As Russia's economy deteriorates, the danger grows that the country's once-privileged nuclear cities will hemorrhage the talent and materials that rogue nations crave for making nuclear bombs

Nuclear Strongholds in Peril

SAROV AND SNEZHINSK, RUSSIA—Vadim Simonenko has the kind of background and experience that make many nuclear weapons experts nervous. He began his career in the 1960s designing atomic explosives for carving out canals and rose through the ranks to become deputy scientific director at the All-Russia Scientific Research Institute for Theoretical Physics (VNIITF)—an elite nuclear weapons design center in Snezhinsk, a closed city set amid a patchwork of lakes and spruce and birch forests east of the Ural Mountains. Simonenko has always enjoyed his work: "My ideas are like a hobby," he says. The problem is that his job now pays like a hobby. Today, Simonenko is scrambling to find money for research and, like his colleagues throughout Russia's vast nuclear research enterprise, he's wondering when he will see his next paycheck.

Simonenko's plight—and that of thousands of other talented Russian nuclear scientists—makes him a prime target for any country wanting to build a nuclear program. His team "is one whose expertise would no doubt be extremely interesting to proliferators," says one U.S. expert. Indeed, at scientific meetings—most recently last July in Italy—Indian and Pakistani scientists have invited Simonenko to visit their countries and give seminars. He turned them down, preferring, he says, to seek collaborations with colleagues in the West. But he acknowledges that, if no Russian or Western organization were to support his work, he would consider other offers. Other suitors, surely, are waiting in the wings. "At nearly every nuclear institute they visit, [U.S. officials] find another recently received Iranian business card," says Matthew Bunn of Harvard's Belfer Center for Science and International Affairs.

Reassuringly, nuclear physicists like Simonenko appear to be resisting these overtures, according to several dozen scientists and government officials interviewed by *Science* during a recent visit behind the barbed wire fences that still surround the country's 10 "nuclear cities." "These people are the real heroes of the story," says Bunn. "It is their devotion to their country and their work that has been the key factor preventing a proliferation catastrophe." But with Russia's economy continuing to erode, lucrative job offers from abroad could become more and more tempting. "There are many countries with a strong proliferation agenda ready and willing to court these nuclear specialists," said U.S. Department of Energy (DOE) Secretary Bill Richardson at a public forum last month to unveil a Nuclear Cities Initiative (NCI) to counteract this threat.

Ominous signs of strain are increasingly evident among the once-elite researchers in these secret cities, the names of which have only recently begun to appear on official maps. Last year, thousands of nuclear workers took to the streets in Snezhinsk and Sarov to protest months of unpaid wages. These nuclear sanctums are bracing for further unrest: Acknowledging that it can no longer maintain its sprawling nuclear weapons complex, Russia's Ministry of Atomic Energy, or Minatom, says that as many as 50,000 of the 130,000 weapons specialists in its nuclear cities may have to find new work in the next several years. And that could be an underestimate. "It could be safely assumed that the nuclear weapons program could be supported by a third of its current staff," says Oleg Bukharin, an authority on Russia's nuclear cities at the Center for Energy and Environmental Studies at Princeton University.

Hoping to prevent a massive nuclear brain drain, Minatom and DOE are teaming up to launch the NCI, a $15 million program to create thousands of jobs in Russia's nuclear cities (see sidebar on p. 160). The goal is not just to keep knowledge behind the barbed wire: In facilities scattered across the former Soviet Union lie enough weapons-grade materials to produce 40,000 nuclear bombs, DOE estimates. "The challenges are absolutely incredible," says NCI director William Desmond, whose daunting task is to convince U.S. companies to invest in cities barely acquainted with the free-market reforms that have transformed Moscow and other major Russian cities.

Nuclear proliferation. During the Cold War, the Soviet Union established this far-flung network of secret nuclear cities.

SOURCE: DOE

The stakes are enormous. "Six years of steady improvement in the security of Russia's nuclear stockpile threatens to unravel under the crushing blow of that country's current economic crisis," says Kenneth Luongo, director of the Russian-American Nuclear Security Advisory Council. "Not since the collapse of the old Soviet Union has the situation been so dire."

A tale of two cities

For researchers like Simonenko, today's hardships are a cruel contrast to the Cold

War era, when the Soviet government poured vast resources into the nation's efforts to match the United States' nuclear might. Within weeks after the obliteration of Nagasaki and Hiroshima, a team led by Igor Kurchatov, the father of the Soviet nuclear program, began scouting for a location for a supersecret nuclear weapons design center. His group eventually settled on a village called Sarov, revered for its mineral waters and for a monastery established in 1706 and dedicated later to St. Seraphim. The area, just 410 kilometers by rail from Moscow, was sparsely populated.

Barbed wire with a view. Security forces patrol Sinara lake, seen at top, to prevent uninvited guests from snorkeling to Snezhinsk.

