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Russian-American Collaborations to Reduce the Nuclear Danger

Number 24 1996

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Russian-American Collaborations to Reduce the Nuclear Danger

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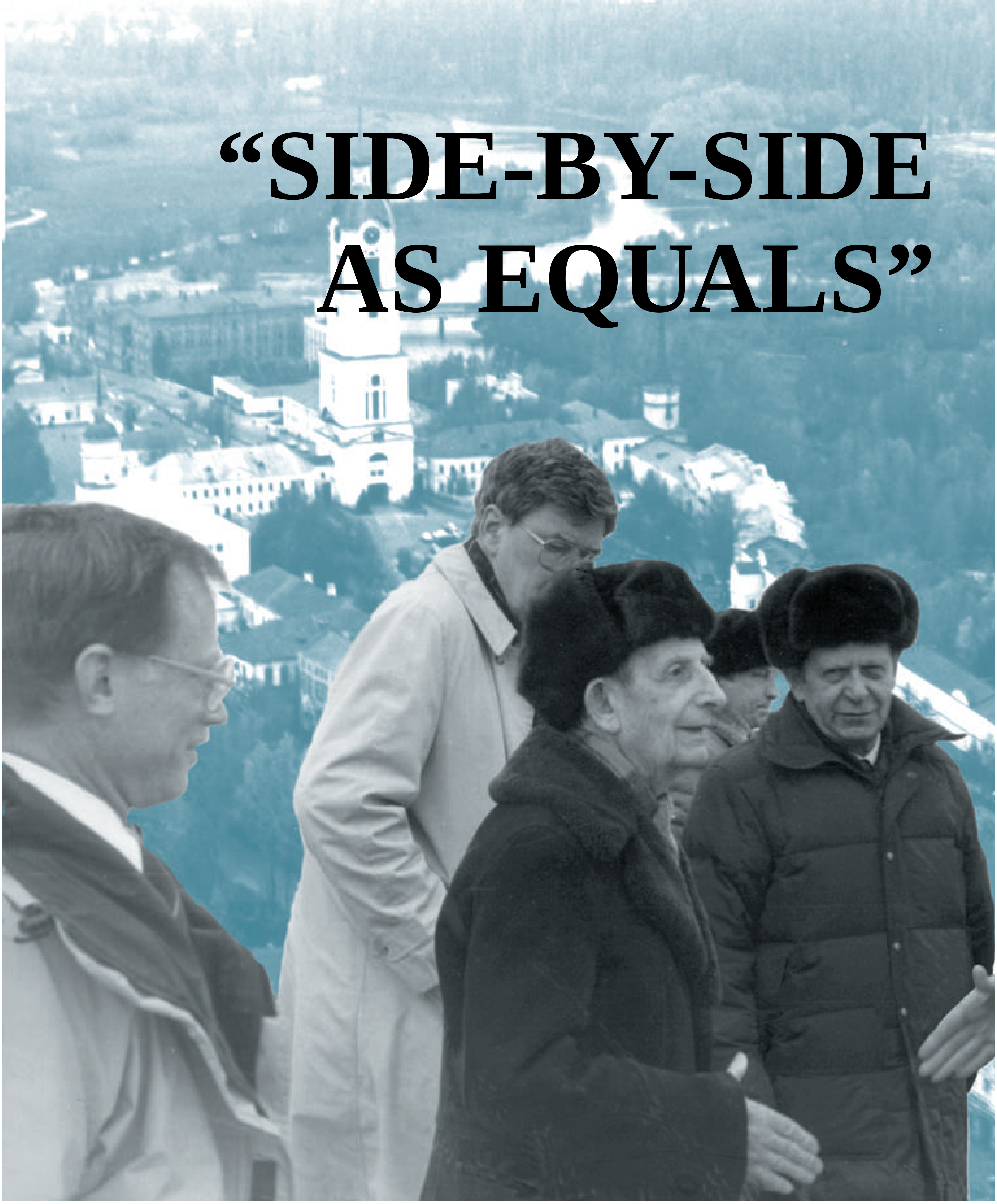
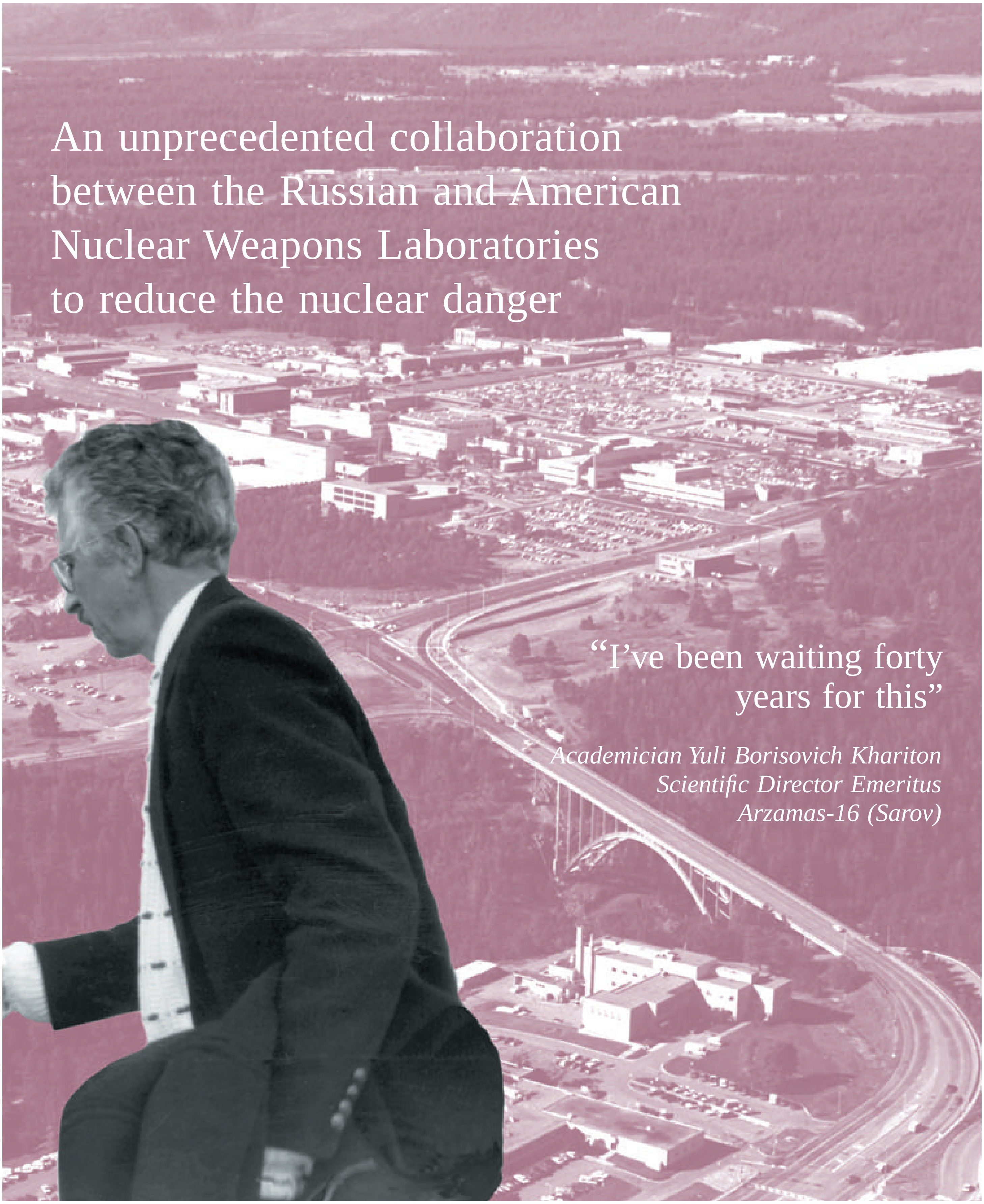
Лэб-ту-Лэб Lab-to-Lab



“SIDE-BY-SIDE AS EQUALS”

An unprecedented collaboration between the Russian and American Nuclear Weapons Laboratories to reduce the nuclear danger



> "I've been waiting forty years for this"
>
> *Academician Yuli Borisovich Khariton*
> *Scientific Director Emeritus*
> *Arzamas-16 (Sarov)*

Memories tend to be short in this rapidly changing world. It has been only four years since the Soviet Union collapsed and separated into independent states. Yet the U.S.-Soviet superpower struggle and the threat of all-out nuclear war are already matters for historical studies. Nuclear weapons stockpiles are being reduced, and the end of the Cold War has enhanced global security. Nevertheless, the collapse of the Soviet Union brought forward new dangers, primary among them being the ultimate fate of the old Soviet nuclear arsenal and the increased threat of nuclear proliferation.

The photo shows the Directors of Los Alamos National Laboratory and Lawrence Livermore National Laboratory being greeted in February 1992 at the airport of the once secret atomic city of Arzamas-16 by leaders of VNIIEF, the All Russian (formerly All Union) Research Institute of Experimental Physics where the first Soviet atomic bomb was built. Front row left to right: Viktor Ivanov, Los Alamos Director Sig Hecker, VNIIEF Director Vladimir Belugin, Livermore Director John Nuckolls, VNIIEF Scientific Director Yuli Khariton, and Academician Alexander Pavlovskii.

Previous two pages: In the foreground, Director Sig Hecker has disembarked at the Arzamas-16 airport and is about to shake hands with Yuli Khariton, the Soviet"Oppenheimer." Shown in the background on the left page is the monastery at Arzamas-16 and on the right page, Los Alamos National Laboratory .

The United States was able to act quickly: To support agreements by Bush and Gorbachev during the fall of 1991 that their respective countries would dismantle a large part of the arsenals of the Cold War, Congress passed legislation to help the Soviet Union destroy nuclear, chemical, and other weapons and establish safeguards against proliferation. Department of Defense (DoD) funds amounting to 400 million dollars per year were redirected into the so-called "Nunn-Lugar" program (named after Senators Sam Nunn and Richard Lugar who initiated the legislation). After the Soviet collapse in December 1991 and in subsequent years, the scope of the Nunn-Lugar program was extended to promote stabilization of defense personnel and, where possible, their conversion to civilian activities. This visionary government initiative under DoD leadership has made significant progress in the destruction of delivery systems and missile silos slated for elimination under the Strategic Arms Reduction Treaty, or START I. However, efforts aimed at stabilizing the people and facilities of the Russian nuclear complex and safeguarding the associated nuclear materials initially proved to be difficult.

In the context of these highly visible efforts, another smaller and quieter effort was proceeding steadily and with remarkable success. Nuclear weapons scientists from Los Alamos and from Arzamas-16 (the birthplace of the Soviet atomic bomb, now called Sarov) began working together on basic science projects almost immediately after the Cold War ended, and the mutual trust and respect gained through that lab-to-lab scientific effort has become a springboard for a larger lab-to-lab effort in nuclear materials control throughout the Russian nuclear complex.

What were the seeds for this unprecedented collaboration, and how did it get official approval? How did it grow into the larger effort in nonproliferation? How are these lab-to-lab efforts affecting the government-to-government efforts started under Nunn-Lugar, and what are the prospects for furthering nonproliferation goals in the future?

We asked Laboratory Director Sig Hecker and other Los Alamos staff involved in the lab-to-lab effort to address those questions. Their experiences of interacting with the Russian nuclear scientists through the remarkable changes of the last decade bear testimony to the power of personal ties and trust in the pursuit of shared interests. These interactions may reflect the universal values of the scientific community and presage the realization of the long-held belief that those values are a key to resolving the most difficult global problems.

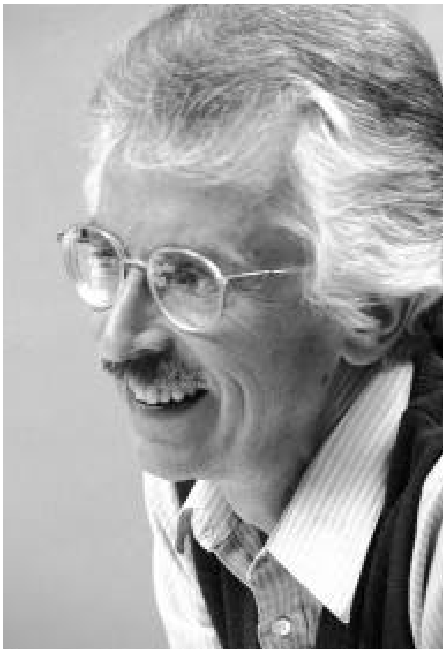
Part I Roots of the Lab-to-Lab Collaboration

The Scientific Roots of the Collaboration

Sig Hecker: Many people have expressed surprise when I tell them of the joint work with our Russian counterparts from the atomic city of Arzamas-16. The fact that we are working not only on peacetime science projects but also on the sensitive issues of nuclear materials control strikes them as even more surprising. I always emphasize that much of our success is due to the trust and personal friendship that we have been able to develop with the Russian nuclear scientists.

Here we’d like to tell the story of how that happened, and to my mind, it starts about ten years ago and has two main threads: One is the work associated with the Joint Verification Experiments, an arms control effort that engaged our nuclear weapons testing experts with their Soviet counterparts in a very close technical working relationship for over two years, and the other is the very significant personal interactions in pure science between people from our nuclear-weapons-design labs and their counterparts in the Soviet Union. John Shaner and Max Fowler of Los Alamos, for example, have been following developments in their fields in the Soviet Union for more than thirty years. I’ll ask John to begin describing those early years.

John Shaner: As early as the late 1950s, Soviets at the nuclear weapons institutes were publishing seminal papers in the open literature in my area of expertise, which is shock-wave and high-pressure physics. Through the 1960s, we got to know each other through publications, we referenced each other’s work, and since we were working on similar problems, we had a pretty good idea of the quality of work on both sides. Although personal contacts with people like Lev Al’tshuler and Rurik Trunin from Arzamas-16, the Russian counterpart to Los Alamos, and Evgenii Avrorin from Chelyabinsk-70, the Russian counterpart to Livermore, did not occur until the 1980s, when they finally happened, it was like meeting old colleagues.


Sig Hecker

> *I always emphasize that much of our success is due to the trust and personal friendship that we have been able to develop with the Russian nuclear scientists.*

Sig Hecker: A particularly important set of meetings were those between Max Fowler and Academician Alexander Pavlovskii of Arzamas-16, one of Andrei Sakharov’s students. Both Max and Pavlovskii were pioneers during the 1960s in the field of explosively-driven pulsed power for the generation of ultra-high magnetic fields. Their interaction provided the initial basis of trust for trying to initiate a lab-to-lab collaboration, and their mutual interest, and that of their junior colleagues, led directly to the work in pulsed power that forms the bulk of lab-to-lab scientific interactions with the nuclear scientists of Arzamas-16. Max, when did it all start?

Max Fowler: I first heard of Alexander Pavlovskii in 1965 in connection with Megagauss-I, the first international conference on using high explosives and magnetic-flux compression to create ultra-high magnetic fields. At Los Alamos, we were interested in using this pulsed-power source to initiate controlled fusion. The Soviet interest was presumably identical. Pavlovskii was an author on four of eight Soviet abstracts submitted to Megagauss-I. We were looking forward to meeting him, but none of those authors were permitted to attend the conference. Supposedly they were from the Kurchatov Institute in Moscow, a civilian institute focussed on nuclear reactors. But at that time, *every* Soviet nuclear scientist had to say he was from Kurchatov. Not until Megagauss-V in 1989, when relationships between the Soviet Union and the United States were thawing, did we learn that Pavlovskii and his colleagues in pulsed power were from a secret city, now known to be Arzamas-16. Sakharov called it “the Installation” in his autobiography, and of course, it is the Soviet nuclear weapons design center where their first atomic and hydrogen bombs were made.

John Shaner: We should remind people that Arzamas-16 and Chelyabinsk-70 were places that weren’t supposed to exist and never appeared on any Soviet maps until after the Cold War.

Los Alamos Science: *Max, when did you first meet Pavlovskii?*

Max Fowler: We had hopes of meeting him, as well as Vladimir Chernyshev, at the second Megagauss conference in Washington, D.C., in 1979. Their papers were actually read at that meeting, but again they were not allowed to attend. So Pavlovskii and I didn't meet until 1982 at a conference at the Lavrentyev Institute of Hydrodynamics in Novosibirsk in Siberia. And it was truly exciting to see each other after knowing for seventeen years that we were working on very similar things. At subsequent conferences, we discussed our work and began to develop a rather strong friendship. He had a tremendous sense of humor, and it was a pleasure to exchange ideas with him even though, or perhaps because, each of us was trying to get information from the other.

Dear Dr. C. M. Fowler.

Owing to circumstances over which I have no control we shouldn't meet at the conference "Megagauss – 5". I feel somewhat unhealthy and doctors don't recommend me to go to Novosibirsk. I'm getting well now.

In spite of this unforeseen situation the preparation of the book shouldn't be delayed.

If you've managed to compilate a variant of plan–prospect of a future book, I ask you to send it with Dr. G. A. Shvetsov and to inform about the adress of correspondence.

There is one more question for discussion. During the last years the evolution of explosive method for superhigh fields obtaining by coaxial shells system magnetic flux compression allows to obtain a field with intensity of about 16 MOe. On this way it seems real to achieve the fields reproducibility of 20 – 30 MOe during the next few years. The reports concerning these problems will be made at the conference. The experiment with such facilities will be both expensive and complicated enough. It seems that it is high time to think about a joint program of works on both superhigh magnetic fields cumulation and experiments setting in such fields. What's your opinion?

Dear Dr. C. M. Fowler, I wish to thank you once more for organization of such a wonderful trip across the USA, which deeply impressed me. I send you the book "The Problems of Modern Experimental and Theoretical Physics" involving the articles on magnetic cumulation, and a small souvenir – a box with your portrait in memory of our first meetings in Novosibirsk. The painter used a photograph of year, 1983, that is why it was difficult to reproduce the versatility as a feature of your character. But his main effort to depict you full of strength and energy I share completely and wish you health and durable creative activities.

I hope for a successful work on the book, scientific contacts expanding and meetings with you. I ask you to give my sincere thanks to your wife for warm reception. My wife thanks you for souvenirs.

Sincerely yours,

A. I. Pavlovskii

30.06-89.

In the meantime, U.S. intelligence had been keeping track of the Soviet activities in this area and knew that their effort became fairly large in the early 1960s. I would guess it was stimulated by our 1960 paper in which we reported using these magnetic-flux-compression generators to create fields in the range of 10 to 15 megagauss and stated our intention to apply those fields to the problem of fusion. The Soviets put quite a bit of money into their effort, and in the early 1980s, the Air Force was so impressed with the reported performance of one of Pavlovskii's high-energy generators that they asked us to duplicate it. That was the LIGA project. Some of the LIGA results were presented at Megagauss-III in 1983. Pavlovskii happened to attend the talk and started asking the speaker some very embarrassing questions. I finally interrupted the speaker and told Pavlovskii, "Yes, we copied your generator to see if it worked as well as you said it did." In fact, our copy worked better than he described in the literature in one sense and not as well in another. And the one I was interested in was the one that didn't work quite as well.

Krik Krikorian: During the lab-to-lab visits, Pavlovskii once brought up the fact that we had duplicated his generator, and he asked, "Why didn't you just order it from us?"

Max Fowler: They actually did offer to sell us one of their high-field generators in June 1989 at Megagauss-V. That was also when Pavlovskii sent me a written offer of collaboration. A few months before, Pavlovskii had made his first visit to the United States in connection with a steering committee meeting for Megagauss-V, and with my help, he had taken a tour of various facilities from Florida and New York to the west coast and places in between. Unfortunately, between then and June, he had his first heart attack and was unable to attend Megagauss-V. But at the conference, I received a letter from him written in English in which he wrote, "It seems that it is high time to think about a joint program of works [sic] on both superhigh magnetic fields cumulation and experiments setting in such fields. What's your opinion?" I brought this letter back to Los Alamos, but there was no way to respond.

