.

[11] See, for example, Yuriy Zavalishin, *"Avangard" Atomic* (Saransk: Krasny Oktyabr', 1999).

[12] "We Must Save the Best (Press-Conference with L. Ryabev)."

[13] S. Sachkova "Hopes of Defense Workers," *Atompressa* (Elektrostal), No. 46 (377), December 1999, p. 3.

[14] "The Priority is the Personnel, Production, and Engineering Potential of the Plant…," *Atompressa* (Elektrostal), No. 34 (365), September 1999, pp. 1-2.

[15] Ibid.

[16] This report uses old (pre-1992) names of the 10 closed nuclear cities. For new names see Table 1.

[17] "From Industry's Papers," *Atompressa* (Elektrostal), No. 19 (350), June 1999, p. 4.

[18] The pace of warhead development is demonstrated by the following statistics: in 1976, the warhead design institutes had 14 R&D and 24 engineering projects. (Presumably, one R&D project could contribute to more than one type of nuclear warhead. Also, some engineering projects possibly related to major subassemblies, not intact warheads.) During the next year, seven more R&D and 25 engineering projects entered the pipeline and four and 17 projects respectively were finished. (See, Boris Litvinov, "Today, This Can Be Told," *Atompressa* (Elektrostal), No. 26 (357), July 1999, p. 1.)

[19] The 2000 budget for Minatom's defense program is reportedly $200 million, more than 20 times less than the budget of the U.S. Department of Energy defense program.

[20] Presentation by Evgeniy Avrorin, VNIITF Science Director, at the International Conference "Helping Russia Downsize its Nuclear Complex," Princeton University, March 14-15, 2000.

[21] According to Anatoliy Dyakov, as of the end of 1997, the active stockpile consisted of 13,620 deployed and reserve warheads. (Anatoliy Dyakov, "Nuclear Arms Reductions and Transparency," *Yaderyny Control* (September-October 1999), pp. 37-42.) This analysis assumes that further reductions to 10,000 warheads have taken place since 1997.

[22] This assumes 1,500 strategic, 3,000 tactical, and 500 reserve and spare warheads. Strategic reductions would occur due to the retirement of strategic delivery systems (such as ICBMs, bombers, and SSBNs). In the absence of new production, the tactical stockpile would also decline because no mass-production of tactical weapons has taken place since the late 1980s and because many warheads would reach the end of their approximately 10-year service life.

[23] See, for example: P. Sukharevsky "Minatom's Science and Technology Council No. 2 is 40," *Atompressa* (Elektrostal), 25, July 1999, p. 1.

[24] The production of automatic, electronic, and other non-nuclear warhead components, as well as the production of specialized manufacturing equipment also takes place at specialized facilities of the weapons complex.

[25] During 1998 Congressional hearings, Dr. Vic Reis, then the head of U.S. DOE defense programs, suggested, "they [Russians] have a somewhat different system where they do tend to go back and remanufacture the whole system. Their system, as best we understand it, is perhaps not quite as finely tuned as ours, so they are perhaps less .. science-based…." (U.S. House of Representatives, Committee on Appropriations, *Hearings before a Subcommittee of the Committee on Appropriations, House of Representatives, 105th Cong., Second Session, Subcommittee on Energy and Water Development, Part 6, Department of Energy, March 17, 1998*, p. 428.)

[26] See Harold Smith, Jr. and Richard Soll, "Challenges of Nuclear Stockpile Stewardship under a Comprehensive Test Ban," *Arms Control Today* 28 (March 1998) pp. 3-6. It should be noted, however, that the suggestion that Russian (relative to U.S.) pits contain significantly more plutonium could be an exaggeration. The use of large amounts of plutonium makes it impossible to maintain one-point safety. Also, there are indications that Russian designers succeeded in bringing down the amount of plutonium in pits to a few kilograms as early as in the mid-1950s (Matthew McKinzie, Natural

Resources Defense Council, correspondence with author, April 2000).

[27] Weapons physics and design principles facilitate stability of the yield and other performance parameters of modern thermonuclear weapons, most of which are believed to include a boosted primary and a thermonuclear secondary. Even a relatively low nuclear yield of less then 1 kt TNT equivalent due to compression of a plutonium pit by high explosives is sufficient to initiate a thermonuclear reaction in the deuterium-tritium boosting gas mixture, which is injected inside the pit prior to implosion. (Frank von Hippel, Harold Feiveson, and Christopher Paine, "A Low Threshold Nuclear Test Ban," *International Security* 12 (Fall 1987) pp. 135-151.) The thermonuclear reaction produces a large number of fast neutrons that contribute to plutonium fission thereby boosting the yield of the primary to approximately 10 kT, which is sufficient for a reliable initiation of the thermonuclear secondary. Thus, the total yield is relatively insensitive to primary implosion—the initial and most critical phase of the nuclear detonation process. The key to successful performance of a boosted primary is the achievement of sufficient compression of the pit material without its turbulent mixing with the boosting gas. Warhead designers study the process of a primary's implosion by conducting hydrodynamic tests in which pit fissile material is replaced with depleted uranium or some other suitable material and the implosion process is diagnosed by X-ray radiography. An additional problem, however, arises because the physical and chemical properties of plutonium, the material of choice for making fission primaries, differ considerably from those of uranium. (To a certain extent, this problem could be avoided in hydrodynamic tests by using plutonium-242. Compared to plutonium-239, plutonium-242 has a much smaller fission cross-section and is therefore not a nuclear yield danger.) To study the behavior of plutonium and effects of plutonium aging on the implosion process warhead designers conduct subcritical tests. Subcritical tests utilize plutonium but are designed in such a way as to preclude a nuclear yield.