In winter 1946, Kurchatov ordered 10 physicists working at two Moscow institutes—Laboratory Number Two, a nuclear research center formed in 1939 that now bears Kurchatov's name, and the Institute of Chemical Physics—to relocate to Sarov. They were assigned to KB-11, the designation for the budding nuclear design center, now called the All-Russia Scientific Research Institute for Experimental Physics (VNIIEF). Sarov disappeared from public maps, even as devout Russians were still flocking to the monastery. "Pilgrims would come and gather outside the barbed wire fence" erected around the town, says Dimitrii Sladkov, a towering young man who, although he dresses in black and wears a long black beard like a Russian Orthodox priest, is assistant director in the nuclear center's information office. Sladkov, a student of Sarov's history, says that to deter pilgrims from wasting their time—and prying into its affairs—the center blew up the monastery's two cathedrals in the early 1950s. All that remains today is the monastery's campanile, the symbol of Sarov.

The physicists who came to live in Sarov—renamed Arzamas-16, a so-called mailbox linked to the city of Arzamas 35 kilometers to the north—were soon joined by hundreds of new recruits, as Arzamas-16 officials scoured the universities for the best young minds. One was Yuri Trutnev, a physical chemist who graduated from Leningrad State University in 1950. "When I was chosen to work here, I was told only that I would work in Middle Russia," he says. "I was told I would have a chance to work with the best scientists." When Trutnev arrived in February 1951, he reported to a division headed by the great physicist Yakov Zel'dovich. "Only when I opened the first report did I understand where I had got to and what I would do. It was a project related to the development of thermonuclear weapons." Much decorated for his scientific achievements, Trutnev was part of the team that designed the Soviet Union's first hydrogen bomb, detonated in Kazakhstan in August 1953—just 4 years after the Soviet Union tested its first atomic bomb, modeled on a U.S. device.

Such work called for the utmost secrecy, and Arzamas-16 was like a prison, a city surrounded by a double barbed wire fence and guarded by armed troops, with entry and exit restricted by the KGB. The city experienced nearly total physical isolation. "The only thing we got from outside Sarov was the fissile materials," says Trutnev, referring to the uranium and plutonium that were purified in other closed cities. "Everything else was produced onsite," including necessities like food and clothing. For the first 5 years of the center's existence, most staff members were not even permitted to leave the city. "When I tried to go on vacation in 1952, my bosses sent me from one boss to another. They tried to make you spend vacations here at the center," says Trutnev. The center paid a sizable bonus—50% of one's monthly salary—to those who complied.

As the nuclear arms race gathered steam in the mid-1950s, Soviet officials felt vulnerable having most of their nuclear weapons scientists concentrated in a single locale. In September 1955, they fissioned the nuclear weapons team at Arzamas-16, sending 40 theoretical physicists and mathematicians, followed in 1957 by a second wave of 370 designers and technicians, to a city newly carved from a spruce forest on a lake about 1400 kilometers southeast of Moscow. This was Chelyabinsk-70, now renamed Snezhinsk, or snowflake—so remote that even now, a lonely shishkabob hut is about the only landmark on the road connecting it to Ekaterinburg, 100 kilometers to the north.

A bomb only a father could love. American H-bomb inventor Edward Teller poses next to copy of 50-megaton bomb during 1994 visit to Snezhinsk.

Chelyabinsk-70 officials also went on a recruiting drive. Among those they pursued was Vladislav Nikitin, a student in the nuclear physics department at Moscow State University. In 1958, the Ministry of Medium Machine Building, the murky name of the Soviet nuclear weapons bureaucracy, "offered me a job in a Siberian plant or in a premier research institute in the Urals," says Nikitin, now deputy director for human resources at VNIITF—not much of a choice. "The manager had a ready-made document—they knew my decision," he says. He did not come to regret it. "We never had a moral problem with what we were doing," he says. "It was a sacred thing."

For 4 decades the two centers competed with each other to draft new designs for the Soviet arsenal, with resources unequaled in other research institutes across the country. The insanity may have peaked in 1961, around the time of the Cuban missile crisis. That's when Arzamas-16 tested a 50-megaton bomb, which released 20 times as much energy as all the bombs in World War II combined. Tested at the Novaya Zemlya site above the Arctic Circle, the bomb's mushroom cloud billowed 20 kilometers wide and the flash was seen for thousands of kilometers; the shock wave circled the globe three times. "It was developed for political reasons, not strategic," says Nikitin.