At that same meeting, we found out that he was from the secret city where the first Soviet atomic bomb was built, and that it was roughly a few hundred miles from Moscow.

Krik Krikorian: Of course, our intelligence people knew that the name of their 'Los Alamos' was Arzamas-16, and that it had been previously called several other names.


Alexander Pavlovskii

Los Alamos Science: *And do we know what the '16' stands for?*

Steve Younger: The Russians like to joke that the '16' was meant to make us look for the other fifteen. In reality it is a postal code.

Irv Lindemuth: Another interesting event at Megagauss-V was when Bob Reinovsky and I met Vladimir Chernyshev, who is also from Arzamas-16 and also a leader in the design of magnetic-flux compression generators. I first heard of Chernyshev in 1988 when our International Technology Division asked me to evaluate Russian papers on fusion. One particularly interesting paper was written by Vladislav Mokhov and Chernyshev and outlined a novel approach to controlled fusion involving pulsed power and magnetic flux compression. My colleagues and I believed then and still believe that the approach is very promising. We now call it magnetized target fusion. The paper attracted interest in part because it had been submitted to the prestigious Soviet physics journal *Doklady* by Yuli Khariton, who was the chief designer of the first Soviet atomic bomb.

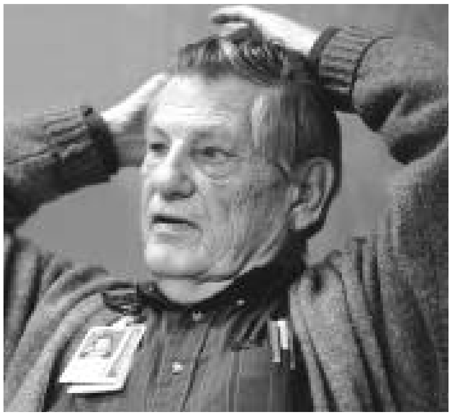
At Megagauss-V, I tried to discuss that very interesting paper with Chernyshev. He apparently was not allowed to talk to Americans about fusion, but he was willing to talk about the Russian pulsed-power capability, which was evidently very impressive, and he even said, "Maybe some day we can do an experiment in which you and your colleagues design the load and we provide the generator."

Los Alamos Science: *It must have been surprising to get offers for collaboration from scientists who were from the closed city of Arzamas-16. After all, this was 1989 and the Cold War was still in progress. Did either of you take these overtures seriously?*

Max Fowler: Not really. But on a later trip to the Soviet Union, we learned that they were quite serious.

Sig Hecker: Max, before we get ahead of our story, let's find out from John how the contacts in high pressure science developed during the 1980s.

John Shaner: The first time I personally met people from the shock wave groups at Arzamas-16 and Chelyabinsk-70 was at an international conference on high pressure science in Kiev in 1987. Well-known people from both of their institutes were anxious to meet their U.S. counterparts to discuss as much as we could of the thirty years of technical work that we had been reading about in the literature. Podurets and Trunin were there from Arzamas-16, and Boris Vodolaga and Avrorin were there from Chelyabinsk-70. Evgenii Avrorin, the technical director from Chelyabinsk-70 even chaired a session. A Russian friend told me during the session that six months earlier Avrorin would not have been allowed to attend a conference with foreigners, let alone chair a session. He was a leading designer of secondaries, the thermonuclear component of the hydrogen bomb.


Max Fowler

… it was truly exciting to see each other after knowing for seventeen years that we were working on very similar things. At subsequent conferences, we discussed our work and began to develop a rather strong friendship. [Pavlovskii] had a tremendous sense of humor, and it was a pleasure to exchange ideas with him even though, or perhaps because, each of us was trying to get information from the other.

The Joint Verification Experiments and Viktor Mikhailov

Sig Hecker: These technical contacts in the late 1980s bring us to the second main thread of our story, which involves the Soviet-American Joint Verification Experiments of 1988 and the effort to ratify the Threshold Test Ban Treaty. In that dramatic effort, the Soviets came to the Nevada Test Site and both sides made an on-site measurement of the yield of a U.S. nuclear device and compared the results, and then both sides did the same for a Soviet devices at their test site in Semipalatinsk. Those joint experiments and the associated negotiations in Geneva involved many interactions with their nuclear scientists, in particular with Viktor Mikhailov. Mikhailov is now the head of MINATOM, the Ministry of Atomic Energy of the Russian Federation, and he has become the primary government authority in Russia supporting the lab-to-lab effort.

Viktor Ivanov and Vern Wetherill (DOE/Nevada) standing in front of a ten-foot-diameter drill bit at the Nevada Test Site in January 1988 during the initial exchange visit to prepare for the Joint Verification Experiments.

To understand the unfolding of events, let’s remember that the Soviet-American interactions of the 1980s were not all wine and roses. President Reagan often referred to the Soviet Union as the evil empire. In 1983, our country had an enormous defense buildup and SDI was born. The nuclear weapons resurgence in terms of new systems and money flowing back into the program was also enormous.

Steve Younger: I remember a Livermore nuclear shot in the mid-1980s and on the nuclear device can was painted in 12-inch letters “Eat neutrons Ivan.” We should also keep in mind that the SDI work we did in the mid-1980s was directed towards shooting down Soviet missiles. They were the targets, and by golly, we studied their vapor trails and all sorts of stuff.

Sig Hecker: And then came the Reagan-Gorbachev summit at Reykjavik in 1986. I was just flabbergasted. I could not believe that these two men were saying they were going to get rid of all nuclear weapons. But they said it. To me that was a really significant change—not completely convincing, but still significant.

I became Director of the Laboratory on January 15, 1986, and at that time, one of the key issues was the ratification of the Threshold Test Ban Treaty. The treaty set a 150-kiloton limit on the yield of underground nuclear tests. The Americans had been observing the treaty for ten years since the signing by Nixon and Brezhnev, and the Soviets claimed they were too. But the means to verify the treaty were not specified, and there were many claims of cheating by both sides. About 160 such claims were on file in Geneva, so the status of the treaty was fairly shaky. Nevertheless, Reagan wanted the treaty ratified by the Senate before he left office in 1988. The Joint Verification Experiments were intended to demonstrate that the methods agreed to by each side to verify treaty compliance could be fielded effectively and without undue interference with nuclear experiments. The activities associated with those experiments were the principal Soviet interface that we thought about and talked about at that time. I’ll let Don Eilers tell you about that.

Don Eilers: President Reagan really wanted better verification of the yields of the Soviet tests, and he would often repeat the phrase “trust but verify” in both Russian and English. He was being pushed by the hardliners in the Defense Department who were concerned that the Soviets were testing more powerful devices than the treaty allowed. In 1984 Reagan made a speech at the United Nations in which he proposed that the CORRTEX technology be used to verify the Soviet yields. That was a startling proposal because CORRTEX requires performing the nuclear yield measurement at the site where the nuclear device is being tested. In the past, we had determined the yields of Soviet nuclear tests by seismic methods at distances thousands of kilometers from the actual test site, and the Soviets presumably did the same for us. But CORRTEX is a hydrodynamic measurement in which the cables must go down into a satellite hole near the nuclear device, and then when the device goes off, the speed of the shock wave along the cable gives you a very accurate estimate of the yield, or explosive power, of the device.

Los Alamos Science: *Was the CORRTEX technology new in 1984?*

Don Eilers: No. Don Westervelt and I had started working on it back in 1975, right after Nixon and Brezhnev signed the Threshold Test Ban Treaty and during the negotiations on the companion Peaceful Nuclear Explosion Treaty, which was signed by Ford and Brezhnev in 1976. We actually fielded the first CORRTEX system in 1976 on one of the U.S. high-yield nuclear tests. Our Soviet counterparts in the 1970s were Vadim Simonenko, Nikolai Voloshin, and all those guys at Chelyabinsk-70 whom we were to meet again in 1986 at the Nuclear Testing Talks in Geneva leading up to the Joint Verification Experiments.

Those talks were a direct result of the Reagan Initiative and were designed to discuss methodologies for verifying the Threshold Test Ban Treaty. The U.S. delegation was led by Ambassador Bob Barker from DOD, and Bob Jeffries and I were part of that delegation. The Soviets were proposing seismic methods to measure the yield, and the United States was proposing CORRTEX measurements. In the course of a year and a half, we went through several two-week sessions in which all we did was basically look at one another across the table. Nothing happened until Secretary of State George Schultz and Soviet Foreign Minister E. A. Shevardnadze got together in September 1987 and proposed full-scale negotiations with the objective of ultimately doing joint verification experiments, or JVEs, in which the two sides would made simultaneous hydrodynamic (CORRTEX-like) measurements of nuclear yield and compare results. By November, there was an agreement to have preliminary exchange visits to our respective nuclear test sites, and in December 1987, Schultz and Shevardnadze signed an agreement on the conduct and objectives of the JVEs.

Now there is some confusion over who proposed those experiments. The Russians think they did and Bob Barker thinks that it was done over a cup of tea in Washington. Voloshin asserts in an unpublished manuscript that, "It was a proposal from the Soviets made during the April 1987 ministerial."

In any case, the preliminary visits were set up for January 1988. The object of these visits was to familiarize one another enough so that we could more easily negotiate an agreement for carrying out the JVEs. They were really kind of exciting times. A delegation of twenty of us led by Bob Barker went first to Moscow, where we had a night at the Bolshoi Ballet, and went on to the Soviet nuclear test site at Semipalatinsk in Kazakhstan.

Left to right: V. Mikhailov, V. Ivanov, R. Trunin, and N. Voloshin standing inside the surface-casing for the ten-foot drill bit at the Nevada Test Site during the preliminary visit. The Soviets were very impressed because they were limited to drilling three-foot diameter holes at their test site.

Sig Hecker: We should point out that you were the first Americans ever to set foot on a Soviet test site, and that was considered a pretty big deal by the hardliners in Washington.

Don Eilers: Right. The Russians flew on the same airplane with us, and we landed in a rip-roaring snowstorm at Semipalatinsk. That evening at dinner, we met Viktor Mikhailov for the first time. He was then the Director of the Scientific Research Institute of Impulse Engineering in Moscow, the institute responsible for many types of nuclear testing diagnostics. He certainly appeared to be leading their technical group, and I thought, "Boy, what an intense guy." He exuded self-confidence and pride. It was quite obvious that he was well respected, and everybody and his brother listened to him. He even gave some of the technical presentations on their timing and firing system during our stay at the test site. Voloshin and Simonenko were also there.

The atmosphere of the visit was eerie. Armed guards surrounded our hotel, and we were permitted to walk only about a few hundred feet down to and along the bank of the Irtysh River.

continued on page 10

Chronology of the

- **_1965 Megagauss-I_**, *the first international conference on ultra-high magnetic fields, reveals first glimpse of Soviet pulsed-power program to Western scientists. Pavlovskii and other Soviet scientists from the secret nuclear-weapons-design city of Arzamas-16 submit abstracts but are not allowed to attend.*

- **_1975 Threshold Test Ban Treaty (TTBT)_**, *signed by Presidents Ford and Brezhnev, limits yields of underground nuclear tests to 150 kilotons.*

- **_1982-1989 Fowler of Los Alamos and Pavlovskii_** *develop connection at Megagauss and other conferences.*

- **_1982-1984 Reagan begins initiative to improve TTBT verification_** *and the prospects for ratification. Reagan suggests CORRTEX methodology, which requires on-site verification of nuclear yields.*

- **_1986 Gorbachev starts policy of glasnost._** *Gorbachev and Reagan hold Reykjavik Summit.*

- **_1986-1988 Negotiations on the verification of TTBT in Geneva._** *Soviet nuclear-weapons scientists, led by Mikhailov, work with their U.S. counterparts to develop verification technologies and procedures.*

- **_1988 Joint Verification Experiments (JVE)_**—*Soviet and U.S. teams develop consistent methodology and then perform joint on-site yield measurements at each other's nuclear weapons test sites. Soviet scientists discuss possibility of collaboration and present possible list of topics.*

- **_1988-1990 Continuing Soviet-American negotiations_** *on procedures for implementing the TTBT.*

- **_1989 First written offer of collaboration—_***Pavlovskii sends offer to Fowler.*

- **_Fall 1990 Opening of the Soviet Nuclear Design Institutes to American Scientists._** *In August, Avrorin, chief scientist of Chelyabinsk-70 invites Shaner and Livermore scientists to visit the nuclear weapons design city of Chelyabinsk-70. Avrorin proposes thirteen areas of collaboration. In October, Mikhailov takes Eilers and U.S. delegation to visit Arzamas-16.*

- **_September 1990 TTBT ratified_** *under the Bush administration.*

- **_1991 Los Alamos Director Hecker_** *speaks with Alessi, head of the Arms Control and Nonproliferation office of the DOE, concerning the possibility of collaborations with the Soviet nuclear institutes.*

- **_August 1991 Unsuccessful coup is staged against the Gorbachev government._**

- **_September 1991 Chernyshev and Mokhov_** *present Lindemuth with a written proposal signed by the Director of Arzamas-16 for joint Russian-American work on magnetized target fusion.*

- **_November 1991 Passage of the Nunn-Lugar legislation_** *earmarking 400 million dollars of the DoD budget to help transport and store Soviet nuclear warheads and establish safeguards against proliferation.*

- **_November-December 1991_** *At the invitation of Pavlovskii and Avrorin, Dan Stillman and Krik Krikorian are the first American scientists from the U.S. nuclear weapons establishment to visit both Arzamas-16 and Chelyabinsk-70. Stillman delivers to Hecker a list of possible areas of collaboration generated by Khariton and Avrorin.*

- **_December 1991 The Soviet Union collapses and Independent States break from Russia._** *Hecker proposes to DOE Secretary Admiral Watkins that lab-to-lab scientific collaborations with Russian nuclear weapons institutes might address President Bush's concern of a potential "brain drain" of Russian nuclear scientists.*

Lab-to-Lab Program

- ***February 1992 Directors' Exchange visits***—*Directors Belugin and Nechai visit Los Alamos and Lawrence Livermore National Laboratories. Later in the month Directors Hecker and Nuckolls visit Arzamas-16 and Chelyabinsk-70 and discuss possibility of lab-to-lab collaborations.*

- ***May 1992 ISTC program is launched under Nunn-Lugar.*** *International Science and Technology Centers are mandated to help redirect weapons of mass destruction expertise to civilian and peacetime activities.*

- ***October 1992 First lab-to-lab contracts signed between Los Alamos and Arzamas-16.*** *Two experimental series are planned.*

- ***August 1992-December 1993 Large-scale, nuclear material storage facility is planned under Nunn-Lugar.*** *Augustson and Mullen from Los Alamos and Il'kaev, Yuferev, and Zykov from Arzamas-16 work together to plan modern MPC&A (materials protection, control, and accounting) system for storage facility.*

- ***February 1993 Pavlovskii dies.***

- ***August 1993 "You are driving us into the hands of the Chinese."*** *Younger receives Russian complaints that no American money has been forthcoming. Younger informs Domenici of the situation. Domenici speaks on the floor of the Senate about the dangers of not supporting the Russians.*

- ***September 1993 IPP program launched.*** *Congress allocates 35 million dollars of foreign appropriations money for an industrial partnership program with Russian scientists to help scientific conversion.*

- ***September 1993 First Russian-American lab-to-lab experiment performed at Arzamas-16.*** *Russians and Americans "working side-by-side as equals."*

- ***October 1993 Second series of lab-to-lab experiments performed at Los Alamos.*** *Measurement of critical magnetic field of high* T_c *superconductor. First Russian scientists allowed behind the fence.*

- ***December 1993 Efforts on Russian storage facility are suspended****.*

- ***January 1994 Lab-to-lab umbrella contracts*** *on scientific conversion activities signed by Hecker and Belugin. Proposal to include MPC&A activities under the umbrella contract is presented.*

- ***March 1994 Curtis of DOE approves Hecker's proposal*** *for a lab-to-lab materials control program.*

- ***June 1994 Hecker and Belugin sign contract*** *to begin lab-to-lab MPC&A program.*

- ***1994-1995 Scientists from Los Alamos and Arzamas-16*** *perform six more series of experiments under umbrella contract.*

- ***1994-Present Lab-to-lab MPC&A program*** *grows from 2 to 45 million dollars. Government-to-government program in MPC&A moves to DOE. Participation in lab-to-lab increases from one Russian institute to eight. Similar growth occurs in the government-to-government program.*

- ***April 1996 Start of Dirac series.*** *Experiments extend Russian-American lab-to-lab work in ultra-high fields to a larger international community.* ■

The Soviets and Americans are installing CORRTEX cables in a satellite hole at the Nevada Test Site in July 1988 in preparation for the U.S. JVE “Kearsarge.” T. McKown (second from left), V. Salnikov (third from left), N. Voloshin (third from right), and W. Storey (second from right) led the work on this shot.

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The first night we had a problem with the guards because we wanted and needed exercise and were quite irritated that the guards had set the boundary about fifty yards short of the agreed walking distance. Fortunately, the issue was quickly resolved by Ambassador Barker and General Ilyenko, Commander of the test site. The nights were cold, about thirty degrees below zero, and the days were filled with trips to the test site, for example, to the forward camp where we and our equipment would be housed during the JVEs, and to a site where they were drilling a hole for a nuclear test and where we were briefed on their drilling and logging operations. It was out there in the middle of nowhere, on a very cold day with the wind howling at fifty miles per hour when they brought us into a double-walled tent and hosted a great feast for us. We were very impressed.

Later that month, they came out to the Nevada Test Site, and we reciprocated with presentations on equipment, operating procedures for conducting tests, a visit to the forward area and to a drilling site, and so on.

I want to emphasize that Mikhailov was certainly somebody to be reckoned with. After going through many months of work on the JVEs, and then working daily together at our test site, a friendship developed. One night Mikhailov was talking to me about what he used to do and said that, among other things, he sat on a committee for targeting U.S. cities. Then he said, “Don, it makes a big difference now that I can place faces at those targets.” He meant the job would be much more difficult.

Max Fowler: Did he speak English?

Don Eilers: Very little, but he understands a lot of English.

Sig Hecker: John, you played an important role in the JVEs, too. Tell us about that.

John Shaner: In January 1988, after the formal negotiations with the Soviets had started, Bob Jeffries came back from Geneva wanting to add a technical expert in experimental shock wave physics, and he asked me to join the technical experts group. My role was to provide technical support during the meetings and negotiations as well as to advise on the requirements on rock samples and experimental procedures we would need as part of the hydrodynamic yield measurements.

Don Eilers: We were going to use a hydrodynamic yield determination methodology that we had been working with since 1962 and that could be carried out by both sides and compared openly. One essential procedure involved measuring the shock properties of the rocks taken from the point of explosion, then using that data to construct a theoretical model of the rock, and using the model in a hydrodynamic calculation of the shock wave generated by the explosion. That methodology was incorporated in the JVE Accord, which was signed by Gorbachev and Reagan in Moscow in May 1988.

John Shaner: I remember many discussions with Vadim Simonenko, from Chelyabinsk-70, concerning the measurements, procedures, and theoretical models. There was some apprehension that our measurements and models might be different enough that we might not agree on the final outcome. In July, at the Nevada Test Site, we compared the first experimental results on shock propagation in the rocks, and they agreed so well that we were both relieved.

Don Eilers: And then everyone’s concerns turned to smiles several weeks later when we exchanged the CORRTEX and the Soviet data from the first JVE explosion “Kearsarge.” The agreement was good, resulting in yields with acceptable uncertainty. The entire process was repeated for “Shagan,” the JVE performed at Semipalatinsk, and it gave similar agreement between the two sides. Those successes demonstrated the viability of hydrodynamic-yield measurement technology and methodology for improved verification of the Threshold Test Ban Treaty.