[28] "Nonnuclear Testing at the Test Site since December 1995," *Atompressa* (Elektrostal), 32, September 1999, p. 3.

[29] At a tritium content of three grams per warhead, 15 kilograms (kg) tritium would be required for a 5,000-warhead arsenal. (Additional amounts of tritium would be required to accommodate production pipeline requirements.) To compensate for the radioactive decay, approximately 0.8 kg tritium would have to be produced every year. The capacity of the Chelyabinsk-65 reactors is classified but some experts believe that it is approximately 1,000 megawatt thermal. (Thomas Cochran, Robert S. Norris and Oleg Bukharin, *Making the Russian Bomb: From Stalin to Yeltsin* [Boulder: Westview Press, 1995], p. 79.) At 80 percent of capacity one 1,000 Megawatt thermal reactor is capable of producing 3.4 kg tritium per year.

[30] Plutonium-241 comprises tenths of a percent of weight of the weapon-grade plutonium and decays with a half-life of 14.3 years.

[31] In the pit manufacturing process plutonium is reduced to metal, alloyed with gallium or other phase-stabilizing material, and cast into blanks that are formed into pit shapes (e.g., hemispheres).

[32] In the United States, pit remanufacturing and americium-241 removal activities took place at the Rocky Flats Plant near Denver, Colorado until the operation was shutdown for environmental and safety reasons in 1989.

[33] Medium-term remanufacturing requirements (including during the transition to warheads with longer service lives) would depend on the mix and age of weapons in the existing stockpile and could be relatively high.

[34] "Problems of Safety and Security of Russian Nuclear Weapons," *Voennyy Vestnik*, No. 7, 1993, pp. 62-76.

[35] Zavalishin, *"Avangard" Atomic,* p. 86.

[36] Dyakov "Nuclear Arms Reductions and Transparency," pp. 37-42.

[37] These two future phases of downsizing are proposed by the author and not by Minatom.

[38] Instead, they provide uranium enrichment and spent fuel management services to domestic and foreign customers and are involved in a variety of other nuclear and non-nuclear commercial activities. All of these facilities, with the exception of the plutonium production center in Krasnoyarsk-26, are also involved in the HEU downblending work under the 1993 U.S.-Russian HEU agreement.

[39] Remarks by Minatom's Deputy Minister Lev Ryabev at the 7th Carnegie Endowment Nonproliferation Conference, Washington, D.C., January 11-13, 1999.

[40] "Trekhgorny's Plans," *Atompressa* (Elektrostal), 13 (344) April 1999, p. 3.

[41] S. Sachkova "Hopes of Defense Workers," *Atompressa* (Elektrostal), No. 46 (377), December 1999, p. 3.

[42] See, for example, "Conversion: Interview with A. Antonov," *Atompressa* (Elektrostal), No. 1 (378) January 2000, pp. 1-2.

[43] A. Gorb "PO 'Sever' in the Program of Restructuring and Conversion of the Nuclear Industry," *Atompressa* (Elektrostal), No. 1 (378) January 2000, p. 3.

[44] The assembly of the last warhead at the Avangard Plant was finished on December 30, 1997. Yu. Zavalishin *"Avangard" Atomic* (Krasny Oktyabr': Saransk, 1999), p. 292.

[45] L. Saratova "How do You Live, Weapons Plant?," *Gorodskoy kuryer* (Sarov), No. 3, January 23, 1999.

[46] "We Must Save the Best (Press-Conference with L. Ryabev)," *Gorodskoy kuryer* (Sarov), March 5, 1998.

[47] *Russian Federal Nuclear Center All-Russian NII of Technical Physics: Scientific and Information Review* (Snezhinsk: RFYaTs-VNIITF, 1998).

[48] Downsizing projections for the nuclear weapons workforce, efforts by Minatom and closed nuclear cities to redirect excess workers on a city-by-city basis, and possible strategies for addressing this problem are discussed in Bukharin, von Hippel, and Weiner, *Conversion and Job Creation in Russia's Closed Nuclear Cities*.

[49] According to Russian law, closed nuclear cities retain regional and federal taxes they collect. Until recently, the closed cities were allowed to provide significant tax benefits to businesses that were registered but often were not physically located in the cities. Most of the funds for job creation efforts by the administrations of the closed nuclear cities outside of nuclear facilities were supported by tax contributions from such off-shore businesses.