Both centers also branched out into nonmilitary uses of nuclear explosives, setting off a total of 156 "peaceful" detonations. Trutnev and his colleagues, for instance, developed a charge that would

CREDITS: VNIITF

U.S. and Russia Join Forces in High-Stakes Job Hunt

Russia's nuclear cities, which flourished during the Cold War as secretive, privileged wards of the Soviet state, might seem an unlikely place for private enterprise. But the cities are rich lodes of high technology, and they have tens of thousands of nuclear weapons experts who might be lured away by would-be nuclear powers as jobs there dwindle. So this year, the U.S.–Russian Nuclear Cities Initiative (NCI) is taking on the task of persuading U.S. companies and others to invest in new ventures in Russia's once-secret nuclear weapons centers.

Russia's Ministry of Atomic Energy (Minatom) says that as many as 50,000 nuclear weapons experts will need new jobs over the next several years—a formidable task in the wake of Russia's sharp economic downturn since last August. The crisis has raised new proliferation concerns (see main text), instilling a sense of urgency in the fledgling program. "Quick successes are important," says NCI director William Desmond. "But we have to be careful in our hurried pace" to create lasting jobs.

The U.S. Department of Energy (DOE) and Minatom had been kicking around the idea for such an initiative "at very high levels" for months, says a DOE official, before Vice President Al Gore and former Russian Prime Minister Sergei Kiriyenko announced NCI last July. The venture will spend $15 million this year to try to stimulate job creation in Snezhinsk, Sarov, and Zheleznogorsk, a center for processing weapons-grade plutonium. It will complement another DOE effort, the Initiatives for Proliferation Prevention (IPP), which will also spend $15 million in the nuclear cities this year, part of its broader portfolio for supporting former Soviet nuclear, chemical, and biological weapons scientists. Whereas IPP essentially serves as a matchmaker, hooking up Russian ventures with U.S. national labs and companies, NCI also hopes to nurture telecommunications and other infrastructure in the nuclear cities needed for businesses to grow, leveraging its resources with those of industry and other players. "We would like to create one major business activity" by the end of this year that provides at least 200 jobs in each city, says Desmond, who also oversees IPP. Officials plan to expand the NCI, expected to last up to 7 years, to as many as seven more cities in 2000 and beyond (see map, p. 158).

One of the biggest challenges for NCI managers will be to infuse a market-driven culture in the nuclear cities. "As a rule, scientists are poor businessmen," says Snezhinsk's Vladimir Lykov, who leads a picosecond laser project with much commercial promise but who is struggling to devise a business plan. One hurdle that he and others say they face is the security in the cities, which limit visits and communication. "We have a hard time making business contacts," says Dmitrii Sladkov of the nuclear center in Sarov, in which visitors must be escorted constantly by security personnel. "It's a major problem."

The initiative hopes to build on some small steps the cities have already taken on their own. For instance, Sarov managers and nuclear center officials a couple of years ago set up a development fund strictly for civilian enterprises; it has provided seed money for about 30 businesses so far. The fund has raised $10 million toward an ambitious goal of $300 million, and it has asked NCI to chip in, a request DOE is considering.

The first NCI efforts, which could get off the ground as early as next month, would establish business centers in each city—places where Russian and Western firms could hold meetings and have free access to e-mail and telephone lines, commodities that are now tightly controlled by the nuclear centers. "In terms of real job creation—that's going to take some time," says a DOE official. One promising venture is an IPP-funded silicon wafer production plant in Zheleznogorsk. That's a "showcase model we hope to extend," says Desmond.

To sweeten the deal for industry, Russia has pledged to "take all necessary measures" to exempt from customs duties and taxes any equipment, supplies, and services provided under the initiative, according to an agreement signed by the two governments last September. Still, Desmond acknowledges, "this will always be a risky activity for U.S. businesses." Industry officials agree, saying they are intrigued but not yet sold. "We know very little about these cities," says a scientist with Westinghouse Energy Systems. "We need to know more for industry to support this." Russia has also said it will invest money of its own in the program, says Rose Gottemoeller, director of DOE's Office of Nonproliferation and National Security. But because of the economic crisis, she says, "we have to take that with a bit of a grain of salt."

More than just the future of the nuclear cities is at stake in the effort, says Desmond. "This is not an American solution to a Russian problem." NCI's main measure of success, he says, will be how it benefits the United States: "We believe we will be successful if we have contributed to our national security." –R.S.

Here to stay. NCI hopes to find work for nuclear weapons experts, including future residents of this apartment building rising in Snezhinsk.

consume most of its radioactive byproducts during the explosion. They placed it 90 meters under a river in Kazakhstan and blew open a huge trench that filled with water. "In a year or two, we could swim and fish there," says Trutnev, who at 71 seems no worse for the experience.