Los Alamos Science: *Sig, what was your experience with the JVEs?*

Sig Hecker: For me, a key event was going out to the actual experiments at Nevada. Mikhailov was leading the Soviet group, and as Don pointed out, he appeared to be a proud and even arrogant scientist type. It was interesting to watch him and the other Russians operate, to see the sense of technical competence and the pride in their work. I remember visiting Mikhailov in the Soviet instrument trailer, and he was very anxious to show me this oscilloscope that he had developed in his institute in Moscow.

Don Eilers: Mikhailov had shipped two SRG-7's—7 gigaherz oscilloscopes—to our test site. They had a bandwidth beyond the range allowed for use by the JVE Accord because they were capable of recording classified device performance information. We had nothing similar in capability on the American side. Mikhailov had them sent just to shake up everybody and to demonstrate that the Soviets had good technology.

Sig Hecker: He certainly was very proud of that equipment. But the conversation that I remember most was in the mess hall with Simonenko. He was sitting there trying to sell me on the idea that we should really be doing joint underground scientific experiments—JSEs instead of JVEs. And so we talked a bit about the type of science that you could do underground. All unclassified, of course.

Don Eilers: Simonenko often talked about doing underground equation-of-state experiments and other high-pressure physics. In fact, when we went back to Geneva following the JVEs, Simonenko, Avrorin, and Voloshin spent the better part of an afternoon in the Soviet Mission discussing this with John Shaner, Don Westervelt, and myself and presenting us with diagrams of proposed experiments.

The U.S. team celebrates after the Soviet JVE "Shagan" at the Semipalatinsk test site in Kazakhstan in September 1988 with a picnic and swimming at Crater Lake. Although created by a peaceful nuclear explosion in 1968, the lake was no longer radioactive and quite safe for swimming. Left to right: A. Popov, G. Fauerbach, K. Alrick, R. Hill, D. Eilers, L. Pirkl, C. McWilliam, W. Storey, and H. Poteet.

Sig Hecker: One striking thing about the JVEs was the enormous pressure to make sure that everything worked. Clearly it would have been an international embarrassment, for instance, if our device hadn't gone off at all, or if the yield were way over the allowed limit, or if the CORRTEX system hadn't worked. I had my fingers crossed.

Don Eilers: Well, we were sure the CORRTEX system would work because of the redundancy and safeguards in the system, but we still worried that the yields be well below the threshold so there would be no complaints about violating the treaty.

We completed the JVEs—both the U.S. shot Kearsarge and the Russian shot Shagan—by September 1988, but the negotiations went on, and the treaties were not complete until May 1990. Many of the issues remaining after the initial demonstration related to the implementation of the treaty and were technical in nature. For example, Don Westervelt, Keith Alrick, Larry Pirkl and I from Los Alamos, David Conrad from Livermore, Horace Poteet from Sandia, Charles McWilliam from DOE/Nevada, and Bill Summa from the Defense Nuclear Agency worked with the Russians on designing devices to prevent classified information from being picked up by the Soviet and U.S. sensing cables. This technical effort was very successful, and we were able to put together a treaty that was not only ratified in 1990 but also implemented on three U.S. tests. In particular, Soviet hydrodynamic yield verification measurements were done on the

Junction test in 1992, one of the last underground tests we did.

Joe Pilat: Don, I think it is important to note that there were some very difficult political as well as implementation issues that had to be addressed by the Soviet and American delegations. For example, the requirement of notification well in advance of a nuclear test and the presence of foreign personnel at the site of a test were real stumbling blocks. But the technical problems were always addressed in a professional, collegial fashion among experts who recognized the common backgrounds they shared.

Don Eilers: Very definitely. Over a period of two years, the Russian and American scientists had been through a period of initial posturing, particularly by the Russians, that neither side liked, but had then gone on to develop a great deal of mutual respect and pride about the actual technical accomplishments. We also developed the level of trust and cooperation that was needed for successful implementation of the treaty.

Don Eilers (left) and Viktor Mikhailov in Geneva in December 1989 for a TTBT meeting to discuss anti-intrusiveness devices and equipment exchanges. Less than a year later, Mikhailov invited the U.S. delegation to Arzamas-16.

Steve Younger: Mikhailov has a trophy table in his office and the biggest thing on it is the JVE plaque. He's very proud of that.

Don Eilers: One thing to remember is that Mikhailov always headed their technical group, both at the JVEs and at the negotiations in Geneva. Even after he became Deputy Minister of MINATOM, Mikhailov took time out to spend three days with us in Moscow in October 1990 negotiating all the technical nitty-gritty details of the anti-intrusiveness devices. He sat there, and he was on top of the issues all the time.

Steve Younger: And he still is. I had lunch at the U.S. Embassy in Moscow in October 1994, and he came up to me and wanted to talk about the calibration of neutron detectors in the recent lab-to-lab experiments on fusion. He can talk about our joint experiments as an expert in the field.

Opening Up the Russian Nuclear Institutes—August 1990 to December 1991

Los Alamos Science: *In 1990, several of you were invited to visit the Soviet nuclear weapons labs. Was this in the context of the negotiations for the Threshold Test Ban Treaty?*

John Shaner: The invitations certainly grew out of those contacts. For example, while negotiating the procedures of the JVEs, Simonenko and I had occasion to discuss basic high-pressure science, which is the subject of an All-Union Conference held every year or so by the Russians. Attendance at those conferences had been restricted to Soviets, and the frankness of the discussions was legendary. By the late 1980s the Soviet scientists thought it would be useful to involve Americans, just as we had involved Russians in our American Physical Society conferences. As a result of those discussions, several scientists from the United States were invited to an All-Union meeting on high-pressure equation-of-state issues to take place near Irkutsk in August 1990. About two weeks before our scheduled departure, Evgenii Avrorin, whom we had gotten to know well in Geneva, arranged for a few of us to stop at Chelyabinsk-70 for a two-day visit on the way to Irkutsk. All of us involved, including Avrorin, understood that we did not have enough time to get all of the correct approvals, but we could probably get the most important ones—and we did. With less than a week to spare, three people from Livermore and I were able to get permission from Washington to make the visit.

We spent the first day of our visit at the original 1955 site of Chelyabinsk-70. There we discussed a wide range of scientific topics including high-pressure science and hydrodynamic instabilities. On the second day, we drove about 15 miles to the north to the present site, where we saw facilities for studying hydrodynamic instabilities, large pulsed reactors and electron-beam machines, and an explosive test site.

On that second day we were presented with a list of 13 potential topics for collaboration in areas of nuclear science and hydrodynamics. That list was very similar to one we had received in Geneva more than a year previously. Then came the surprise. Chuck MacDonald

The U.S. delegation at a picnic at Arzamas-16 in October 1990. The trip, the first visit by Americans to Arzamas-16, was arranged by V. Mikhailov (standing at far end of table). Seated left to right facing camera: V. Belugin, G. Tsyrkov, U.S. Embassy interpreter, D. Eilers, D. Westervelt, and B. Summa.

from Livermore and I were asked to participate in a video-taped interview with Avrorin to discuss our reactions to this historic visit. Chuck and I were pretty concerned about this as neither of us were very experienced in this kind of sensitive public discussion. I never did find out how Avrorin used this tape.

Los Alamos Science: *Don, didn't you get to visit Arzamas-16 at about the same time?*

Don Eilers: Yes. While in Moscow at the October 1990 negotiations on anti-intrusiveness devices, Mikhailov surprised us and seized the initiative by inviting the U.S. delegation, including myself, Keith Alrick, Don Westervelt, and Larry Pirkl, to visit their secret nuclear weapon design city Arzamas-16. Such an invitation to Arzamas-16 had never been made before, and of course, it was not clear to the delegation members that the United States would give permission.

The approval took some time in coming, but when it finally did, they flew us to Arzamas-16 for a most extraordinary day. We were greeted by a whole crowd including Khariton, Belugin, Trutnev, Pavlovskii, and others. They showed us an accelerator, a high-powered laser system, and a few things like that, and then we had a wonderful picnic with a big bonfire, snow flurries falling, and lots of good food and vodka.

At one point, Mikhailov told Westervelt, "You are looking at the most peace-loving men in the world. They have been working here for forty years, and the only reason they were working on nuclear weapons was to make damn sure we never had a war." Similarly, when we first arrived at Arzamas, Khariton gave us a little speech in the House of Scientists, and one of the first things he said was, "I've been waiting forty years for this."

While we were in Arzamas-16, Chernyshev gave me a letter to bring back to the Laboratory. It was addressed to Denny Erickson and in it he mentioned Max Fowler's recent visit to Siberia and the discussions on pulsed power, and then he wrote, "I would like to raise a question on collaboration in this field."

Los Alamos Science: *Max, what happened on that trip?*

An outdoor feast at Arzamas-16 in October 1990 during the one-day visit by the American delegation.

Max Fowler: As I alluded to earlier, during my trip to Novosibirsk in September 1990, Pavlovskii told me that he could get my Laboratory Director and possibly me into his "Explosives Firing Area." In hindsight I would guess this was the first indication that Arzamas-16 might be opened up to American nuclear scientists. Pavlovskii and I exchanged telegrams back and forth about this visit and in November he indicated that we could bring even more people. My return message suggested the names of John Birely and John Browne as two high-level Los Alamos people who might have special interest in such a visit. At that time, I also spoke with Don Westervelt about his trip to Arzamas-16, and we decided to alert Sig that he might receive two independent invitations to Arzamas-16.

Los Alamos Science: *What was the official U.S. reaction to these unofficial visits and offers of collaboration from these formerly secret cities?*

John Shaner: Well, the National Security Council stepped in and demanded that Admiral Watkins, then Secretary of Energy, develop a plan for future visits**.** Watkins, in turn, called in the DOE Lab Directors and demanded a plan for future interactions. I drew one up for Sig, dated December 10, 1990, that outlined a step-by-step process for starting collaborative efforts. The process would begin with an exchange of lab directors, followed by a meeting to establish topics and procedures, then bilateral technical discussions to establish details of the collaborations, and finally the initiation of active collaborations. Sig really liked the proposal and sent it to the National Security Council, but they were preoccupied at that time with the Gulf War, so we heard nothing from Washington for about nine months.

Irv Lindemuth: But we did respond to the pulsed-power group at Arzamas-16. First of all, Don Eilers brought back from his visit to Arzamas-16 a prospectus in Russian describing what was going on at their laboratory (called VNIIEF). And a few innocent statements in that brochure provided clear confirmation that they were, indeed, working on the magnetized target approach to controlled fusion that we had found so interesting. We then wrote a letter to Chernyshev, and in addition to asking about a paper of his, we also asked if a collaboration was really possible. The letter went unanswered, but then Bob Reinovsky and I and several others from Phillips Laboratory and Livermore had extensive discussions with Chernyshev and Pavlovskii at the IEEE Pulsed Power Conference in San Diego in June 1991. Academician Mesyats, a Vice President of the Soviet Academy of Sciences, was leading the delegation, and the Soviets were openly courting collaborative work in pulsed power. The discussions were primarily between Los Alamos and Phillips Laboratory and the Arzamas-16 people. The

Russians seemed very confident that, if the United States was interested in collaboration, then such a collaboration was possible. They even indicated that if we expressed interest, Gorbachev would bring it up with Bush at their July summit meeting. That did not happen, but Pavlovskii and Chernyshev visited Phillips Laboratory and Los Alamos after the San Diego conference and continued discussions about collaboration. One of the outcomes was the recognition of a common interest and an invitation for us to come visit Arzamas-16.

Los Alamos Science: *Did that visit take place before the collapse of the Soviet Union?*

Irv Lindemuth: No, I don't think they were quite ready. However, I was invited by the Soviet Academy of Sciences to teach at the International School on Plasma Physics and Controlled Fusion in September of 1991 in a resort town on the Black Sea, and I was hoping to visit Arzamas-16 in connection with that trip. You remember there was a lot of unrest in the Soviet Union at that time. The coup attempt had been made in August 1991 and many trips to the Soviet Union were being cancelled. But my wife and I decided to go anyway. We spent the week and a half at the conference and when we returned to Moscow, we were taken to an apartment in Kurchatov Institute. About three hours later, someone came and knocked and said, "Chernyshev and Mokhov and some of their people are here to meet with you." Chernyshev and Mokhov were very apologetic that it wasn't possible to take us to Arzamas-16, but they then presented a written proposal signed by Belugin, the Director of Arzamas-16, as well as them selves for joint U.S. work on the magnetized target approach to controlled fusion (they call it MAGO). After I read the proposal, my first statement to them was, "Wow, I don't know if our government is ready for this. All I can do is take it back and see what happens." On the front page of the proposal were blanks for Sig Hecker and others at Los Alamos to sign.

Sig Hecker: That brings us to the Soviet collapse in December and the breakthrough on our side. But I think the events from August 1990 to December 1991 are quite important. For the most part, it was one of fits and starts and not getting very far. I felt the pressure from you folks coming back from Russia, and from John Shaner in particular, that we have an opportunity to go over there and learn something about the Soviets and their programs. And so I tried to work with the Washington folks at DOE, principally Vic Alessi who was heading up the Office of Nonproliferation and Arms Control. Vic was really one of the avant garde DOE people, but even he didn't really pick up on this opportunity until later.

Reaching Out

Los Alamos Science: *What do you believe was the origin of the opening up of the Russian nuclear institutes and the offers of collaboration, and was this a more general phenomenon?*

Krik Krikorian: In Colin Powell's recent autobiography, he describes a conversation he had in Moscow in 1987 with Anatoly Dobrynin, Soviet Ambassador to the United States during during much of the Cold War. Dobrynin said, in effect, we finally have a lawyer running this country, and this lawyer is saying to the military, "Why do you tell me we have to have this weapon or that weapon? I don't intend to conquer the Americans." I think the winds of change started with the book Gorbachev wrote on perestroika in 1987. The idea that the door was opening filtered out to the people in Russia and we saw the effects at Los Alamos. For instance, in 1988 Academician Vladimir Fortov, who was on the Chernobyl safety committee, visited Los Alamos. He approached Sig about information on reactor safety, and the next day, there was a stack of paper a foot high to take back to Moscow. The Lab has always been open to developing contacts and exchanges with the Russians in unclassified areas of research.

The Soviets were also working collaboratively with us on issues of nonproliferation of nuclear weapons through IAEA safeguards and the Nonproliferation Treaty. Los Alamos has had a long history of sending Laboratory staff to the IAEA—the International Atomic Energy Agency—in Vienna. And there, you would meet a certain side of the Russian technical community—they were nuclear people, but definitely not nuclear weapons types. The Soviets set up a support program to the IAEA similar to the U.S. program, and as part of the exchanges that took place, Americans got to visit various facilities associated with their nuclear fuel cycle, nuclear reactors, and such.

Ron Augustson: I was there in 1988 with the IAEA to help the Soviets teach a course on safeguards in Dimitrograd. And we got very, very, royal treatment. At one point, I was left in Moscow for a couple of days, and to my surprise, I was completely free to wander all over Moscow on my own. The next year, two of my Soviet hosts from Dimitrograd came to Los Alamos and we did some measurements on spent fuel at the Omega West Reactor. Now the government-to-government MPC&A program will be working with Dimitrograd to set up collaborations on improving safeguards of their nuclear material.

Hugh Casey: Tech transfer was another area that started to open up during glasnost and perestroika. In 1988, the Soviets started a series of conferences that they advertised as attempts to bring their defense technology to the west. In fact Krik, myself, and Tony Rollett attended what they called a MATec conference—Materials and Manufacturing Conference—in Helsinki, Finland.

Representatives from key Soviet defense institutes and the Academy of Sciences were there, although none from the nuclear weapons centers. I was astonished by one presentation in which they were trying to market the very specialized technologies that had been used for building ICF capsules. I couldn't imagine who they thought the buyers would be.

Krik Krikorian: At that time it was clear that the Russians had no concept of marketing. They thought if you had a good product, people would just jump on the bandwagon and buy it. Well that wasn't the case at all.

Hugh Casey: There were only a handful of Americans at the Helsinki conference, a few western Europeans and a few Japanese. Most attendees were from eastern Europe. Our presence drew a lot of attention, and they seemed to know an awful lot about us. Probably they had done some background checks. But the interactions were quite demonstrative and very friendly. Most important, we were able to identify some interesting equipment and technology that subsequently became one of the models for the current lab-to-lab Industrial Partnership Program.

Los Alamos Science: *What area of Russian technology was so intriguing?*

Hugh Casey: We were particularly intrigued with high-powered gyrotrons that produce ultrahigh-frequency collimated microwave beams. We were interested in some applications involving the sintering of ceramics and had a proposal in to DOE to build our own equipment, but it would have been very costly. After the collapse of the Soviet Union, we were able to acquire those original pieces of equipment, and they are now installed in an industrial user facility operated by the Laboratory's accelerator division. We actually ended up getting the equipment free of charge through an industrial partner that became involved with Los Alamos through the technology transfer initiative of the early 1990s. It is now an on-going project that has been running for many years and will be one of the larger success stories in terms of transfer of high technology to U.S. industry. Ford Motor Company, for example, is the first major corporation to actually have put these to use into production-scale processing.

Hugh Casey

Tech transfer was another area that started to open up during glasnost and perestroika. In 1988, the Russians started a series of conferences that they advertised as attempts to bring their defense technology to the west.

Los Alamos Science: *Was there some sort asymmetry during the late 1980s? Were the Russians reaching out while we Americans were holding back?*

Sig Hecker: You are asking whether the Russian nuclear scientists were really more aggressive in trying to build bridges with us, and I think the answer is yes. We were also enormously interested and curious because we knew so little about their weapons program. There was an enormous asymmetry in the knowledge of our programs and our science because we do almost everything in the open, and so little of their work made it into the literature. But it took a long time for us to get over the intelligence mode and into the outreach mode. We suspected them of being interested purely for the intelligence reason. And yet, I think they were interested in the partnering outreach mode probably much earlier than we were.

Don Eilers: I believe our 1990 visit to Arzamas-16 is an example. When Mikhailov invited us, he explained how difficult it had been for him to arrange the visit. It involved two discussions with Gorbachev's deputy and many others. Then, to help the U.S. delegation win consent for the visit, he assured us that there were no conditions attached to the visit—in other words, reciprocity by the United States was not an issue. But we knew from the discussions at the Nevada Test Site and in Geneva during the previous two years that the possibility of collaboration was of great interest to the Russians.

Krik Krikorian: In the same vein, Khariton and Pavlovskii took the initiative to give us a list of topics for possible collaboration when Dan Stillman and I visited Arzamas in December 1991. Dan delivered that list to Sig.

Sig Hecker: In terms of motivations, Don Westervelt and others suggested in their trip reports that the Russian nuclear scientists believed working with Los Alamos would give them credibility within their own country and would help them get funding from their government. That was a key driving force. The Russian scientists were also concerned with how to keep their people interested in their programs. Everything was heading downhill so fast for them, and working with the Americans offered a ray of hope. That was evident in 1990. But I didn't experience it directly until February 1992 when I went to Russia for the Directors' exchanges.


Don Eilers

[Defense] conversion was the main topic of the briefing we received on our 1990 visit to Arzamas-16… In fact, they told us…they had already converted about 15 per cent of their activities to non-defense work.

Paul White: It's interesting that the technical interactions in Geneva during the Threshold Test Ban Treaty negotiations were, in many ways, the very first contacts that the Russian nuclear scientists from the weapons institutes had with the international scientific community. And it was very important for them to try to establish their reputations as bona fide scientists in that community. So, after some initial posturing, they were very forthcoming.

Steve Younger: There was a cultural element too. For a thousand years in Russia, interaction with the West in areas of science, literature, and so on has been considered a social distinction.

Hugh Casey: Economic pressures in the form of food and medical shortages and missed paychecks were being felt in Russia for years before the Soviet collapse. Research and development funds for defense work were drying up, and so financial woes also provided some motivation to look to the West for new opportunities.

Krik Krikorian: There is another factor that needs to be brought out. Irv was exposed to it, and so were Danny Stillman and I. The fact is they had already started defense conversion. They even gave us a videotape describing it.

Don Eilers: Conversion was the main topic of the briefing we received on our 1990 visit to Arzamas-16, and it was also the main topic of the prospectus that Irv mentioned earlier. In fact, they told us during the visit that they had already converted about 15 per cent of their activities to non-defense work.

Joe Pilat: With regard to what Don, Krik, and Hugh have said, I think it would be a mistake to attribute to Soviet scientists a free reign during this period. Prior to the Soviet collapse, I believe they were still operating largely within, or in some cases, at the margins of a fairly limited and circumscribed governmental agenda.

Certainly, the interactions that Max, John, and Irv described, and the ones that Steve Younger and Ron Augustson will describe later, are an object of total fascination. Ten years ago, one couldn't have imagined the breakthroughs we have witnessed in recent times. But one of the biggest problems in dealing with historical reflection is reading the future back into the past. Many of the issues that are really germane to this discussion are questions that don't have consensus answers. When did the Cold War end? When did the roles of the nuclear weapons in the United States and the Soviet Union (and then Russia) begin to change to reflect changes in the world? When was this reflected in policies and postures in governments and then the laboratories? I think we need to look at the laboratory interactions in that broader context.

For the moment, I will just offer my concept of when things changed. Looking back at the Gorbachev era, there is a tendency to see in its early years and throughout its existence many of the things that happened only after Gorbachev got ousted from power. For example, the golden age of arms control that occurred during the Gorbachev era, from the INF treaty to START I, was a continuation of classical arms control. It was an effort to create stability through restraints of various kinds. And although it included unprecedented reductions of nuclear arms, the agreements were essentially Cold War agreements in content, context, and structure. They were bilateral, and they were designed to ameliorate a fundamental U.S.-Soviet conflict. Gorbachev did put forward proposals for total disarmament. But should those have been taken seriously? Probably not. If you look at the long history of Soviet arms-control negotiations, you see these kinds of sweeping proposals.


Krik Krikorian

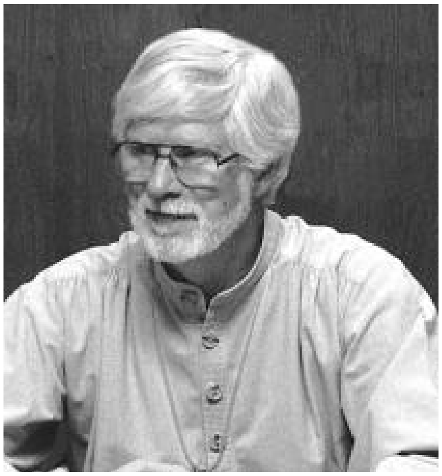
… Khariton and Pavlovskii took the initiative to give us a list of topics for possible collaboration when Dan Stillman and I visited Arzamas-16 in December 1991. Dan delivered that list to Sig.

In 1946, the Soviet reaction to the Baruch plan to put nuclear weapons under international control was, "No, but let's disarm totally." The statement was meant to create a political high-ground and at the same time serve the political interest of the Soviet Union, which was to have their own nuclear arsenal.

When put to the test, Gorbachev did not act as if he took these broader goals seriously. If you remember, it took him two weeks to admit that the accident at Chernobyl happened. Near the end of his reign, the United States put forward the Open Skies proposal, a transparency measure that had very little negative security consequences, but Gorbachev stonewalled on that, primarily in response to the concerns of his military.

I believe the real government-level changes didn't start until the coup, its failure, and then the collapse of the Soviet Union. And for anything that occurred prior to the collapse that portended later changes, one really needs to ask oneself whether or not that was the intention. Soviet diplomats and academics, for example, were traveling to international conferences and starting every statement with the words, "Now I offer only my personal opinion." It was somewhat surprising to all of us in that era of glasnost that all their personal opinions were the same!

Steve Younger: I agree with Joe in many respects. Certainly, information was tightly controlled until the 1990s. There were some publication of forbidden novels, but it was a crime to have them, and they were viewed as socially unacceptable, almost as pornography is viewed in this country. Foreign magazines and newspapers were available to only a very limited number of people. And Sakharov, the golden boy of their nuclear program, was treated very roughly, as were some of their other scientists. One other thing I'd like to mention. Sometimes Americans like to think that the Russians didn't really like communism and wanted to be just like us. But that's not true. Many of them believed in communism as a philosophical system that was better than capitalism. And many of them still do today. Until recently Russians lived in an element of fear. They were not "just like us" in this respect.



Paul White

I agree that the direction of the individual technical contacts was very different than the direction in which the government was moving at the time. … Then, when the political environment changed in December 1991, those relationships made it possible for a reaching out to occur with official sanctions and with a successful outcome.

Sig Hecker: It's probably true that the capitalistic system didn't look very good to them. After all, what was featured in their media year after year was the poverty, the street people, the crime, and all of that.

Joe Pilat: Look at the recent Duma elections. The communists are the top party. Even during glasnost, Gorbachev's behavior was often in contradiction to the goals of his book. Glasnost has come before in Russian history, and each time it passed by very quickly. All I'm saying is, if one talks about a wind of change, one needs to be very careful about how you attribute causality to it.

Paul White: I agree that the direction of the individual technical contacts was very different than the direction in which the government was moving at the time. Certainly the contacts between people like Max, and Krik, and others in a variety of circles, made it possible for the proposal for collaboration on fusion research that was made to Irv. It could not have happened without all that went before. Those contacts built a set of personal relationships and the first beginnings of some institutional relationships. Then, when the political environment changed in December 1991, those relationships made it possible for a reaching out to occur with official sanctions and with a successful outcome.

Steve Younger: Before the collapse, the Russians lived under a system in which they had just a few very close friends because, if they talked too freely outside that circle, they could end up disappearing one night, and their names would be removed from the official registers. So I don't think it's possible to overestimate the importance of these personal interactions. The relationship between Max Fowler and Pavlovskii, for example, during the initial stages of starting up the scientific interactions with Arzamas-16 was absolutely essential to getting things off the ground.

Sig Hecker: The progress since then was immensely faster because we happened to have a number of people who over the years have been able to build personal relationships, from John Shaner, to Max Fowler, to Don Eilers, to Hugh Casey, and so forth.

Part II The Lab-to-Lab Program in Scientific Conversion and Nuclear Materials Control

The Soviet Collapse and the Lab Directors' Visits

Sig Hecker: The big opportunity to get Washington support for direct collaborations with the Russian nuclear institutes came on December 16, 1991 in Leesburg, Virginia. Admiral Watkins, then Secretary of Energy, was holding a retreat for DOE Lab Directors. Many momentous events had already occurred in the Soviet Union, including the abortive coup attempt and Yeltsin's heroic stand, and it was clear that the Soviet Union was breaking up into separate independent states. President Bush was worrying about a possible "brain drain"of Russian nuclear scientists to would-be nuclear proliferants such as Iran and Iraq, and Congress was working on the Nunn-Lugar legislation to help prevent the Soviet nuclear arsenal from being broken up.

Watkins raised the topic of a brain drain with the Lab Directors, and so we organized a special evening session at which Vic Alessi outlined some background on arms control and nonproliferation. At one point Watkins, showing obvious frustration and concern, asked us, "What can be done to keep their scientists there?" Of course, I had been trying to get Washington interested in letting us work with their nuclear institutes for a year or more. I raised my hand and I said, "Let me tell you Admiral. If I were in their shoes, as a director of one of their institutes, I would have all kinds of ideas about how to keep my scientists at home. So why don't we go ask them?" Watkins responded immediately with, "Why don't you?" And at the end of that session, Polly Gault, who was his Chief of Staff, walked up to me and John Nuckolls and said, "Can you go to Russia before Christmas?" Christmas was too soon, but by mid-February their Directors were here, and by the end of February, John Nuckolls and I went over to Russia. Those were the first steps toward the lab-to-lab program.

"Let me tell you Admiral. If I were in their shoes, as a director of one of their institutes, I would have all kinds of ideas about how to keep my scientists at home. So why don't we go ask them?"

Los Alamos Science: *Did the DOE finally get behind the lab-to-lab effort?*

Sig Hecker: Yes, once Watkins said it was important, everyone felt liberated and became very supportive from that point on. And so our folks worked closely with the DOE and the State Department to make the visits happen. Also, Irv Lindemuth and Bob Reinovsky made a trip to Arzamas-16 in January, and we asked Irv and Bob to request that Directors Belugin and Nechai extend an invitation to the DOE Lab Directors to visit Arzamas-16 and Chelyabinsk-70. They evidently agreed immediately.

Irv Lindemuth: Bob and I made sure that we established, not just interest on the part of Belugin and Nechai, but also specific dates for the visits. We also delivered the first formal scientific seminars to be presented at Arzamas-16 by Americans.

Los Alamos Science: *Who was making it happen in Russia?*

Sig Hecker: I think Viktor Mikhailov was a substantial driver. He certainly gave his blessing to the Directors' exchanges, and it appears from all the stories we just heard that he may have masterminded the early visits to Arzamas-16 and Chelyabinsk-70 in 1990 and so forth. In all the deliberations that followed the initial Directors' exchanges, their Directors and scientists seemed able to call the shots and to guarantee that Mikhailov would approve.

Los Alamos Science: *In the initial exchange, Vladimir Belugin, the Director of Arzamas-16 and Vladimir Nechai, the Director of Chelyabinsk-70 visited Livermore and Los Alamos.*

Sig Hecker: Yes. And for the most part the interactions were quite formal and even suspicious. The friendliest part was an interaction between Boris Litvinov and my wife at our museum.

My wife speaks Polish, and it turned out his Ukranian and her Polish were close enough that they could actually carry on a conversation.

Steve Younger: But for me there was certainly some scientific excitement during their visit to Los Alamos, especially during the lecture that Pavlovskii delivered. It was the most exciting physics talk that I ever heard. He spoke about nuclear reactors and atomic physics and plasma physics and pulsed power and lasers and everything you could think of, all with the air of someone who had worked extensively in every area. I knew right then that no matter where he was from, we had to work with him.

Los Alamos Science: *Sig, in what way was the visit to Russia different?*

Sig Hecker: From the moment we stepped off the plane at Arzamas-16, the offer of friendship was obvious. I had brought John Immele, then Associate Director for Nuclear Weapons, and John Shaner from Los Alamos, and John Nuckolls, then Director of Livermore, had brought along George Miller and Chuck McDonald. That evening Khariton gave a talk on the early days of nuclear weapons. He talked about his doctoral work in the UK at the Cavendish Laboratory under Rutherford from 1926 to 1928, and he related the story of why they copied and tested our device when they were first designing their atomic bomb—they knew it would work, and their lives were at stake.

The next morning John Immele and I experienced the pleasing irony of being the first two Americans to take an early morning jog in this once secret city. The temperature was a grizzly minus 5 degrees fahrenheit, but we couldn’t turn down the opportunity. The first morning a guard restricted our run to the circumference of a nearby soccer field. But afterwards I complained to Belugin, and then John and I were free to run into town, through apartment building complexes, and in

Left to right: V. Chernyshev, I. Lindemuth, L. Gerdova, R. Reinovsky, Alevtina, and N. Bidylo during Lindemuth’s and Reinovsky’s January 1992 visit to Arzamas-16. They are standing in front of the house once occupied by Andrei Sakharov.

Discussions in the House of Scientists at Arzamas-16 during the February 1992 visit by DOE Lab Directors. In the foreground, John Immele (right) sits across from Alexander Pavlovskii and Sig Hecker sits across from Yuli Khariton.

The participants in the February 1992 Directors’ exchange visit are standing in front of the monumental statue of Igor Kurchatov (scientific leader of the Soviet nuclear energy program) at the nuclear design institute at Chelyabinsk-70.

their beautiful woods along the river.

We were also treated to fine dinners every night, and of course, the Russians like to drink vodka and make toast after toast. The best toast I gave was at the big banquet at Arzamas at the end of our stay there. I said, “Now after fifty years of competition and being adversaries, we are learning to work with the Russians, and we are finding that we have much in common. However, we all know that competition is important to success. So thank God for Livermore! But, then maybe we can learn to work with them as well.” They all broke out in laughter—because the relationship between Arzamas-16 and Chelyabinsk-70 is just as competitive as the relationship between Los Alamos and Livermore.

John Shaner: We spent some time at Chelyabinsk-70 during this visit to Russia. And while there, we worked out the beginnings of an agreement for collaboration with both institutes.

Sig Hecker: The scene at Chelyabinsk-70 was fantastic. There we were, people from Los Alamos and Livermore, and then Chelyabinsk-70 and Arzamas-16, sitting around a table crafting this document in Litvinov’s office with a picture of Lenin on the wall and beside it, a big picture of Kurchatov, the scientific leader of the nuclear energy program.

John Shaner: It was like the Tokyo stock exchange. People running around

During the Directors’ exchange visit of February 1992, the tour bus at Arzamas-16 stops at the firing site where several old flux compression generators are on display.

Pavlovskii shows Directors Sig Hecker and John Nuckolls a laser lab at Arzamas-16.

with sheets of paper yelling and screaming in at least two different languages.

Sig Hecker: We would get into roadblocks because the same word means different things in Russian and English. The amazing thing is we came up with an agreement. And, of course, the Russians wanted us to sign it, so we did, but only after including a large number of caveats that the agreement was not binding without U.S. government approval. The list of topics for collaboration began with scientific experiments and then went down through nuclear materials control, nuclear safety and security, and various arms-control-related things. We promised to take it back to Admiral Watkins for approval, and they said they would take it to Mikhailov.

Los Alamos Science: *Was there any indication during that first visit or later that their scientists were worried about a brain drain, an exodus of talent and ideas?*

Sig Hecker: It was certainly apparent that they were facing economic hardship, but they did not approach us on that basis. They made it clear from the beginning that what they wanted from us was collaboration. Pavlovskii, in particular, indicated very forcibly during the Los Alamos visit that they were not interested in welfare. They clearly felt that they were our equals and did not want to be treated in any other way. And more to the point, they said that being able to demonstrate that they could work with Los Alamos on scientific projects would buy them significant credibility with their government. That was a key issue. In due time we also realized that they knew a few U.S. dollars went a long way in Russia, and that fact was, of course, very important in all that has happened.

John Shaner: Sig, during that first visit to Russia, we also tried to get them interested in participating in ISTC.

Sig Hecker: That’s right. John is referring to the International Science and Technology Center, which was spawned by Secretary of State Jim Baker in connection with the Nunn-Lugar program. The idea was that the United States, the European Union, and Japan would provide funding to help keep scientists from the New Independent States busy working on non-nuclear-weapons-related topics. So that initiative had some of the same motivations as our lab-to-lab effort (see “The International Science and Technology Centers in the Former Soviet Union”). Our government really wanted the Russian defense labs to take advantage of the ISTC funding mode. I pushed that pretty hard at Arzamas, but Belugin and Trutnev were extremely negative. They saw working with us as a ray of hope and a mechanism for keep-

Pavlovskii shows the DOE Lab Directors his laboratory for ultra-high magnetic field experiments.

ing their people stable and working, but they saw ISTC as nearly worthless. I told them that if they refused to cooperate with this international effort, it would put us in a rather difficult position. Their response was interesting. They said that as we get closer to sensitive issues such as those associated with nonproliferation, they didn't mind sharing with us, but they wouldn't want to share with this kind of broader international community. So despite the years and years of being Cold War enemies, they had a lot more trust and more interest in working with us than with any neutral parties. Later on, of course, they did get involved in the ISTC program.

John Shaner: Right now, they probably have a quarter to a third of the total ISTC funding, which is about 84 million dollars. ISTC didn't start dispersing real money until 1994, but then the scientists at Arzamas-16 and Chelyabinsk-70 got involved.

Los Alamos Science: *The Nunn-Lugar program had been announced prior to your trip, so the Russians must have been expecting some financial commitment.*

Sig Hecker: Yes. Before leaving Russia, we had a close-out dinner with Mikhailov in Moscow and he was already complaining about the lack of action and the lack of money. If I hadn't met him at the test site, I would never have suspected that he was a very dedicated knowledgeable scientist. He acted much more like a hard-nosed Russian bureaucrat. Afterwards though, Nechai and Belugin assured us that Mikhailov would support the collaborations if we could get approval by the U.S. government.

Don Eilers: I'd like to say a few words about Mikhailov's position. As minister of MINATOM**,** Mikhailov is responsible for ten closed cities and twenty-five other cities that make up the nuclear-weapons industrial complex. And he always gave the impression that it was his personal responsibility to make sure that each of the one million people who worked in that complex was supported somehow. He feels a tremendous sense of responsibility.

Sig Hecker: It seems that Directors Belugin and Nechai feel the same way. During our visit they proudly told us that the MINATOM complex is responsible for about half of the gold mining in the country and about a third of the fertilizer production. MINATOM also built the 1980s stadium for what was to be the Olympics in Moscow. The reason they gave was that the MINATOM complex was an organization that worked, whereas much of the rest of Russia was not functioning very well. Now the gold stems from uranium mining, and the fertilizer is closely related to the production of explosives. So those activities are not so surprising. But the MINATOM cities were doing many other things that were not so obviously related to nuclear weapons and nuclear power.

What struck me most, though, was the enormous commonality we had with the Russians from Arzamas-16 in terms of how we treated our jobs, how we felt about the science we had to do, how we understood the reasons it needed to be done, and the patriotism we felt for our country. As I listened to them talk, I could swear, except for the translation, that they were telling our story. Belugin was giving the pitch I used to give about nuclear testing, and Trutnev was trying to convince me of why we can't possibly have a comprehensive test ban. I listened and then I said, "We've made all those arguments. We've lost those arguments. And just like us, you have to start thinking that you have to do this job in another way." And so the feelings about our jobs are just about as identical as you can get.

The Lab-to-Lab Effort: Getting It Off the Ground

Sig Hecker: On the way back from Russia, John Nuckolls and I stopped to see Watkins and presented him with the agreement we had constructed with the Russians. Just about instantly he gave us the go-ahead to do the scientific col-

A picnic in a meadow at Arzamas-16 during the June 1992 visit by the Los Alamos pulsed-power group.

During the June 1992 visit, Steve Younger (second from left) sits across the table from Yuli Khariton and discusses the Los Alamos response to the topics for collaboration proposed by the scientists at Arzamas-16.

laboration. And that was the birth of the lab-to-lab program. He also said that all the other topics needed to be approved and worked through the same government interagency process that all Nunn-Lugar programs were subject to. So he could not approve nuclear materials control and accounting or even the environmental topics.

John Shaner: I guess we had gotten a little carried away with respect to nuclear-weapons safety and security issues, and the National Security Council said, "There's no way you are going to do that without interagency oversight."

Sig Hecker: When we got back to Los Alamos, John Immele asked Steve Younger if he would like to be involved. Steve, as program manager for ICF (inertial confinement fusion), was already working in the area of pulsed power and was interested in working with Pavlovskii. So he picked up the ball and really started to run with it.

John Shaner: Next, in May 1992, Paul Stokes from Sandia, Bill Dunlop from Livermore, and I had a meeting with Vic Alessi and Bob Galucci from the State Department in which we established the ground rules for the lab-to-lab process, including getting everything briefed in Washington and supporting other State Department activities such as ISTC. Galucci was the one who led the group trapped in the Baghdad parking lot at the end of the Gulf war, and he also negotiated the agreement with North Korea to stop reprocessing their reactor fuel. We were lucky to get his attention to our projects in between those events. Later in May 1992, Steve Younger and I and others from Los Alamos, Sandia, and Livermore went to Moscow to meet with the Russians and lay the groundwork for scientific interactions.

It took another eighteen months for ISTC to get all the bureaucracy in place and to actually dispense money. Our lab-to-lab effort was able to start right away and included actual contracts to be paid by our own laboratory-directed research and development (LDRD) funds as well as expert exchanges in the topics for which we'd agreed to develop proposals.