Not to be outdone, Chelyabinsk-70 devised nuclear charges for extinguishing oil fires, blasting ore deposits, and mapping the Earth. In the 1970s, a team led by scientists from Chelyabinsk-70 divided Siberia into a 500-square grid, intending to explode charges at each grid point to discern the rock types in the crust, a project that was halted after 100 explosions. Russia performed its last nuclear test in 1990; the Comprehensive Nuclear Test Ban Treaty, signed by Russia in 1996 although not yet ratified by the Russian parliament or the U.S. Senate, would outlaw any further explosions. The treaty also marked the end of an era in which Russia held its nuclear scientists in high esteem. "The social environment in the country is changing rapidly," says Nikitin, who is openly nostalgic for the days when he and his colleagues could con-

CREDIT: (RIGHT) R. STONE

duct peaceful nuclear explosions. "The image of nuclear physics here has gone from very well respected to a kind of monster."

Opening up to the world

The weapons scientists' fall from grace began long before the test ban treaty finally brought an end to the ultimate demonstration of their handiwork. The end of the Cold War and the collapse of the Soviet Union suddenly eliminated the nuclear cities' main raison d'être. Like their counterparts in the U.S. weapons labs, Russian nuclear scientists were suddenly faced with a new mission: Instead of the cat-and-mouse game of nuclear deterrence, their main goal became ensuring the reliability and safety of existing weapons. But unlike their U.S. counterparts, they were forced to take on this role with limited resources, in a country in economic turmoil. Says VNIITF scientific director Evgeny Avrorin, "Nuclear weapons are not on the list of priorities in Russia now."

As the labs were trying to adjust to the new era, Russians everywhere were coping with the harsh realities of life after communism: bread lines and poverty after the ruble's value plummeted in 1991 and 1992. The nuclear cities weathered the crisis reasonably well, at first. "There was no affluence as you would see on Malibu beach, but they were doing OK," says John Shaner, head of the Center for International Security Affairs at Los Alamos, who has visited Sarov and Snezhinsk several times since 1992.

As conditions in the nuclear cities began to deteriorate, Western analysts began sounding the alarm about a potential nuclear brain drain. The Russian side fueled those fears: In 1992, for example, the Kurchatov Institute acknowledged that Libya had offered two of its scientists $2000 a month to work at its Tajura Nuclear Center, which the Soviet Union had helped Libya build a decade earlier. Minatom added to Western concerns in the early 1990s when it founded Chetek Corp., a company composed of scientists from the nuclear cities that offered to conduct nuclear explosions in other countries for, among other things, incinerating chemical weapons stocks. Although Chetek disappeared about 4 years ago—a Minatom spokesperson claimed to *Science* that he has never even heard of the firm—its formation underlined fears that a proliferation threat was emerging from the post-Soviet turmoil.

The response from the West was a series of initiatives designed to help Russian weapons scientists make the difficult transition into civilian research. First off the mark in the United States was DOE, which runs the United States' own nuclear labs.

Genius in residence. The Sarov home of Andrei Sakharov, whose pioneering work on magnetic fields was the basis for U.S.–Russian nuclear physics rapprochement.

Even before the collapse of the Soviet Union, U.S. weapons scientists had begun to reach out to their former Cold War adversaries. In 1988, U.S. and Soviet weapons experts performed joint underground nuclear explosions at the Nevada Test Site and at Semipalatinsk, Kazakhstan; the aim was to develop improved techniques for monitoring each country's nuclear tests. These early meetings triggered a delicate pas de deux between the weapons labs that resulted in a groundbreaking event in 1992, just months after the Soviet Union dissolved. That February, the directors of the Los Alamos and Lawrence Livermore national labs visited Arzamas-16 and Chelyabinsk-70—cities off limits even to most Russian citizens (*Science*, 28 April 1995, p. 488). "The lack of trust quickly evaporated," recalls Avrorin, who last month stepped down as VNIITF director. "We did not find James Bond among the Americans, and they did not find horned devils among our side."

Lifetime in "Middle Russia." Yuri Trutnev says he didn't know he would be on a team designing the Soviet H-bomb until after he arrived in Sarov.

The visit sparked an ongoing series of experiments between the weapons scientists, called the lab-to-lab program, that began with studies on high-energy magnetic fields—an area pioneered by weapons scientist–turned-dissident Andrei Sakharov—and has since branched off into disciplines as diverse as systems for accounting for nuclear materials and environmental remediation. The collaborations "are an important confidence-building measure that allows U.S. and Russian scientists to get to know one another and understand each other's facilities," says Scott Parrish, a policy analyst with the Center for Nonproliferation Studies (CNS) at the Monterey Institute of International Studies.

Both sides have had to tiptoe around certain projects that straddle the border between open and classified research, however. Particularly touchy is work on ISKRA-5 at VNIIEF, the second most powerful laser in the world after Livermore's NOVA. Both lasers are designed to test the feasibility of using inertial confinement fusion as an energy source, and both are also used to study deuterium-tritium implosions and other phenomena that could yield knowledge useful for modeling nuclear weapons. "We have contacts with Livermore, we exchange experimental results, but we haven't had any joint experiments. The work at these facilities is in a so-called sensitive area," says project scientist Sergei Garanin. "Both sides have national security issues, secrets that should not be shared," adds Nikitin.