Steve Younger: At that May 1992 meeting, a curious thing happened. Although I was not the head of the delegation nor an expert on Russian science, Pavlovskii singled me out and said, "I want to give you a list of proposed topics of collaboration, and I want you to write comments on it and give it back to me in the morning." I was later told that the Russians at Arzamas-16 had picked me as their principal representative in the United States. Perhaps it was because I was in charge of the Los Alamos pulsed-power effort, which was the area of collaboration that Pavlovskii and his colleagues had been pushing for some time. In any case, I marked up the list and crossed out huge sections because some of them were very sensitive and others were outright classified. It was apparent from their list and from the interactions at that meeting in May that one reason the Russians wanted to work with us was because we were the other nuclear superpower, and they wanted to work on nuclear things. They said, now that the Cold War is over, let’s work together to exploit the peaceful opportunities of nuclear explosives or nuclear energy, but also as the nuclear stewards of the superpowers, it’s our responsibility to work together. Our response to many of their proposals was that we weren’t allowed to talk about many of the things on their list, but there were some topics that were real possibilities.

Los Alamos Science: *When did you reach a substantive agreement on joint projects?*

Steve Younger: One month later during our visit to Arzamas-16, we worked out a specific agreement. Other members of the Los Alamos pulsed-power group went with me: Max Fowler, Irv Lindemuth, and Bob Reinovsky. The week started out in a less than congenial fashion with Belugin’s saying to me, “I’m tired of Americans coming to the Institute and making promises and not delivering anything. Americans talk, talk, talk but never do anything. Unless this meeting results in something substantive, this will be your last visit to Arzamas-16.” Then he got up and walked out of the meeting room. Pavlovskii then asked to me to give the American response to the 11-page list of topics he had handed me in Moscow. Khariton was sitting across from me taking detailed notes as I spoke. We were all in roles we could never have anticipated. During the week we carried out a delicate dance as we explored which projects in pulsed power were of mutual interest. They also demonstrated one of their pulsed-power generators, and they invited Max to be the first American to press a detonator button at a Russian nuclear weapons institute.


Steve Younger

We wanted to develop real collaborations, to work side by side as equals. That phrase is very important, because there were a lot of Americans running around the country… buying Russian technology for a song… Instead, we were saying, “We’re going to be here this year, we’re going to be here next year, and if politics allows, we’re going to be here ten years from now.

Max Fowler: Yes, it was my one and only visit to Arzamas-16, and they honored me by letting me push the button. Pavlovskii was still alive then.

Steve Younger: Max was also the first American to accept payment for working at Arzamas-16.

Max Fowler: Yes, I told Pavlovskii, “You know, I’m working for you now, and I would suggest payment—maybe an extra vodka toast.” They later gave me a bottle of vodka as payment, and everyone signed the label.

Steve Younger: During that trip we also became acutely aware that many of the scientists were facing financial catastrophe. And I’m not using that word lightly. It’s one thing not to be able to replace the TV if it breaks. It’s quite another not to be able to buy insulin for your kid who is a diabetic and who is going to die unless you find some money. That’s the kind of financial pressure they were facing.

Irv Lindemuth: Even that past January, when Bob Reinovsky and I visited, we saw that the people were extremely concerned about their future. Inflation had taken off. They had missed a few pay checks. And they didn’t know what the future would bring. During the June visit Steve made it clear to them that we wanted a real collaboration, that we were there for the long term, and that real dollars would be involved. We also expressed our concern on a more personal level, which eventually grew into an exciting cultural and humanitarian exchange between the Los Alamos and Arzamas-16 communities—what we call the sister city connection. (See “Arzamas-16 and Los Alamos—The Sister City Relationship”)

Steve Younger: The week was successful on a number of levels. By Friday we had identified six topics in pulsed power and had written and signed a protocol saying we were going to do experiments on two of those topics, we were going to find funding for the experiments, and we were going to carry them out within the next fiscal year. When I got back to the United States, I wrote to Mikhailov saying that, in my opinion, a collaboration existed between Arzamas-16 and Los Alamos.

Then, over the summer we worked out the difficult process of how to finance these activities and how to write suitable contracts.

Sig Hecker: Steve came to me and suggested that LDRD funds would be the most neutral funding source and quite appropriate because we were going to engage the Russians in basic scientific enterprises. But we were on extremely thin ice in terms of the funding.

Left to right: I. Lindemuth, S. Younger, V. Chernyshev, R. Il'kaev. and Y. Tuminov visit the new Weapons Museum at Arzamas-16 in September 1993 prior to the first joint experiment. The museum was inspired by the Bradbury Science Museum at Los Alamos.

Steve Younger: There were many people in the United States who didn't want us to work with the nuclear institutes. They were afraid we might be working on nuclear weapons and giving away secrets. Or maybe we were all spies, or maybe all the money we spent would go to the communist party.

Irv Lindemuth: John and Steve took many trips to Washington to inform people that we were going to spend LDRD money for this purpose. Although some people raised flags, most were glad that somebody was doing something.

Sig Hecker: John and Steve pounded the pavement until they won the support of the folks at the DOE. DOE didn't come up with any money. We had to go into our own coffers, but the DOE did back us up so that we could get this money to the Russians.

Steve Younger: We had another big problem, and that was how to move money because there was no precedent for this type of collaboration. John Shaner and I came up with the concept of deliverables. When they delivered the work, we'd give them the money. Since no up-front money was involved, there was no way to complain that the money was being used for some inappropriate activity.

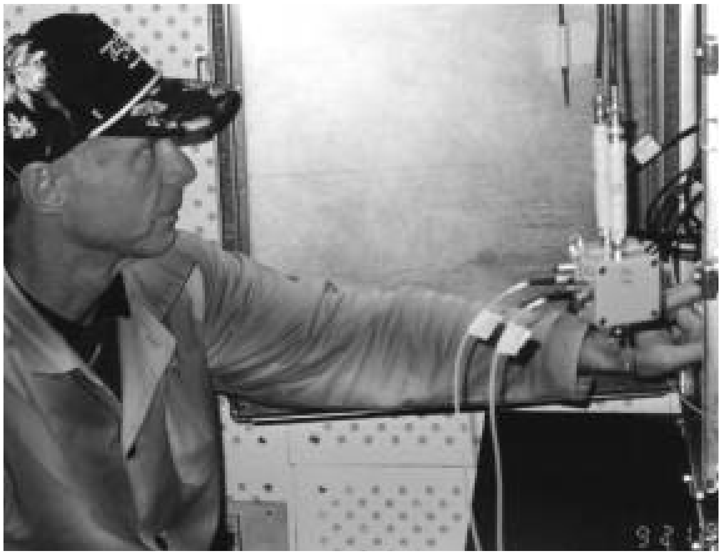
Sig Hecker: In contrast to the government-to-government approach, which we will be discussing shortly, we decided not to keep track in detail of what our Russian collaborators did with that money. We didn't know whether they had to pay taxes or support infrastructure. The only thing we knew is that we got one heck of a lot of return for the money that we gave them.

Steve Younger: And they feel they received a fair exchange for what they gave us. But that summer of 1992, we had many table-pounding conversations in which they would say we were paying them too little, and we would say, "Hey look, this is how much money we have. You claim you have lots other buyers? Where are they?" And after calling their bluff, we would come to an agreement. Then, in October 1992, Pavlovskii and Chernyshev came to Los Alamos to sign the first contracts between Arzamas and Los Alamos.

Los Alamos Science: *What was the agreement in those first contracts?*

Steve Younger: We formalized what we had agreed to in June, namely, to collaborate on two experiments. One was a test of Chernyshev's very big high-explosive pulsed-power generator to be done at Arzamas. The second was a series of experiments in which Pavlovskii's generators would be used to produce the ultra-high magnetic fields and apply them to the measurement of the critical magnetic fields of high-temperature superconductors. That series was to be done at Los Alamos in Ancho Canyon (see "Lab-to-Lab Scientific Collaborations between Los Alamos and Arzamas-16 using Explosive-Driven Flux Compression Generators").

The contracts included dollar amounts for various deliverables. For example, to test Chernyshev's generator at Arzamas, we agreed to pay 100,000 dollars, and for the second set of experiments at Ancho Canyon, we paid 100,000 dollars for five of Pavlovskii's high-magnetic-field generators, and we paid the way for the Russians to come to Los Alamos. The funding for both came from LDRD, and all of that money went to Russia. At that time



Scenes from the first joint Los Alamos-Arzamas-16 experiment in September 1993. The purpose was to test the DEMG, Chernyshev's high-current generator. Top left: Lynn Veeser makes final adjustments to Los Alamos diagnostics. Top right: The experimental group poses at the firing site on the evening before the test. Right: Americans, dressed in VNIIEF protective clothing, pose before Chernyshev's generator.

DOE did not want money that had been appropriated for the U.S. nuclear weapons program to go to Russia. Afterwards, that restriction was relaxed, and we were able to spend programmatic money. This year we will send about 550,000 dollars to Russia. This money will fund unique science that neither side could do on its own.

Krik Krikorian: As a contrast, it cost us almost 300,000 dollars in 1982-1983 to replicate the Pavlovskii generator for project LIGA.

Los Alamos Science: *Pavlovskii died February 12, 1993. Since his relationship with Max Fowler was one of the mainstays of trust for building the collaboration, were you concerned that his death might threaten progress ?*

Steve Younger: Yes, very. At the

Preparations in Ancho Canyon, Los Alamos in September 1993 for a shot to measure the critical field of high-temperature superconductors.

Bob Reinovsky (right) is in the instrumentation trailer at Ancho Canyon giving instructions to Olga Tatsenko about the next joint experiment in the series.

time we received notice of his death, Carl Ekdahl, Denny Erickson, Jim Goforth, Irv Lindemuth, Bob Reinovsky, and I were within a few days of leaving for a visit to Arzamas-16. We had to postpone the visit, and Irv scrambled to reconstitute the visit within a few weeks. As soon as we arrived in Arzamas-16, they took our team to see Pavlovskii's grave, which was mounded with flowers. We added a large basket with the inscription "From the American colleagues," and the whole scene was recorded by the Russians on videotape.

At the big banquet that evening, I was seated next to Yuri A. Trutnev, the deputy chief scientist at Arzamas-16 under Khariton and also a leading designer of nuclear-weapon secondaries. To begin with, Trutnev was extremely skeptical about the joint work with us. He did not see a path to real collaboration and worried about our buying technology and walking away. But we spoke intensely through the entire banquet—so much so that during one of the breaks (Russian banquets are marathon affairs so they have breaks!), one of the officials at Arzamas said to Trutnev, "You are not allowing Steve to eat. He must be hungry." Trutnev merely pushed him away. Neither of us ate anything that evening, but by the end we were great friends, and Trutnev understood that we were all dedicated to the national security mission of our respective laboratories and that working together might promote the stability and integrity of both institutions. As to how to do it, that dinner was the origin of the "step-by-step" approach that became the cornerstone of the lab-to-lab process.

During that week, they began to understand that we were there for the long haul. We didn't want to steal their technology and run. We wanted to develop real collaborations, to work *side by side as equals*. That phrase is very important, because there were a lot of Americans running around the country touting the fact that they were buying Russian technology for a song, that the Russians weren't business men, so they were able to rob them blind. Instead, we were saying, "We're going to be here this year, we're going to be here next year, and if politics allows, we're going to be here ten years from now."

Los Alamos Science: *Did all go smoothly after your March visit?*

Steve Younger: Not exactly. The first experiment was set for August 1993 in Arzamas. But shortly before the scheduled date, I received word that the experiment would have to be delayed because they were not ready. I lost my temper at that point and had Irv Lindemuth call Chernyshev at 1:00 am Arzamas-16 time. I told him that I wanted an explanation and I would be in Moscow to be picked up at the appointed time. During that visit we were taken, as a kind of consolation prize, to their device assembly area, which is one of the tightest security areas at VNIIEF (the nuclear institute at Arzamas-16). And there, behind so many fences that I lost count of the number, we saw Chernyshev’s generator. It is a column ten feet tall and is mounted vertically. The whole time we were surrounded by a ring of Russian technicians, each one a huge bear of a person. And when we moved even twenty feet from the generator, they would let us know we were out of line by literally bumping up against us. At one point Jim Goforth stood on a chair to view the top of the generator, and one of those big burly Russians came over, and with a big smile, just picked up Jim at the knees with one arm to give him a better view.

One month later, that was September 1993, we were back for the first joint experiment. The Russians were clearly very excited about it. They held a news conference before the shot. Mikhailov, who was out of the country, was being given daily reports about our progress. And three TV crews were out at the firing point to witness the actual test. Chernyshev’s generator outfitted with American diagnostics was flanked on either side by a Russian and an American flag. The tension was so high you could have cut it with a knife. Everyone worked feverishly to get ready for the countdown, and then five, four, three, two, one . . . The bunker shook and we knew immediately that all had gone well. There was a tremendous shaking of hands and congratulations and on-the-spot interviews by the press. At that very first joint experiment, everyone was aware that we were making history.

At the banquet the next night, when all the pressure was off and after the usual toasts, someone began playing an accordion and there developed a most amazing sight—Russian and American weapons scientists dancing together and telling jokes and trading family pictures at what had been the most secret place in the Soviet Union. I was reminded of the statement by former Laboratory Director Norris Bradbury that the purpose of nuclear weapons is not to wage war, but to give the politicians time to solve the problems.


Sasha Bykov gives Steve Younger an enormous bear hug after the first joint shot at Ancho Canyon.

… I’m rather proud of [the critical magnetic field] work. It was also a historic series in the sense that those were the first joint Russian-American experiments done behind the fence at Los Alamos.

Max Fowler: The next month, a team of eight Russians came to Los Alamos to do a series of high-magnetic-field experiments using a Pavlovskii generator and some of our own as well. We were able to measure the value of the critical magnetic field in a high-temperature superconductor and how that value changes with temperature. I guess I’m rather proud of that work. It was also a historic series in the sense that those were the first joint Russian-American experiments done behind the fence at Los Alamos.

Sig Hecker: After those successes, Steve was able to engineer a major lab-to-lab umbrella contract with Arzamas-16 that would allow the two labs to work together on scientific topics of mutual interest. We put a cap on the amount that could be spent, a total of 2 million dollars, and identified a large number of potential topics for collaboration. The first task orders were written in a mid-night meeting in Jim Jefferis' office that involved Steve, John, and Valeri Zorya from Arzamas-16. By then, Steve had been able to deliver money for the experiments that we just talked about, the first money that Arzamas had received from the United States, and so Steve was really golden in their eyes. They trusted him and they liked him. Similarly, in January 1994 when Director Belugin and Radi Il'kaev came here for the big signing ceremony, a real friendship developed between Belugin and me. He was at my home for dinner, and I have photos of him watching me carve the turkey in my kitchen and later singing Russian folk songs in my dining room.

Los Alamos Science: *Is the umbrella contract still in effect, and what has been done under it?*

Steve Younger: Yes, it is still in effect and it has become the mainstay of our collaboration. Rather than having to hash out all of the legal details on every contract, the Master Task Order specifies this up front so that work can begin with as little as a two page task order. This is why Los Alamos was able to move so quickly. Similar agreements are now in place with many other Russian institutes, and other U.S. labs have copied our idea.

Irv Lindemuth: In terms of the pulsed power work, following the initial experiments Steve mentioned earlier, we did six additional experimental campaigns covering a spectrum from pulsed-power technology to solid-state physics to controlled fusion.

Sig Hecker: In retrospect, the end of 1993 through the beginning of 1994 was the time when the lab-to-lab effort really began to take off. The pulsed-power work with Arzamas-16 was securely established, but also the Industrial Partnership Program was born.

A flux compression generator is on its side at Chernyshev's firing site at Arzamas-16 in April 1994 and is being prepared to measure the properties of magnetized plasmas.

Steve Younger: The importance of the Industrial Partnership Program (IPP) and also the umbrella contract were highlighted in the August 1993 visit before the first joint experiment. During that visit, Director Belugin called me aside for a private conversation with no security people present. Only Valeri Zorya, senior manager at Arzamas was there to translate. Belugin said to me, "The Americans have made a lot of promises, but we have not received any money. We are facing extreme hardship. We are not receiving regular salaries from our government, we do not have money to buy medical supplies for our children, and we are getting desperate. If America isn't going to help us, we are going to have to do something else."

On my return, I reported this conversation to Senator Pete Domenici. That's the origin of Domenici's summary of the plight of the Russian nuclear scientists, "You're driving us into the hands of the Chinese." He said that on the floor of the Senate during his plea for a foreign aid appropriation to support to the Russian scientists. During the fall of 1993, Irv Lindemuth and I went all over Washington to drum up money and support, and to sell the idea of scientific conversion, the idea that we need to support Russian nuclear scientists to do non-nuclear scientific work. John Shaner and I developed the concept of scientific conversions—engaging the core Russians nuclear weapons experts on topics of basic scientific interest and integrating them into the international scientific community. After all, you weren't going to convert a secondary designer into a designer of bicycles. They were proud of their skills. Scientific conversion tried to apply those skills to peaceful projects, sort of a half-way house in getting them into long term, Russian-funded research projects. At the same time, John Hnatio, a DOE employee on assignment with Domenici's staff, was trying to develop the concept of an industrial partnership program with the scientists of the former Soviet Union.

Hugh Casey: Yes, this was an extremely fortunate coincidence. John Hnatio was the DOE program manager who was in charge of the early stages of the technology transfer program at DOE and helped us acquire the gyrotron equipment from the Ukraine that we had first discussed at the MATec conference back in 1988. He was also instrumental in setting up the Special Metals Processing Consortium at Sandia National Laboratory. Those two programs involved Russian technology, and when John moved to Domenici's office, he proposed them as models for partnering among industry, the national labs, and the Russian institutes.

John formed a lab team from Los Alamos, Lawrence Livermore, Sandia, Argonne, and Oak Ridge National Laboratories to develop a program plan that DOE could propose to the State Department. Domenici initiated legislation to provide funds. And those actions resulted in the development of the program (see "The New Independent States Industrial Partnership Program").

IPP differed from ISTC in encouraging direct interaction between U.S. laboratory and NIS institute staff. Also the IPP concept involved an 'exit strategy' whereby the funding responsibility would transfer from the government to private industry over the life of the project. Technology transfer and commercialization were to be used as a nonproliferation tool to prevent "brain drain."

John Shaner: The congressional language stated that the program was to address institutes and scientists with knowledge of weapons of mass destruction. The other criterion was that funds be used for projects that were potentially self-sustainable economically. IPP has an end game of self-sustainability.

Los Alamos Science: *What level of funding was obtained for IPP?*

Hugh Casey: Domenici succeeded in getting an appropriation of 35 million dollars for fiscal year 1994, which was intended to grow to 50 million dollars for fiscal year 1995 and continue for a period of five years at which time we hoped that projects would be supported entirely by private industry. In fact, we received the 35 million dollars at the end of fiscal year 1994 and only after great bureaucratic arm wrestling. We received no funds in fiscal year 1995, but we have 10 million dollars of DOE funds for fiscal year 1996, and we expect an additional 10 million dollars of DOD Nunn-Lugar funds for this year. Despite the funding struggles, the program has been most successful, and we are aware of Senate-committee recommendations calling for increases in funding for fiscal year 1997 and beyond. We are extremely optimistic about the future of IPP.

John Shaner: Along with these efforts, we have continued to support other government programs such as ISTC. As early as October 1992, we had the first of our topical expert exchanges that had been worked out during the previous May meeting. Fourteen of us from Los Alamos, Sandia, and Livermore flew to Chelyabinsk-70, picking up a contingent from Arzamas-16 on the way, for a week-long conference on environmental science. As a result of that conference, we not only got to know a new set of faces, but we also worked out a set of twelve proposals for joint work. To date, seven or eight have been funded through ISTC. We have also held technical meetings on reactor safety, applied math, and computer science.