VNIIEF's ambitions for the pricey laser facility suggest that the government, at least on paper, is willing to commit major funding to maintaining stockpile reliability. To keep up with Livermore, which is building its next-generation laser, the National Ignition Facility (NIF), VNIIEF is laying the groundwork for ISKRA-6, a niobium-based laser. VNIIEF hopes to have ISKRA-6's first module, dubbed Luch (Russian for beamlet, named after NIF's Beamlet module), up and running by 2001, says Garanin, "if the financial crisis doesn't postpone it." Indeed, Western experts are skeptical that Russia will ever come up with the $300 million needed to build the rest of ISKRA-6.

While the informal lab-to-lab collaborations were taking shape, the United States, the European Union, Japan, and Russia banded together in November 1992 to create the most ambitious effort so far to provide a lifeline to weapons scientists: the International Science and Technology Center (ISTC). The center has committed $190 million to projects employing 21,000 weapons experts across the former Soviet Union. About 17% of that sum has gone to Sarov and Snezhinsk. "Nobody has become rich thanks to ISTC," says theoretical physicist Boris Vodolaga, deputy director for international collaboration and conversion at VNIITF, "but clothing for children and medicines have been purchased with ISTC money."

Some scientists don't like to imagine their lives today if the ISTC hadn't come to

CREDITS: R. STONE

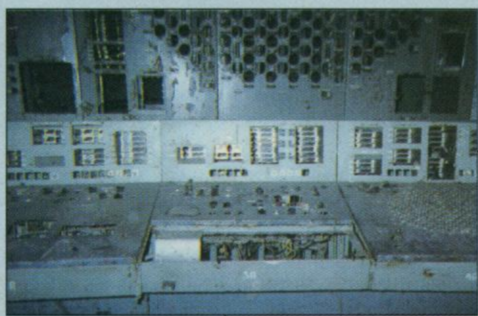
Keeping a Wary Eye on Chornobyl's Unsettled Remains

CHORNOBYL, UKRAINE—The downpour on 27 June 1990 came as a welcome gift for Ukrainian farmers toiling in their last summer under Soviet rule, but it triggered alarm bells here at the infamous Chornobyl* Nuclear Power Plant, the scene 4 years earlier of the world's worst nuclear accident. Deep in the bowels of the burned-out reactor number 4 building, in a room filled with a jumble of uranium fuel and building materials, detectors vigilant for signs of fissioning atoms started screaming. Within hours, neutron counts in room 304/3 had soared from 2.5 to 156 counts per second. Chornobyl scientists feared that rainwater leaking into the ruined reactor was slowing neutrons emitted by the fuel, leading to a self-sustained fission reaction marked by a telltale surge in neutrons. A physicist dashed into 304/3, risking his life to dump neutron-quenching gadolinium nitrate on the seething mass.

That brave deed ended the immediate crisis, for neutron counts ebbed over the next few days. But the drama that June and several later flare-ups following rainstorms have left an enduring mystery for nuclear physicists: How big is the threat posed by the tons of uranium fuel scattered through the damaged reactor building? Among those trying to answer this question have been researchers from Russia's closed nuclear cities, aided by Western funds (see main text). New data presented at a recent conference† suggest the odds of a second explosion are small. But researchers are continuing to monitor the situation: Western experts recently installed new devices for watching the scary chemistry.

A crack team of Soviet nuclear physicists, many of whom were drawn from the nuclear cities, was dispatched to Chornobyl immediately after the explosion and subsequent fire on 26 April 1986. Their first task was to advise a military effort to gather radioactive debris into several hundred dumps near the plant and to build a massive concrete sarcophagus over the destroyed reactor hall. The scientists took some unusual precautions. "When we worked in very high radiation areas, we were told to take 50 grams of spirits beforehand" to supposedly fortify the body against radiation damage, says Lev Belovodsky of the All-Russia Scientific Research Institute for Experimental Physics (VNIIEF) in Sarov, who was in charge of measuring the radiation doses of people who built the sarcophagus. "But in the spirit of our country, we added a half-liter."

VNIIEF scientists have since played a prominent role in tracing the steps that led to the explosion. "We have always been involved with the risks of transient nuclear processes," explains Vyatcheslav Solovyev, deputy head of the theoretical division at VNIIEF. The weaponeers soon spotted a glaring deficiency: "We found that there was a lack of computer codes in our country and abroad to predict this kind of accident." Over the past decade Solovyev and his colleagues have developed computer programs for analyzing conditions inside RBMK-class reactors like the one that blew up at Chornobyl, which are still operating at several other power stations across the former Soviet Union.