Hugh Casey: It's interesting that we have experienced spontaneous integration of ISTC and IPP projects. That increases the possibility of funding larger projects and also brings industry in as a full partner in the early stages of these projects.

One last point. In all my experience with international exchanges, including those with the British, the French, and the Japanese, the Russian exchanges provide the only example in which technical information is flowing predominantly into, as opposed to out of, the United States. The former Soviet Union is our technological equal in many areas, and because of the economic crisis in the New Independent States, we are gaining valuable knowledge for modest investments. This fact is not appreciated by those that dismiss our efforts as "foreign aid," and "industrial welfare."

Nunn-Lugar and the Lab-to-Lab Materials Control Program

Sig Hecker: We are at a point to tell the nuclear material controls story, which has been my primary interest from the beginning. Shortly after Secretary of Energy O'Leary was appointed, I wrote a letter to her and identified the control of nuclear materials in the former Soviet Union as the most important national security issue facing the DOE. I did not get much of a response from Washington until over a year later in April 1994 when Charlie Curtis was appointed as Under Secretary in charge of national security programs. Our introductory meeting happened to be on the day after he had been taken to task at a Congressional hearing on reported thefts of nuclear materials in the former Soviet Union. The hearing was instigated by Tom Cochran of the Natural Resources Defense Council and other antinuclear watchdogs. There were complaints that the government-to-government efforts in nuclear material control under Nunn-Lugar were bogged down, that we were at loggerheads with the Russians, and that nothing much was being done to prevent theft of these dangerous materials.

When I walked in to see Curtis, I started giving the speech on materials control that I'd been giving for almost a year. Curtis responded immediately with, "What do you want to do?" And I had a plan in my back pocket that had been laid out at the Los Alamos meeting in January 1994 when Belugin and I had signed the lab-to-lab umbrella contract. At that time Mark Mullen, Ron Augustson, and some of the folks from Arzamas-16 had suggested that a lab-to-lab materials control component to be included in the lab-to-lab umbrella contract. They were very frustrated with the lack of progress on the big storage facility they had been working on through the Nunn-Lugar channels, and they also explained that the Nunn-Lugar effort to institute materials control at civilian institutes was floundering. Consequently, the lab-to-lab channel looked like a much more hopeful route to improving materials control in Russia. Don Cobb, Program Director for Nonproliferation at Los Alamos, discussed this possibility with Belugin and myself at that January meeting, and we all agreed that it was a good idea.

But remember, we were under some restrictions set by DOE. John Birely, Paul White, Ron Augustson and many other folks at the Lab were working in the government-to-government mode since 1992 because Watkins had told us that all topics other than pure science had to be considered through the interagency process associated with the Nunn-Lugar legislation.

Los Alamos Science: *Before we go forward with the lab-to-lab materials story, let's backtrack for a moment and ask Paul White to give us a little background on the purpose of the Nunn-Lugar program.*

Paul White: The Nunn-Lugar effort grew out of a meeting in September of 1991 between Bush and Gorbachev. They were proposing literally unprecedented reductions in nuclear warheads, especially tactical warheads, some of which were agreed to under START I or planned under START II. They also began talking specifically about dismantlement of those warheads. Noting the economic burden involved, Bush offered U.S. assistance for the dismantlement of those strategic and tactical systems. The official implementation of that offer came in November of 1991 with the so-called Nunn-Lugar program, which authorized the use of 400 million dollars of Department of Defense funds, funds that had already been appropriated for other things.

The program got off the ground in March of 1992 at a big meeting with the Russians involving 60 representatives of the United States. Some of the framework agreements under which Nunn-Lugar assistance would be provided were crafted at that meeting. The movement of missile systems and warheads back to Russia would increase the exposure of these systems to the possibility for an accident, so emergency response equipment was one area of assistance that was on the table. Other areas for assistance included storage facilities for putting the materials that would come out of dismantlement, containers for moving the materials, increased security and protection for the warheads while they were in transit, and material control and accounting systems for the storage facilities. Materials control and accounting systems for civilian nuclear facilities were also discussed at that time.

Shortly after Secretary of Energy O'Leary was appointed, I wrote a letter to her and identified the control of nuclear materials in the former Soviet Union as the most important national security issue facing the DOE.

Los Alamos Science: *Was there any indication that the Russians were worried about the security of their nuclear materials?*

Krik Krikorian: By that time the Soviet Union had become a confederation of independent states, and nuclear weapons were in the Ukraine, Belarus, Kazakhstan and so on. Somehow those weapons had to be brought into Russia and put somewhere and disassembled. But the physical security forces were no longer reporting to one government, so there were inherent problems of materials control.

Paul White: Actually separate agreements were crafted with Ukraine, with Kazakhstan, and with Belarus. The agreement with the Russian Federation really emphasized a new look at the existing system of government security and accounting for nuclear materials and then the development of appropriate changes to accommodate the new political situation. There weren't really any discussions about weaknesses in the basic security. But during informal conversations, one of the first questions some Russians asked me was how to deal with the question of personnel reliability at their nuclear facilities.

John Shaner: And in the less formal lab-to-lab context, I remember one of the chief designers at Arzamas-16 saying, "You Americans are lucky. Your borders have always been permeable and your military not very well disciplined, so you had to design these materials controls into your system. We had impermeable borders and a well disciplined military until a few years ago, and now we have neither, and we don't have those controls designed into our system." So the scientists already knew that there was a potential problem there.

Steve Younger is flanked by Radi Il'kaev and his wife Lydia after a late night meeting at Arzamas-16. To the right of Lydia are Yuri Romanov, who wrote the computer code for the design of the first hydrogen bomb, and Vladimir Rogatchev, the deputy director of the theoretical division. Their friendship was instrumental in helping to start the lab-to-lab materials control program.

In June 1994, Directors Belugin and Hecker sign contracts to build a materials control demonstration at Arzamas-16 as Il'kaev (seated), Augustson (standing at back left), and others look on. The demonstration was up and running by January 1995.

Sig Hecker: John's comments hit the nail right on the head in terms of the overall security problems of both the weapons and the materials. But the materials control and accountability issue was one of the most difficult things to get the Russians at Arzamas-16 and Chelyabinsk-70 to talk about. During our February 1992 visit, I asked questions and essentially got no answers. At Arzamas-16, I told them I had a personal interest in plutonium, and I kept asking, "Where do you do the plutonium work?" At Arzamas-16 they said they do it someplace else. In Chelyabinsk-70 they actually toured us through their plutonium lab, which was up on the third story of some building.

John Shaner: Right above the tritium lab.

Sig Hecker: It's clear they would not have passed inspection by Admiral Watkins' Tiger Teams that had just been through Los Alamos. I would ask them, "Suppose there was some sort of a threat in the country and you would have to ascertain within a couple of hours whether you have all of your plutonium. How would you respond to that kind of question." I just got this stony silence.

Paul White: These materials control issues are so closely tied with their security system that they constitute a very difficult area for them to talk about. The initial contacts on materials control were at the government level under Nunn-Lugar. And they weren't about to admit officially that they had difficulties. So progress was agonizingly slow, particularly in that area.

Ron Augustson: Mark Mullen and I participated in the government-to-government program to design and build a storage facility for retired nuclear warheads, and our job was to design a modern MPC&A system, that is, Materials Protection, Control, and Accounting system, for the facility. It turns out that our Russian counterparts for this task were Radi Il'kaev, Sergei Zykov, and Vladimir Yuferev from Arzamas-16. We first met them at the meeting held by the U.S. Corps of Engineers in Omaha, Nebraska in August 1992. At that time they expressed their commitment and responsibility regarding the retirement and disposal of nuclear weapons. Il'kaev said very earnestly to Mark and me, "Arzamas-16 and Los Alamos have caused this problem, and it is up to us to solve it."

However, progress on the storage facility was extremely slow. Meetings were held through 1992 and 1993, but everything was bogged down in the politics and administrative requirements of working with the Department of Defense. There was no money to pay the workers in Russia to build the facility and no money to buy Russian materials and equipment. The DOD wanted all the money to be spent here in this country. On the other side, the Russians did not admit the importance of our particular interests, which were safety analysis and protecting materials from insider threats.

It was all very discouraging, but we did continue to talk with Il'kaev and particularly with Zykov and Yuferev. For example, Mark met them in October of 1992 at a Nunn-Lugar-sponsored seminar in St. Petersburg on MPC&A. There were about a hundred Russian participants, but Mark spent most of his time with the folks from Arzamas-16 and started to communicate more intensely. He also began describing to them the components of a modern computerized material control and accounting system and even drew one on a paper napkin that would be suitable for a storage facility. Mark was gratified to see how quickly Sergei Zykov picked up the concepts, and he and Sergei were able to discuss specific designs and problems almost immediately.

Los Alamos Science: *Did the Russians finally admit that they needed such systems?*

Ron Augustson: During the spring of 1992 and through the summer, we still weren't hearing that there was a problem. But as the contacts grew, not only with the folks from Arzamas but with others as well, we learned that the Russians have a tremendous system of paper records, but nobody checks those records, and they were never meant to be used to draw an inventory. The emphasis was on putting product out, making a certain number of weapons from a certain amount of material. If they had a good process, they'd have more plutonium than they needed and they'd put that aside in case they ever had a need for it. After a while, they would lose track of where they put the stuff. Through the fall of 1992 and into 1993, we were definitely getting the picture that they didn't have a good idea of how much plutonium or highly enriched uranium they had at any given location.

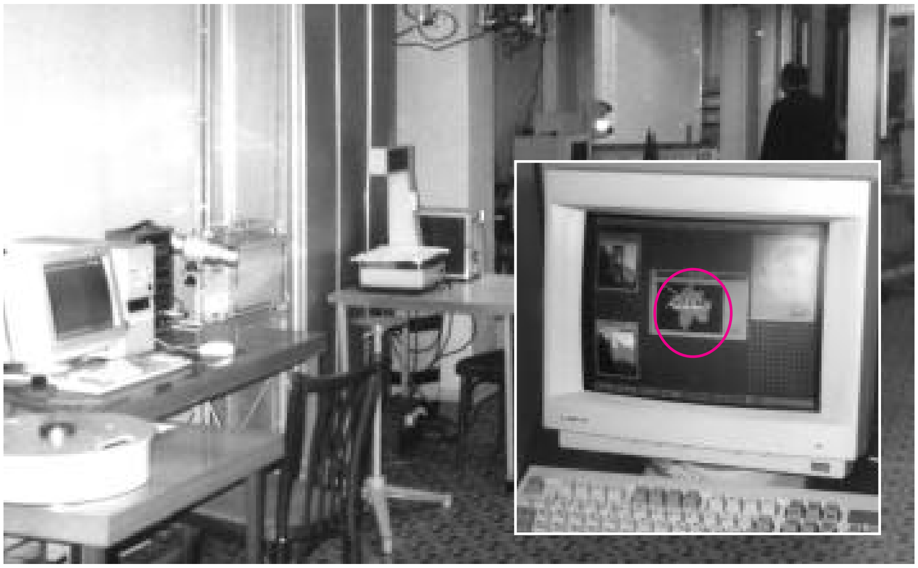
> *[Under Secretary Charlie Curtis] had been challenged by Congress on the issue of theft and on the fact that the Nunn-Lugar effort was not getting anywhere. So when I suggested a lab-to-lab materials control effort, he jumped at the chance and said that he would come up with some money if we could make the arrangements*

Sig Hecker: In April 1993, Trutnev was here, and he also started to open up a little bit on this issue. It wasn't until I was at Arzamas-16 in June 1994 to sign the lab-to-lab agreement on nuclear materials control, more than two years after I had first broached the subject, that Belugin admitted they had that kind of problem. We went to visit the famous convent at Divejevo, about twenty kilometers outside of Arzamas-16, and we went through a double guarded fence. And I asked, "How do you know that someone doesn't get out of this place with plutonium in their lunchbox?" And he said, "It can't happen." And I said, "How do you know it can't?" And he said, "Because the consequences would be grave if someone tried to do this." And I pressed further, "But how do you know that they're not getting any out? And then he finally said, "It's a problem." It took that long for them to really admit they would not know if someone had stolen some material. They were pretty well protected from the outsider threat. After all, they still do have the double fence around the whole town, not just their facilities. But with Russia falling apart, the insider threat became worrisome and that's what finally got them to agree to working with us on the problem.

Ron Augustson: Before that, in the fall of 1993, Mark and I had developed a close working relationship with Il'kaev, Yuferev, and Zykov, and that's when we decided to ask Sig if we could include the materials work in the umbrella contract of January 1994. Sig told us he couldn't do it without DOE approval.

Los Alamos Science: *Sig, how did you finally break through this bureaucratic barrier and get the materials control work off the ground?*

Sig Hecker: It started with that introductory meeting with Under Secretary Curtis in April 1994. As I said earlier, he had been challenged by Congress on the issue of theft and on the fact that the Nunn-Lugar effort was not getting anywhere. So when I suggested a lab-to-lab materials control effort, he jumped at the chance and said that he would come up with some money if we could make the arrangements. How much did we need? I said about two million dollars for fiscal year 1994 and maybe ten million for the next year. Charlie said he would find the money one way or another and we should just go do it. And we decided it would be included under the lab-to-lab umbrella contract that we had signed in January with Arzamas-16. I then went to Steve Younger and the next key moment was when Steve called Il'kaev on the tele-



The assembly/disassembly area at the MPC&A demonstration at Arzamas-16. All equipment is hooked up to central computers, and when unauthorized changes are detected, an alarm appears on the monitor (see circled image in the inset photo) and is broadcast throughout the system.

The Kurchatov Institute in Moscow houses some nuclear materials, but not until the institute joined the lab-to-lab MPC&A program were appropriate safeguards installed.

phone and proposed that we do a joint MPC&A program. That’s when the trust we had built up through the scientific interactions really paid off.

Steve Younger: I called Il’kaev and said, “Look, I know it’s an issue of national sovereignty, but my government considers it important that we begin a lab-to-lab program on materials control. Is that possible?” Il’kaev, of course, had to get guidance from Moscow, from Mikhailov I assume, but it took only one weekend of telephoning back and forth and we had approval from the Russian side. After that Mark Mullen, Gene Kutyreff, and Ron Augustson took over and did the enormous job of planning the actual program. I think they worked round the clock for several days to get a plan organized that we could present to Charlie Curtis.

Sig then told Charlie that it was a “go” with the Russians, and Charlie carved out two million dollars for fiscal year 1994. Six weeks later Sig was at Arzamas-16 to sign the first six contracts for a lab-to-lab nuclear material control program. And within two months a demonstration of MPC&A was being constructed at Arzamas-16. Half of the equipment at the demonstration was Russian and half was American. Everything about the demonstration was planned together, and the plan was written in Russian and English.

Los Alamos Science: *How did all this happen so quickly?*

Ron Augustson: Well, we had been discussing materials control systems for the storage facility, and specifically the Russian capabilities in that area, for almost two years with Zykov, Yuferev, and Il’kaev. So it was rather easy to develop plans that would involve the Russians as real partners with us. The idea was to create a demonstration of control and accounting systems at Arzamas that could be viewed by officials at other institutions in MINATOM. It would demonstrate the value of modern computerized systems to counter threats from insiders.

Paul White: We need to recognize that this lab-to-lab agreement on doing materials control was a tremendous breakthrough. The government-to-government process was completely paralyzed by a collection of difficulties: the sensitivity of the issue, the questions of pride, the organizational questions within the Russian government of who’s responsible for what. But while these difficulties were occurring, discussions were going on between Mark Mullen and Sergei Zykov and others. And personal friendship and trust with people like Il’kaev were being established through the scientific interactions, and both of these allowed the breakthrough to occur.

Steve Younger: As we've stressed, the issue of personal trust is extremely important in Russia. I still remember when Sig and Belugin signed the first nuclear materials control contracts in June 1994. There was a pause as Belugin picked up his pen. He looked over at Sig, and you could see him thinking, "I'm taking a hell of a risk here. And you had better be telling me the truth." Not only their careers, but also their families' reputations and their children's' education were at stake. They all remembered what happened to people after Khruschev's thaw froze again.

Sig Hecker: Belugin gave me his pen after the signing.

Krik Krikorian: It's clear that the lab-to-lab science programs were the confidence building programs in dealing with those folks. I think that's the bottom line. Money was transferred, good faith was transferred, the products actually came out, and the respect was developed.

We should also point out that apparently Mikhailov has been behind the MPC&A from the beginning and his endorsement opened the door to fast implementation.

Los Alamos Science: *How did Los Alamos expand the MPC&A activities beyond MINATOM to Kurchatov and the other civilian institutions?*

Sig Hecker: Most important was that Charlie Curtis had given me clear jurisdiction to make decisions, saying, "Look Sig, Los Alamos should lead the labs in doing this and you should do the right thing." So we were able to assure the Russians at these institutions that we were the lead laboratory and could determine the way things were going to happen. Il'kaev definitely wanted Arzamas to take the lead in the MINATOM complex, and he thought Mikhailov would support that approach, but Kurchatov was run independently, and then there was their GAN, which is the Russian equivalent to our Nuclear Regulatory Commission.

For those organizations, we again built on the personal contacts that Ron and his whole crew had developed through many years of work in the IAEA. For example, Ron and Mark Mullen had friends at Kurchatov who had participated in IAEA activities and actually understood materials problems. So during the June 1994 trip, we went to Kurchatov to establish an agreement on MPC&A. While at Kurchatov, we witnessed their security problems in real time. We went into their reactor where they have a lot of highly enriched uranium, and there was a guard on duty, but he didn't even have a rifle. The institute is right off the streets of Moscow. There were not even bars on some of the windows. And so it was brought home that materials protection and control really is a serious issue. We signed an agreement with Kurchatov, and then through the lab-to-lab approach, we have expanded to other institutions that have significant amounts of weapons material.


Ron Augustson

With this experience and expertise under our belts, the United States and Russia will be in a position to provide leadership to the world in global management of nuclear material.

Ron Augustson: Actually, our contacts at Kurchatov are doing us a big favor right now, because they served as an entree into the Russian naval fuel storage facilities for ship and submarine reactors. And this week, as we speak, there is a group of lab-to-lab people over at Kurchatov showing the navy people how we do vulnerability assessments.

Los Alamos Science: *What is the present status of the materials work?*

Ron Augustson: It's been going remarkably well. First, I should point out that, although Los Alamos is the lead laboratory for this activity, five other DOE national laboratories are now participating: Lawrence Livermore, Sandia, Brookhaven, Oak Ridge, and Pacific Northwest. Together we've developed a working relationship and a program plan with eight MINATOM institutes, and we plan to add two more to the list this spring. Within the program, the Russians are working busily on implementing MPC&A systems, integrating U.S. equipment into the systems, and gearing up to produce Russian equipment to use at the most sensitive locations within their facilities. In the process of implementation, hundreds of Russian technical people are becoming MPC&A experts. Those experts are needed to operate, maintain, design, and update the MPC&A systems in the near future. So together, we're implementing and building infrastructure for short- and long-term improved safeguards (see "Russian-American MPC&A: Nuclear Materials Protection, Control, and Accounting in Russia").

Our success in this area led to the transfer of the government-to-government effort in MPC&A from DOD to DOE. That transfer became official in fiscal year 1996. The understanding was that DOE would operate the program in the manner of the lab-to-lab program, which included the ability to write contracts to pay for work by Russians and the ability to buy Russian as well as American equipment. So the government-to-government effort is now proceeding in parallel with the lab-to-lab effort.

Funding levels are also on the rise. This year the lab-to-lab effort, including the work with the Russian naval storage facilities, has 5 million dollars in funding; the DOE-to-GAN program has 10 million dollars; and the government-to-government MPC&A program for the civilian institutes has 30 million dollars. Moreover, DOE is asking for an increase in fiscal year 1997 and is hopeful that they’ll get it.