Grim vigil. Researchers have lowered the odds of a nuclear explosion occurring inside the Chornobyl sarcophagus; the 1986 catastrophe started at this control panel (*inset*).

Researchers from the nuclear weapons complex have also helped gauge the threat lurking in the sarcophagus. Recent estimates suggest that about 170 tons, or 90% of the original uranium dioxide, flowed as lava into the warren of rooms beneath the reactor hall. Along the way it mixed with tons of building metal and concrete as well as sand, boron, and other materials dumped from helicopters after the explosion in an effort to quench the smoldering fuel. The lava solidified into a unique mineral, in its crude form called fuel containing masses (FCMs). "Its structure is very complicated," says Solovyev.

At the conference, researchers downplayed the risk that the fuel will go critical. After analyzing sketchy data on the distribution of FCMs and neutron moderators such as water and graphite, Leo LeSage and Ronald Turski of Argonne National Laboratory concluded that the FCMs can barely sustain a fission reaction, even under the most favorable conditions. "You can't rule out [an explosion], but it's very remote," says LeSage. However, longtime Chornobyl researcher Alexander Borovoi of Moscow's Kurchatov Institute points to a new threat: The gadolinium nitrate dumped in the sarcophagus has begun to disassociate. Free gadolinium slows neutrons and could foster a chain reaction. "Thus, instead of a nuclear safety provision as an absorber it becomes a nuclear hazard," he says.

Some experts contend that high neutron counts like the June 1990 surge were red herrings that may have resulted from moisture-sensitive detectors. "I don't believe there are any oscillations in neutrons, simply false signals," says Belovodsky. Technicians at the sarcophagus last month installed a series of new boron trifluoride–based neutron and gamma ray detectors, designed by a team at the Pacific Northwest National Laboratory (PNNL). The arrays should eliminate spurious neutron counts if the detectors are more sensitive when wet, says George Vargo of PNNL's International Nuclear Safety Program.

Everyone agrees that finding a way to prevent water from accumulating in the sarcophagus would remove any criticality threat; Chornobyl management has plugged holes in the leaky sarcophagus, but an estimated 1000 cubic meters of water still finds its way inside each year, much of it during the spring melt.

As fears of a second explosion ease, the debate is heating up over the long-term fate of the sarcophagus. Ukrainian officials want to remove the FCMs and bury them elsewhere, but for now such a strategy is too dangerous, says PNNL's Roger Anderson: "It could expose workers to lots of radiation." In Belovodsky's view, "The best and cheapest solution is to fill the sarcophagus with concrete and make it a grave forever." **–R.S.**

* New spelling adapted from Ukrainian. † International Cooperation for Chornobyl, 13–16 October 1998, Slavutych, Ukraine.

CREDITS: R. STONE

the rescue. "The ISTC project changed my life," says Sergey Shumsky, a senior research fellow at the Lebedev Physics Institute in Moscow. Shumsky, a former plasma physicist, is part of a team led by Serge Terekhov at Snezhinsk that 3 years ago won a $600,000 ISTC grant to design neural nets for doing everything from searching the Internet to discerning explosions from both nuclear devices and natural events such as earthquakes and meteoroid strikes. Their computer program for analyzing seismic data is so precise, he claims, that "one can even locate the mine shaft where an explosion took place." The team is now negotiating licensing deals with Russian companies. Snezhinsk is also doing environmental studies, including a highly regarded ISTC-sponsored project to reconstruct events surrounding an explosion 40 years ago at a nuclear waste facility, which blanketed a nearby swath of land with radioactive isotopes (see sidebar on p. 164).

But Terekhov and other researchers, particularly in Snezhinsk, express a growing disenchantment with ISTC. The center "just does nothing to promote commercialization of projects and their outcomes," says Yury Lazarev, who managed a project completed a year ago that laid the theoretical groundwork for a microwave laser capable of delivering short, intense pulses. Instead of funding projects for 2 years or so, Vodolaga argues, ISTC should provide long-term support for worthy projects, shepherding them to the market. ISTC deputy executive director Sergey Zykov says, however, that such an approach would limit the number of people his organization could help.

Indeed, neither of the two heavyweight programs aiding weapons scientists—ISTC and DOE's Initiatives for Proliferation Prevention—"has yet succeeded in fostering the establishment of a single self-sustaining commercial enterprise employing a significant number of people in a nuclear city," a group led by Princeton nonproliferation guru Frank von Hippel points out in the September/October 1998 issue of *The Bulletin of the Atomic Scientists*. All of this has heaped a heavier burden on the newly formed NCI, which will focus exclusively on creating jobs in the cities that support the nuclear institutes.

What will tomorrow bring?