In terms of the program’s future, we're heading toward including all MINATOM facilities with inventories of highly enriched uranium and plutonium. That means, for example, dismantlement facilities as well as the naval storage facilities. With this experience and expertise under our belts, the United States and Russia will be in a position to provide leadership to the world in global management of nuclear material.

Sig Hecker: That’s truly exciting. The thing to remember about the MPC&A program is that it had to be done. Whatever the Russians do later on, if they themselves know where their materials are, the world will have gained immeasurably.

Lab-to-Lab versus Government-to-Government

Joe Pilat: I want to raise an issue here. In looking back at the early years of Nunn-Lugar MPC&A, we’ve implied a lot of criticism of the U.S. bureaucracy, but it would be wrong to create the impression that the Russian bureaucracy, which includes representatives from government, MINATOM, and the Ministry of Defense, wasn’t equally or more responsible for the stalemate in the government-to-government sphere.

Sig Hecker: Bureaucratic difficulties notwithstanding, I personally think that Nunn-Lugar was one of those visionary pieces of legislation. It provided the umbrella for us to do the lab-to-lab effort in stabilizing both people and materials. Otherwise, we would have been accused of making policy. The Nunn-Lugar program has proceeded in the fashion in which you make treaties—very slowly and painfully arguing about every single word. We were able to tunnel underneath the bureaucracy and do the direct lab-to-lab but still under the auspices of the U.S. government.

> *… I personally think that Nunn-Lugar was one of those visionary pieces of legislation. It provided the umbrella for us to do the lab-to-lab effort in stabilizing both people and materials. Otherwise we would have been accused of making policy.*

Also, we thought the lab-to-lab scientific collaborations were a jump start and eventually would merge with ISTC. At first, the Russians at Arzamas-16 preferred to deal with us on a one-to-one basis rather than to deal with us through this much larger bureaucracy, but now both avenues are working. Similarly, we always thought that our program in materials control would eventually merge with the government-to-government program because we had the same people working on both, and as Ron just pointed out, that is coming to pass.

Paul White: The restrictions of the government-to-government program—wherein no money could go to the Russians and everything must be done with U.S. people and materials—has now been dropped, at least in principle. In practice, our government still has to learn how to do this, but things have changed. Since the start of the Nunn-Lugar program, over a million U.S. dollars have been authorized to be spent directly in the former Soviet Union. (This is in contrast, however, to the hundreds of millions spent on U.S. goods and services provided to the former Soviet Union.) Also, working in collaboration with the Russians rather than imposing our will is now part of the program. The discussion we are having here has pointed out the importance of the psychological aspect in making things work. The policy kinds of things have to be in place. But to lubricate the process, these personal interactions are very important.

Ron Augustson: It’s interesting that at the meeting last week in Washington, Mikhailov and O’Leary signed a simple one-page joint statement on MPC&A that was not possible until very recently. It listed six new facilities that Mikhailov is opening up to the MPC&A program, including Krasnoyarsk-26 and Sverdlosk-44, which are part of the nuclear weapons complex, and four other facilities that are part of the government-to-government activities. So the government-to-government and lab-to-lab programs are meshed together in the one document.

Los Alamos Science: *What progress has been made in the government-to-government program*

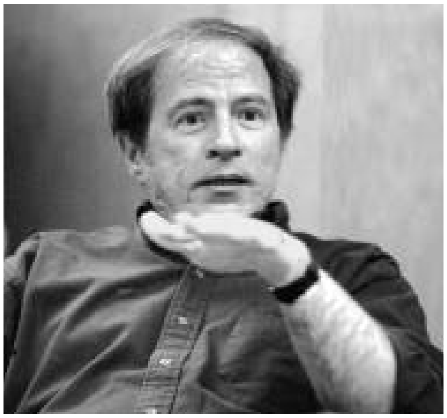
Paul White: Over one billion dollars has been spent on the overall program. The vast majority of that money has gone for demilitarization of delivery vehicles and filling up silos with concrete. And generally, the money was spent to purchase U.S. material for delivery to Russia.

Sig Hecker: An approach needed to get public support . . .

Paul White: Right. We may occasionally quibble about some of the difficulties of working within the government-to-government framework, but it would be wrong to underestimate the significant progress made by this more formal aspect of our cooperative efforts with the Former Soviet Union.

We've already mentioned U.S. assistance to facilitate the destruction of the delivery vehicles, including ICBMs, scheduled for elimination under the START I agreement. In many cases, the silos that held those missiles are being destroyed as well, with Secretary of Defense Perry being on hand for one well-publicized such event. Under agreements with Belarus, Ukraine, and Kazakhstan, warheads stationed on these territories have been, or are being, transported back to the Russian Federation for dismantlement, and U.S.-provided equipment has helped to ensure that these transfers are accomplished safely. In partnerships between the DOD and the DOE labs, the United States has supplied flexible armored blankets to shroud warheads during transportation. Accident response equipment has been provided to ensure effective assessment and remediation in case of any accident during such transfers. Rail cars used for such transfers have been upgraded with U.S. assistance, and containers for fissile material are being supplied for shipment and storage of the nuclear materials resulting from the dismantlement of the warheads themselves. With help from this program, the Soviet nuclear arsenal has been moving steadily on its course back to Russia. Kazakhstan has already returned all of its nuclear weapons, and Belarus and Ukraine are expected to become non-nuclear states by the end of 1996.

Right now, in one of the biggest efforts under the Nunn-Lugar program, the DOD is working productively with MINATOM on the design and construction of the large storage facility that Ron and Mark Mullen were involved in at the very beginning of the effort in 1992. Los Alamos is continuing its support of this effort with analysis of facility safety and the review of the Russian design for the facility's nuclear material protection, control and accounting system.


Joe Pilat

… right now we're plugging our fingers in a dike. The question is whether we'll be ultimately successful in helping the Russians and others from the former Soviet Union to safeguard their nuclear materials.

We should also note that there are some non-nuclear aspects of the Nunn-Lugar Program—for example, assistance is being provided to the Russian Federation in the demilitarization of chemical and biological weapons. Finally, we need to point out the importance of the cooperative working relationships that have developed between personnel of the Russian Ministry of Defense and the U.S. Department of Defense. Those relationships are at least as significant to the reduction of tensions and the creation of a new, cooperative atmosphere between our two countries as those between our nuclear laboratories.

Successes and Future Prospects of the Lab-to Lab Program

Los Alamos Science: *What are the successes of the lab-to-lab program in terms of nonproliferation goals? For example, is scientific conversion working, and is it a realistic goal?*

Sig Hecker: We have contributed to the stability of the scientists at the nuclear weapons institutes and to their involvement in non-military projects. But did we convert them? I don't necessarily think so, nor is this a realistic goal. If we didn't have the nuclear materials MPC&A project, then I would say it would be way too early to judge the ultimate effect of this lab-to-lab effort. On the other hand, I believe the materials control effort is a real contribution to nonproliferation objectives. It represents a quantum jump in the overall world security because the real issue is nuclear weapons proliferation We would have liked to have started earlier, but the double fences around Arzamas-16 and many of the other nuclear installations are still pretty impressive. So I think we might have gotten through this window of opportunity just in the nick of time.

The danger of losing the scientists to Iraq or Iran has always seemed quite small to me because those folks are patriots. Given the way they grew up in those closed towns, they're not likely to go live in Iraq. But in a very short period of time that could change because they won't have to leave their country to design a bomb for a rogue nation. It will require only a few scientists hooked up through the Internet to the leader of that nation. Then the seriousness of the threat increases significantly. But for the time being, I think we've made some contribution through scientific conversion as well.

Joe Pilat: I would share Sig's impressions on the nonproliferation benefits of the lab-to-lab programs. But there's one element that I would like to explore. I think we've done the right things in the lab-to-lab MPC&A, but right now we're plugging our fingers in a dike. The question is whether we'll be ultimately successful in helping the Russians and others from the former Soviet Union to safeguard their nuclear materials. The extent of the Russian political drift to the left (or right), the funding from the Russians themselves that is ultimately needed to make materials control successful and operational over the years, and whether, in fact, we can continue to push the process in Russia are all open issues or questions. We've done as well as we can at this stage, but it's still too soon to tell how these unprecedented experiments in cooperation will pan out.


John Shaner

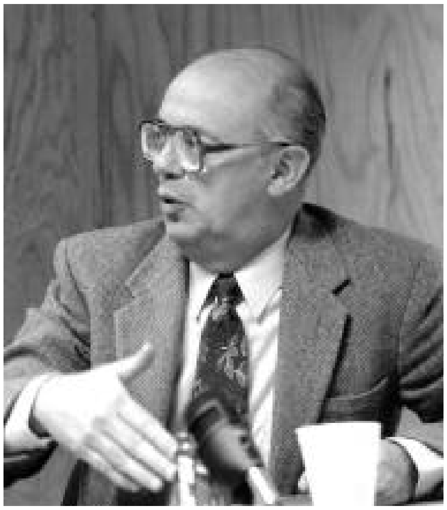
We believe that stabilizing the institutes, although it's a debated topic in Washington, has to be a good thing.

Sig Hecker: Let me just add to Joe's concern. Whatever we do to secure nuclear materials, we are still going to be faced with the fact that the material is there. And so future political upheavals could result in the wrong people getting their hands on this material and using it for aggressive or terrorist purposes. So we're really not done. And that's why I drew up what I call a plutonium road map. The road map outlines some possible ways to get to an end state in which there is significantly less weapons-grade nuclear material in the world. And the ways to reach that state can be productive in the sense that they extract a good amount of the energy from the nuclear material as it is being transformed. Only when we reach that end state can we rest easier. We're talking about a very long-term, maybe a 100-year, problem. And if we let up at any point along the way, we will have still opened the flood gates.

Paul White: This long-term problem of how to deal with nuclear materials is another area where we are having very constructive engagement with the Russians through official government channels. For example, there is a Joint U.S.-Russian Steering Committee on Plutonium Disposition. Several technical working-groups under this committee are cooperatively examining a variety of methods for long-term material disposition.

Sig Hecker: On the front page of the New York Times a couple of years ago, there was a picture of Mikhailov and O'Leary, and O'Leary is quoted as saying that plutonium is not only a security liability but also an economic liability. And Mikhailov says plutonium is for my children, which is exactly the view that the Russians have. And that's one of the reasons that my vision for the long-term plutonium road map includes the importance of international collaborations. I doubt that our government will bury our plutonium if the Russians keep theirs above ground. There's just no way.

Paul White: I would definitely agree that the aspect of nonproliferation that deals with the nuclear materials question is far more important than science conversion. On the other hand, Arzamas-16, and Chelyabinsk-70 were, by and large, single-purpose laboratories, whereas Los Alamos and Livermore were multi-program laboratories engaged in issues of nonproliferation, materials control, and other scientific applications. Now, through the lab-to-lab effort, Arzamas-16 and Chelyabinsk-70 are very actively engaged in supporting MPC&A technology in their country and are also actively looking for ways in which they can apply their knowledge of radiation detectors and materials analysis to other problems of nonproliferation. They are branching out and finding activities other than just the design and manufacture of nuclear warheads, and so MPC&A is actually playing a role in science conversion.


Irv Lindemuth

We've certainly started the process of integrating their laboratories into the world-wide scientific community.

John Shaner: And all these scientific conversion activities increase their prospects for getting a broader support base within their own government. Ultimately, the U.S. government is not going to underwrite the whole Russian nuclear weapons complex. The conversion activities are providing work that's not directly related to weapons of mass destruction. It also gives a chance for a little bit of stability while the economy has a chance to recover.

Los Alamos Science: *Is there a hope that the nuclear institutes will become integrated into the larger scientific community?*

Irv Lindemuth: Yes. We've certainly started the process of integrating their laboratories into the world-wide scientific community. I've always felt that the best thing that we could hope for with Arzamas-16 is that somehow they evolve into a laboratory something like ours.

Joe Pilat: Clearly, we don't want to see a catastrophic collapse leading to a brain drain and the like, but we need to be careful here. Many people in our country would say that the maintenance of healthy nuclear weapons labs in Russia is not necessarily in the U.S. interests. On the other hand, the goal of scientific conversion or integration is certainly in our interests.

John Shaner: The point is that stabilizing the materials through MPC&A won't do the whole job. We need to stabilize people as well. That's going to require making their economic situation good enough that this very small minority of people who know about nuclear weapons are not driven to desperation. We believe that stabilizing the institutes, although it's a debated topic in Washington, has to be a good thing. As long as they have nuclear weapons to worry about and nuclear materials to worry about, we think it would be really foolish to get rid of all the people that know how to worry about them. So, in the long term, MPC&A is one part of it, but we need to continue to look for other ways of stabilizing the situation.

One avenue is the Industrial Partnership Program, which is a wonderful program with an end game to accelerate Russian entry into an international economic regime. At first it ran into problems in Washington because it involved both foreign countries and private industry. Now that has turned around. We need a long-term consistent policy of continuing to accelerate the engagement of the Russians into a world economy. If we have difficulties with that idea, we raise the risk that people could be driven by desperation to do unpolitical, unpatriotic things.

Sometimes we've been criticized when the MC&A program has given the Russians equipment and systems to control and keep track of these things even though they do not allow us to install them ourselves. Some say that means the program is a failure and should be cut off. On the other hand, if you watch the enthusiasm of the director of that facility grow as he sees these MC&A systems installed, it gives you a warmer feeling than if you never got to talk to him at all.

Los Alamos Science: *Are the employees of the nuclear institutes subject to black market temptations?*

John Shaner: I think they are subject. Although there is no questioning the patriotism of our Russian colleagues, catastrophic economic conditions can make anything possible.

Krik Krikorian: There's always the hundredth of one per cent of people, and it doesn't take very many to mess up a system. But there has not been a universal threat from that so far.

Joe Pilat: I think Krik's right. It's just like the brain drain. That threat was initially exaggerated and the theft scenarios are also exaggerated. There is a concern, there are problems that need to be resolved. And John gave an excellent overview of what we can do to help, but ultimately the Russians have to resolve their own problems.

Irv Lindemuth: Do you see other countries trying to foster a long-term relationship with the Russians?

John Shaner: Arzamas-16 is working with France and Germany on a number of science and technology projects. They are certainly developing short-term relationships. I know that industrial firms trying to work in Russia are indeed taking a long view of this issue of integrating Russia into the world economy, both for what they can contribute and for the potential market down stream.

Joe Pilat: All the nuclear-weapons-states' laboratories and institutes are very interested in how they could diversify their portfolios. And the sooner we can look carefully at those issues and try to find a means of addressing them broadly, the better off we will be.

Sig Hecker: In a sense the lab-to-lab program has been a means to jump start this process of conversion from work on weapons of mass destruction to work on projects that are not weapons-related.

Los Alamos Science: *Is Los Alamos trying to use the lab-to-lab approach to promote nonproliferation in other parts of the world?*

John Shaner: China obviously is another player in this nuclear future. In our little way, we are trying to lay the groundwork for a small group of people to establish technical respect and trust at their nuclear institutes. From there we would hope to build a growing relationship and take advantage of opportunities like we did in the case of nuclear material control in Russia. But it's a much more complicated phenomenon when you start adding more and more countries to the playing field and you're not exactly sure where they're headed.

Los Alamos Science: *What effect will a more conservative Russian regime have on the lab-to-lab efforts?*

John Shaner: These efforts are so clearly in the interest of both sides that I'm confident that even a more conservative regime will look relatively favorably on it. The material control program has started to engage the most sensitive nuclear institutes, but that engagement is very controlled, and it could probably be made acceptable even to a very conservative regime.

Ron Augustson: I would hope that the scientific conversion activities would also continue. They provide a very necessary foundation and they engage the academicians and the really top-notch scientists who don't have much interest in MPC&A as a technical topic but are interested in ultra-high magnetic fields and topics like that. And in turn, those people are listened to by people within the government.

Krik Krikorian: One of the fundamental problems is that Russian science and funding for Russian science are declining. For instance, the number of people employed by MINATOM has gone from roughly a million down to 800,000 or 700,000. That's a severe change. Their science is so big that they really can't afford it all. MINATOM has one empire, the Russian Academy is another empire. And guys like Velikhov have wangled their institutes away from both.

Joe Pilat: I would share John's assessment that the likely political path in Russia is a continued drift to authoritarianism, and that the MPC&A activities should survive that drift. Scientific collaborations, so long as they're not too close to sensitive areas, also have a decent chance of survival, in part because they represent a source of funds.

The areas that concern me most are the more far reaching, especially the prospect of major collaborative efforts in dismantlement and further arms control. A continued drift to the left (or right) is going to create a climate more hostile to those activities. In terms of the issues we're interested in, there is a significant minority in Russia that has viewed as treasonous all of the arms control and collaborative activities with the United States since the time of Shevardnadze (former Soviet foreign minister, and now president of Georgia) and Gorbachev.

Nevertheless, we are likely to see some level of cooperation. Even during the Cold War, we had some shared objectives, so there is no reason we shouldn't have them now. I think it is of particular interest that the Laboratory has been able to supplement, complement, and push a relatively well-defined government-to-government agenda through the lab-to-lab programs that we are discussing today. But we will have to see how the new political situation created by the Duma elections affects both the lab-to-lab efforts and the broader government efforts that they serve and on which they are based.

Steve Younger: We should not be surprised if there are some problems along the way. Don't forget that getting the first contract signed, doing the first scientific experiment, and getting the MPC&A program going were all very challenging at the times that we did them. Now we want to work together on improving the security of real weapons material. Despite the problems, I am encouraged by the determination on both sides to get this important job done. If we and the Russians don't do it, who will?

Sig Hecker: Thank you all for participating in this round table and sharing your views on how our collaborations with the Russians began. The views presented tell the story from a Los Alamos point of view. Today, five other Department of Energy laboratories are contributing to efforts designed to help Russia control its nuclear materials. It would also be very interesting to hear the Russian version of this story. Since all along we have worked side-by-side as equals, maybe we'll hear their story some day.

I can't predict which way Russian politics will turn in the future, but I will sleep better knowing that they are in greater control of their nuclear materials today than they were just two years ago. This dialogue recounts a story that is a testament to what can be accomplished when scientists and engineers are encouraged by a courageous government official, Charles Curtis in this case, to help solve a crucial international problem. ■

The Participants

Sig Hecker is the Director of the Los Alamos National Laboratory, a position he has held since 1986. He joined the Laboratory as a technical staff member in the Physical Metallurgy Group and has served as Chairman of the Center for Materials Science and as Division Leader of the Materials Science and Technology Division prior to becoming Director. Sig began his professional career as a senior research metallurgist with the General Motors Research Laboratories in 1970 after two years as a postdoctoral appointee at Los Alamos.

Steve Younger is the Director of the Los Alamos Center for International Security Affairs (CISA) and is responsible for overseeing Los Alamos interactions in Russia, China, and elsewhere. In 1992, he organized the first scientific collaboration between the U.S. and Russian nuclear laboratories and has participated in many joint experiments involving our counterpart institute at Arzamas-16. Previously, Steve was Deputy Program Director for Nuclear Weapons Technology. He maintains an active research interest in atomic and molecular physics and has extensively published in these fields.

John Shaner is a Laboratory and American Physical Society Fellow and has been the Deputy Director of CISA since its inception. His responsibilities include oversight of active programs involving Los Alamos and sensitive technical institutions in sensitive countries. John is currently involved in joint projects with institutions in the republics of the Former Soviet Union, and has responsibility for developing a lab-to-lab program with the institutes of the China Academy of Engineering Physics, the agency responsible for the Chinese nuclear weapons. In 1993, John was the recipient of the E.O. Lawrence Award for National Security.