If any one event captured the new, darkening mood in the nuclear cities, it was the tragic death 2 years ago of VNIITF director Vladimir Nechai. In October 1996, as winter was approaching, Nechai had no money to pay salaries for his 10,500 employees. Almost 2 months earlier, he had written to then–Prime Minister Viktor Chernomyrdin and to the head of Minatom, decrying the $20 million debt the government owed VNIITF. His letter produced a response: In late October, Minatom transferred enough money to VNIITF's bank account to pay pensions and salaries. But, according to a Minatom spokesperson, the institute's account had been frozen temporarily because it had not paid its utility bills, and it could not withdraw the money right away. On 31 October Nechai shot and killed himself. "It was quite a shock," says Shumsky. "Most people respected him; he was young and energetic."

The funeral the next day drew thousands of mourners, but the Kremlin appeared to pay little attention: No government officials showed up for the event. Prominent Russian politician Grigory Yavlinsky, leader of the opposition Yabloko Party, noted that fact in an editorial in *The New York Times*. "Nechai sacrificed his life to call attention to the plight of Russian science," Yavlinsky wrote. "And he was not heard."

MAJOR PROGRAMS THAT SUPPORT FORMER SOVIET WEAPONS SCIENTISTS

Program	Start date	Funds to date (millions $)	Projects	Scientists
International Science and Technology Center (ISTC)	1994	190	654	21,000
Initiatives for Proliferation Prevention (IPP)	1994	114	400	4,400
Civilian Research and Development Foundation (CRDF)	1995	39	682	3,500
Nuclear Cities Initiative (NCI)	1999	15	–	–

A different kind of tragedy shook Sarov 8 months later. Alexander Zakharov, a 45-year-old senior scientist at VNIIEF, was working alone on a secret experiment with what institute officials refer to only as a bench-top "critical assembly." Zakharov was holding the assembly in his hands when it suddenly "began to work," says VNIIEF's Sladkov, drenching Zakharov in an estimated 600 rems of radiation—thousands of times the dose most people receive in an entire year. "He immediately understood what happened," says Sladkov. "He knew he was severely damaged and was becoming very sick." Zakharov was flown to Moscow for treatment but died 2 days later. A Minatom investigation, which included interviews with Zakharov on his deathbed, concluded that the researcher had turned off safety features that would have prevented the accident. VNIIEF staff accept the finding that Zakharov was to blame, but they say the incident added to the malaise in Sarov. "It caused a lot of heartache in the town and at the institute," says Sladkov.

Since those twin tragedies, researchers in both nuclear cities have become increasingly outspoken in demanding better conditions. Last July, 3500 VNIIEF staff members went on an unprecedented daylong strike; in November, 3000 of their colleagues in Snezhinsk followed suit. "Life has become more full with hardships and an absence of confidence in the future," says Avrorin, who resumed his previous post as VNIITF's scientific director last month when theoretical physicist Georgy Rykovanov became the institute's new director.

Western experts say they know little about the ongoing classified research in the nuclear cities and how it fits with Russia's emerging stockpile stewardship program. "We do know that people are still computing and explosive shots get fired; experiments are going on at Novaya Zemlya, even if we do not know exactly what they are doing," says Los Alamos's Shaner. "We can guess that their computations are not going on anything like the teraflop machines coming online at the U.S. labs. They are certainly trying to develop some kind of stockpile stewardship program, but we do not know a lot of details about it."

But even for those scientists still working on weapons research, life has changed. One major handicap is a lack of current journals; VNIITF now can only manage subscriptions to a few major ones. "We have a constant feeling of information hunger," says Vladimir Ananiychuk, head of VNIITF's information department. And like their colleagues throughout the rest of Russia, many scientists in the nuclear cities—particularly those not on Western grants—have less time for research because they supplement their income by working second and third jobs. One scientist in Snezhinsk manages the local department store; another in Sarov has started a company that makes margarine.

If many nuclear scientists were to lose their jobs and find themselves in dire straits, says Vodolaga, "nobody can guarantee that won't be used as a lever by terrorists, who would be willing to avail themselves of the experts here." He points out, however, that the institute has locked up the foreign passports of scientists privy to state secrets and "will never authorize a trip" to Libya or other countries deemed a proliferation threat.

Another sobering restraint that may be keeping nuclear scientists in Russia is fear

Retracing Mayak's Radioactive Cloud

The yellow smoke pouring out the doors of the radioactive waste storage building at the Mayak Production Association that cloudy fall day was an ominous sign. Two workers were dispatched to investigate what had gone awry inside a concrete bunker used to store radioactively contaminated liquids, byproducts of processing plutonium for weapons. The duo donned gas masks and descended into the crypt, where they were met by a blast of heat. Unable to see anything in the smoky corridor, they switched on a fan and left.

Lucky for them. A few minutes later, at 4:20 p.m. on Sunday, 29 September 1957, a gigantic explosion ripped through the radwaste pit, the report reverberating all the way to Chelyabinsk-40, a closed nuclear city some 10 kilometers away. At the storage facility, the workers—amazingly, all of them escaped injury—watched as billowing dust clouds blotted out the fading daylight. That night the clouds glimmered crimson; residents of an open city 70 km to the south thought they were watching the northern lights. Little did they know that radioactive fallout was settling over a 400-km-long swath of land.

Ill winds. Map depicts spread of strontium-90 (curies per km^2); the contamination missed major cities to the north and south of Mayak, but blighted several villages.

That chilling account was pieced together from public sources and Mayak archives by Mikhail Avramenko, a nuclear physicist at the All-Russia Scientific Research Institute for Theoretical Physics in Snezhinsk, some 40 km north of the accident scene. Avramenko compiled this picture—parts of which he has submitted to the journal *Atmospheric Environment*—in an effort, sponsored by the International Science and Technology Center, to devise computer programs for modeling the fate of radionuclides released into the atmosphere. The simulations, which model how weather conditions, air currents, and other factors might disperse radioactive particles, are meant to help forecast the consequences of another explosion at any of the several nuclear sites in the Chelyabinsk region (see map on p. 158). "Accidents at these facilities could affect many towns," says Avramenko, who has established a center at Snezhinsk dedicated to such modeling.

The explosion in 1957 dispersed 2 million curies over some 20,000 square km, prompting the evacuation of more than 10,000 people from contaminated villages. Based on Mayak records, Avramenko calculated that the ill-fated 250-cubic-meter storage tank contained about 20 million curies of radioactivity, including such long-lived isotopes as strontium-90, cesium-137, and plutonium. More horrific releases occurred on purpose: From 1949 to 1956, Mayak dumped an estimated 76 million cubic meters of liquid radioactive waste directly into the Techa River. Some 64,000 people who lived downstream are the subjects of a Russian–U.S. effort to reconstruct the doses they absorbed and to study their health effects (*Science*, 24 February 1995, p. 1084).

Avramenko found no evidence to dispute the official explanation for the accident: that a water cooling system had failed, drying out the waste and cooking the precipitated salts until they ignited in a chemical inferno. He estimates that the blast was equivalent to the detonation of 25 tons of TNT, about a third of original estimates. "This study was excellent, with a very sound approach to determining the chemistry, the energy release, and doing some interesting modeling," says Steve Gittomer of Los Alamos National Laboratory. Avramenko hopes his data won't have to be put to a real-life test. "Now we know much more about the process of storage of radioactive waste," he says. But with Russia hard-pressed these days to fund its stockpile stewardship program and maintain its radwaste facilities, observers fear that residents of the Chelyabinsk region may be sitting on a nuclear tinderbox.

–R.S.

for their own lives. The CNS's Parrish says that weapons scientists have told him that colleagues are unwilling to take jobs in such countries "because they fear that they would be killed after finishing whatever work they contracted to carry out in order to keep the program in question a secret." CNS, which keeps a database on nuclear trafficking, has not heard of any cases of Russian nuclear scientists going to rogue nations to work on weapons programs. However, "there is now increasing concern that some Russian scientists could be serving as consultants" via e-mail and other forms of communication, says Parrish. "A large degree of assistance could be rendered in this sort of way without anyone traveling to Iran or Libya."

An even higher security risk may be the young, poorly paid guards who patrol the fences surrounding Snezhinsk and the other nuclear cities, says CNS director William Potter. "They are largely ignorant about proliferation concerns and are exceptionally vulnerable to recruitment by organized crime," he says. Some observers say there is only one foolproof way to bottle up the makings of a bomb. "To ensure that no one in the former Soviet Union could, in any way, provide Iran or Iraq with scientific knowledge would require the reinstitution of many of the hated features of a police state," argues Susan Eisenhower, chair of the Center for Political and Strategic Studies.

Few people want to return to that kind of rule, but one reminder of it—the fences that separate the nuclear cities from the outside world—is likely to persist. About 10 years ago, says Avrorin, Minatom officials began debating whether to take down the perimeter fences but leave up the electrified ones surrounding the fissile materials. At the time, he says, inhabitants had a mixed opinion about whether the fences should stay. They remain in place, and "if a referendum were held today to take them down, I'd predict it would be defeated almost unanimously," says Avrorin. The fences, he says, have shielded the cities from the organized crime that pervades the rest of Russia and have deterred petty thugs: "Nobody is afraid to go outside after dark."

Thus fenced off from the outside world are the ingredients for making nuclear bombs and the chefs that know the recipes. "These people are endearing," says Tom Owens of the U.S. Civilian Research and Development Foundation, a fund that supports R&D collaborations between U.S. scientists and former Soviet weapons scientists. "You have to pinch yourself to remember what they were doing 10 years ago." But what will they be doing 10 years from now?

–RICHARD STONE

SOURCE: VNIITF