Max Fowler joined the Laboratory to organize a team to develop and apply explosive-driven magnetic flux compression devices. Over the years, he and his colleagues have used this technique to generate energy sources to power a number of plasma-producing devices, lasers, imploding foils, electron-beam accelerators, and rail guns. This early work influenced subsequent megagauss solid state research, liner implosion of plasmas, and the initiation of the “Megagauss” Conferences. Max is a Laboratory Fellow and has recently been awarded an Honorary Doctorate from Novosibirsk State University for his work in high-energy density physics and in furthering scientific relations between the United States and Russia.

Donald Eilers has served as a CORRTEX technical expert on the U.S. delegation to the bilateral Nuclear Testing Talks whose goal was improving verification of the Threshold Test Ban Treaty. He held the position of U.S. Scientific Team Leader on both the U.S. Kearsarge and the Soviet Shagan Joint Verification Experiments whose sets of experiments successfully demonstrated the CORRTEX verification technology at those nuclear test sites. Don had the distinction of being among the first scientists to visit the Soviet nuclear weapons test site in Semipalatinsk and the nuclear design facility of Arzamas-16. Don received the Laboratory’s Distinguished Performance Award and the Department of Energy’s Award of Excellence.

Nerses (Krik) Krikorian currently is a Laboratory Fellow who began his career as a physical chemist with the Manhattan Project. During his career, Krik was Deputy Group Leader and Group Leader of the Critical Technologies Group of the International Technology Division. He has visited over fifteen Russian laboratories as well as the nuclear weapons design laboratories and several Chinese scientific laboratories Through Krik’s numerous publications on rare earth and refractory carbides, intermetallic phase relationships, thermodynamics, crystallography, and superconductivity, he has developed an international reputation in high-temperature chemistry.

Hugh Casey is the Project Leader for the New Independent States Industrial Partnering Program (IPP), located in CISA. In his current assignment, he is the Chairman of the IPP Inter-Laboratory Advisory Board (ILAB), representing the ten DOE multi-program laboratories responsible for implementing the cooperative projects with the weapons institutes in the former Soviet Union. Hugh's technical expertise and interests include joining, net shape processing, rapid solidification processing, advanced materials, and applications of modeling of materials synthesis and processing.

Irv Lindemuth is currently Project Leader for International Collaboration in Pulsed Power Applications with responsibility for providing technical leadership for the pulsed-power/magnetized-target fusion collaboration between Los Alamos and its Russian counterpart, the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF), located at Arzamas-16 (Sarov). His areas of expertise include thermonuclear fusion, advanced numerical methods for the computer simulation of fusion plasmas, and related pulsed-power technology. He received the Distinguished Performance Award in 1992 for his work in the formative stages of the LANL/VNIIEF collaboration.

Paul White is a member of CISA where he has been applying his experience to the development of technical collaborations between the U.S. and Russian nuclear weapons laboratories. Paul has long been interested in issues at the intersection of technology and national security policy and was, for several years, Deputy Director and later Acting Director of the Center for National Security Studies. Paul was involved as a technical expert on the U.S. delegation to the Nuclear Testing Talks in Geneva .

Ronald H. Augustson is the Project Leader for the US-Russian Lab-to-Lab Nuclear Material Protection, Control, and Accounting (MPC&A) Program at the Laboratory. Ron is a member of the Lab-to-Lab Steering Group. His duties include oversight of the LANL technical support activities to the program, establishment of strong working relationships with our Russian collaborators, and providing program support to the steering group.

Joseph Pilat is a member of the Nonproliferation and International Security Division with the Laboratory. His work has included special advisor to the Department of Energy’s representative at the Third Review Conference of the Nuclear Non-proliferation Treaty (NPT) and advisor to the U.S. Delegation at the 1995 NPT Review and Extension Conference. Joseph also served as representative of the Secretary of Defense on the Fourth NPT Conference. ■

Los Alamos and Arzamas-16: the “Sister Cities” Relationship

The two cities of Arzamas-16 and Los Alamos are situated on opposite sides of the globe, separated by ten time zones, and once separated by Cold War secrecy and politics. Each is a nuclear weapons research city and the birthplace of its country's atomic bomb. Moreover, each began its existence as a secret city. As the people of Arzamas-16 and Los Alamos came to know each other over the last several years, the recognition of similar histories, national security missions, and educational, family, and patriotic values led the two communities to reach out to each other and begin to share a “sisterhood.”

In February 1995, the administration of Arzamas-16 presented the Los Alamos City Council with a traditional Russian-cast brass bell. Left to right: Bob Reinovsky, County Council Chairman Lawry Mann, and Irv Lindemuth admire its workmanship.

Interactions between Los Alamos and Arzamas-16 began with the lab-to-lab scientific collaborations between their respective nuclear institutes. Los Alamos scientist Irv Lindemuth, who participated in the lab-to-lab collaborations in pulsed power and high magnetic fields, has played a key role in the interactions as messenger between the two communities.

The sister cities story begins with Lena Panevkina, Alexander Pavlovskii’s personal interpreter, who thought that the scientific interactions between Arzamas-16 and Los Alamos could be extended to include a cultural exchange. During a November 1992 visit to Los Alamos, Panevkina raised the issue with Lindemuth, and that discussion led to a series of letters exchanged between government officials of the two cities. In December of 1993, Lindemuth made a presentation to the Los Alamos City Council that told the history of Arzamas-16. He explained the similarities between the two cities to the Council and noted that the community of Arzamas-16 sometimes jokingly refers to itself as “Los Arzamas.” The council voted unanimously to invite Arzamas-16 to become a “sister city” to Los Alamos (see “Sister Cities International”).

Also in 1992, Lena Gerdova, an interpreter for Vladimir Chernyshev, started a pen-pal exchange between high school students in Arzamas-16 and Los Alamos. Through Lindemuth, Gerdova arranged to visit Ann Eilert’s tenth grade class at Los Alamos High School. A number of the students wrote pen-pal letters, and Gerdova returned to Russia with the letters in her suitcase. Lindemuth came back from Arzamas-16 in March 1993 with the first replies. Additionally, in December 1993, some two-hundred Los Alamos students contributed artwork to a Bradbury-Science-Museum-sponsored “Friendship Book” on the theme of peaceful relations between the two nations, a book that in January 1994 was presented to Arzamas-16 Director Vladimir Belugin.

The pen-pals relationship spread to Gallup, NM when scientists from Arzamas -16 came to New Mexico in November 1993 for a joint experimental campaign in Los Alamos’ Ancho Canyon. During a side trip to the Grand Canyon, Jim Goforth, a member of the pulsed-power group, and his sister, Marge Spurlin, a high school teacher from Gallup, arranged for the visitors to be welcomed into the homes of Gallup residents. That visit combined with Spurlin’s enthusiasm led students in Gallup to join the letter-writing campaign.

Ultimately, the letter writing spread throughout the Los Alamos school system and to several schools in Arzamas-16. Several hundred students from both sides of the Atlantic have participated.

Earlier that year,when the Los Alamos pulsed-power group was in Arzamas-16 for the first joint scientific experiment, they were taken to visit the local hospital. There, they learned from Dr. Valentina Ponomaryova, the director of the childhood and maternity center, that essential medical supplies

We would like to thank the Los Alamos Monitor for allowing us to use information from articles written by Steve Shankland and Chairman Schaller.

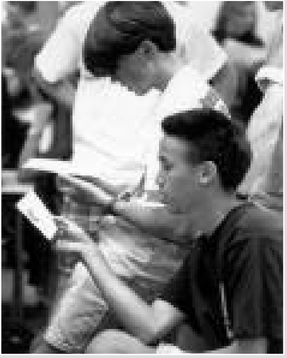
"The idea of sister-city relationships is one of "people-to-people," of citizen diplomacy "from heart-to-heart." Only in this way will the ice left from the cold war be melted.…We would like to believe that if all Americans are like the "citizens" that visited Arzamas-16, then you and I will not perish on this fragile planet." *From a report in the Arzamas-16 Courier covering the May 1995 visit of the Los Alamos civic delegation.*

were available in Russia but were priced beyond the reach of the citizens of Arzamas-16, who were regularly going unpaid as the Russian government struggled financially.

When the Los Alamos scientists returned home and reported what they had seen, the Los Alamos community expressed a desire to help. Upon the advice from the U.S. Embassy in Moscow that cash donations to the Arzamas-16 hospital would be the most expedient and effective way to help, Lindemuth and John Eilert of the Laboratory's Environmental Safety and Health Group opened a bank account in December 1993 to launch the Arzamas-16 Children's Medical fund. Donations from Los Alamos, the surrounding communities, and even from Colorado and Pennsylvania began to arrive. When Arzamas-16 Director Vladimir Belugin visited Los Alamos in January 1994, he was given more than six hundred dollars to take to Dr. Ponomaryova. Later, Cari Zocco took over as Chairwoman of the Medical Fund, and over the years, additional cash donations have been forwarded to Dr. Ponomaryova.

Soon thereafter, Ken Bower, a member of the Laboratory's Community Involvement and Outreach Office, and then Treasurer of the American Chemical Society Central New Mexico Chapter, told Lindemuth that his Chapter had accumulated a cash surplus and would like to distribute the money in Russia. Lindemuth and Bower first located a charitable medical organization (MAP International) that had access to surplus medical supplies and then a U.S.-State-Department-supported shipping organization that would ship to Russia at no cost to the donor. Bower leveraged ten thousand dollars in Medical Funds and American Chemical Society fund donations into a twenty-foot shipping container full of medical supplies that arrived in Arzamas-16 in early 1995. The medical supplies had a U.S. wholesale value of five-hundred thousand dollars.

The sister cities relationship was consummated in May 1994 with the visit to Los Alamos by eight students and two teachers from Arzamas-16 and their participation in the first New Mexico High School Critical Issues Forum, a series sponsored by the Laboratory's Science Education and Outreach Group. The topic of the first forum was to be nuclear dismantlement; the format would involve teams of students from New Mexico high schools researching dismantlement and then developing proposed policies for U.S. assistance to Russia. When Lindemuth heard about the forum he called Judith Kaye, leader of the Outreach group, who agreed that Russian students could participate. Frantic phone calls to Arzamas-16 and



Above: Russian students and teachers from Arzamas-16 at the athletic field of Los Alamos high school n October 1995. Right: Los Alamos students Tony Maggiore and Chih-Cheng Peng open pen-pal letters from fellow students in Arzamas-16. Bottom: Bob Reinovsky (left) greets Russian high school teacher during visit to Arzamas-16.

Sister Cities International

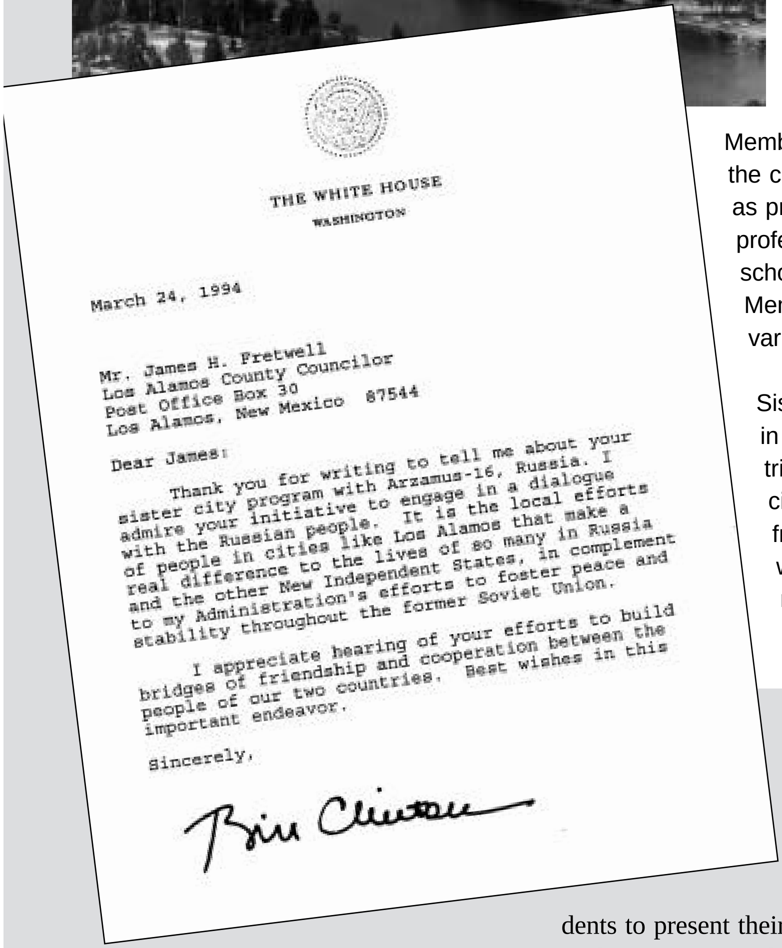
Sister Cities International is a national, non-profit, volunteer-membership organization joining United States and foreign communities. Sister city affiliations lead the national movement for volunteer participation and community development in the international arena.

The Sister City Program began shortly after World War II and developed into a national initiative when President Dwight D. Eisenhower proposed the people-to-people program at a White House Conference in 1956. He hoped that involving citizens internationally might lessen the chance of future world conflicts. Initially grouped with the National League of Cities, Sister Cities International became a separate, not-for-profit organization in 1967. The procedure for establishing an official Sister City affiliation requires that an agreement be signed by the respective mayor of each city and ratified by each city council, or its equivalent.

Membership in Sister Cities International is designed to improve the cultural understanding of people of different nations as well as provide new prospects for trade and business. Student and professional exchanges and other learning experiences in schools may be initiated through direct inter-school contracts. Membership in Sister Cities International provides eligibility for various grant programs.

Sister Cities International represents 125 million Americans in 1,200 U.S. cities and their 1,900 partners in 120 countries worldwide. Since 1986, partnerships between U.S. cities and those in the Former Soviet Union have grown from six to one hundred and fifty-two. Today, partnerships with Japanese and German cities represent the largest number of sister-city affiliations by country.

Like Los Alamos, modern Arzamas-16 (upper photo) is situated in a region of great natural beauty. The Sarovka and Satis Rivers flow into the Volga River separating the city into distinct sections.



THE WHITE HOUSE
WASHINGTON

March 24, 1994

Mr. James H. Pretwell
Los Alamos County Councilor
Post Office Box 30
Los Alamos, New Mexico 87544

Dear James:

Thank you for writing to tell me about your sister city program with Arzamus-16, Russia. I admire your initiative to engage in a dialogue with the Russian people. It is the local efforts of people in cities like Los Alamos that make a real difference to the lives of so many in Russia and the other New Independent States, in complement to my Administration's efforts to foster peace and stability throughout the former Soviet Union.

I appreciate hearing of your efforts to build bridges of friendship and cooperation between the people of our two countries. Best wishes in this important endeavor.

Sincerely,

Bill Clinton

hours of paperwork on the part of the Russians produced two teams of Arzamas-16 students to present their ideas on the dismantlement issue. The combined plan of the participating teams produced the clever acronym “TRUST, ”The Russian-United States Transition. After the forum, the plan was presented to U.S. Department of State personnel Joe Dethomas and Ann Harrington in Washington, D.C. Some pen-pals were able to meet face-to-face during this visit.

In February 1995, two gifts were presented to Bob Reinovsky and Lindemuth by Gennadi Karatayev, the Arzamas-16 City Administrator. A cast bronze bell and an invitation for a Los Alamos civic delegation to visit Arzamas-16 to participate in the May 9 Victory Day celebration commemorating the end of World War II in Europe. A seven-member delegation accepted the invitation and became the first U.S. civic visitors permitted into Arzamas-16 by the Russian government. Among the delegation was Steve Shankland of the Los Alamos Monitor, the first non-Russian media representative ever permitted into the city.

The May 1995 visit to Arzamas-16 set the stage for an October visit to Los Alamos by a 15-member Arzamas-16 delegation. In January of this year, Los Alamos Middle School teacher Jeanne Allen was notified that she had been awarded a twenty-nine thousand dollar thematic exchange grant from Sister Cities International. Through this grant, five students and a teacher from Los Alamos and San Ildefonso Pueblo will visit Arzamas-16, and five Arzamas-16 students and a teacher will come to Los Alamos. The students will research water-quality issues, using New Mexico's Rio Grande and tributaries of Russia's Moksha River. The Laboratory will participate in this project by providing tours, lectures, and analytical assistance.

From the beginning of their modern existence, the people of Los Alamos and Arzamas-16 have been committed to the security of their respective nations. When the changing global political climate made it possible to work together to reduce the nuclear danger, the two cities embraced the opportunity. ■

Arzamas-16 Changes Name

A formal request by the people of Arzamas-16 in August 1995 led Boris Yeltsin to officially change the name of the city back to its historic name of Sarov.

Originally a provincial center, the town was the site of the Sarova monastery next to the Sarovka River. Before the Communist revolution, thousands of Russians, including the czar, made pilgrimages to the site to benefit from the pure water of the Sarovka River. The water is said to have healing powers and is a marketable commodity of the city today. In 1923, the monastery was closed by the communists and many priests were executed. Many of the buildings, including a spectacular cathedral, were destroyed, and the remaining buildings were converted to secular use. The high bell tower visible from much of the city stands as a monument to the earlier times.

The city disappeared from unclassified maps in 1946, the same year the All-Russian Scientific Research Institute of Experimental Physics, the weapons design facility, was built. The village was then given status as a city and, over the years, labeled with a series of classified code names. In 1990, the Soviet government first acknowledged the city's existence openly. Most in Sarov support the name change, but others feel that Arzamas-16 more correctly reflects the city's greatest achievements–nuclear weapons.

The city of Sarov remains a "closed" city with entrances and exits carefully monitored by armed guards at the periphery. Mr. Gennadi Karatayev, the City Administrator, recognizes that considerable time and money will be required to separate the necessarily classified technical areas from the remainder of the Institute and from the community. Nevertheless, Karatayev has expressed the hope that within ten years his city and much of the Institute will be "open," not unlike Los Alamos. Once again, members of the Russian Orthodox Church may now make pilgrimages to the sacred shrines of St. Serafim, the monastery's most famous resident.

The Patriarch of the Russian Orthodox Church visits the monastery of St. Serafim. Academician Yuli Khariton, the "Soviet Oppenheimer," is on the right.

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The two cities of Arzamas-16 and Los Alamos are situated on opposite sides of the globe, separated by ten time zones, and once separated by Cold War secrecy and politics. Each is a nuclear weapons research city and the birthplace of its country's atomic bomb. Moreover, each began its existence as a secret city. As the people of Arzamas-16 and Los Alamos came to know each other over the last several years, the recognition of similar histories, national security missions, and educational, family, and patriotic values led the two communities to reach out to each other and begin to share a "sisterhood."

Interactions between Los Alamos and Arzamas-16 began with the lab-to-lab scientific collaborations between their respective nuclear institutes. Los Alamos scientist Irv Lindemuth, who participated in the lab-to-lab collaborations in pulsed power and high magnetic fields, has played a key role in the interactions as messenger between the two communities.

The sister cities story begins with Lena Panevkina, Alexander Pavlovskii's personal interpreter, who thought that the scientific interactions between Arzamas-16 and Los Alamos could be extended to include a cultural exchange. During a November 1992 visit to Los Alamos, Panevkina raised the issue with Lindemuth, and that discussion led to a series of letters exchanged between government officials of the two cities. In December of 1993, Lindemuth made a presentation to the Los Alamos City Council that told the history of Arzamas-16. He explained the similarities between the two cities to the Council and noted that the community of Arzamas-16 sometimes jokingly refers to itself as "Los Arzamas." The council voted unanimously to invite Arzamas-16 to become a "sister city" to Los Alamos (see "Sister Cities International").

In February 1995, the administration of Arzamas-16 presented the Los Alamos City Council with a traditional Russian-cast brass bell. Left to right: Bob Reinovsky, County Council Chairman Lawry Mann, and Irv Lindemuth admire its workmanship.

Also in 1992, Lena Gerdova, an interpreter for Vladimir Chernyshev, started a pen-pal exchange between high school students in Arzamas-16 and Los Alamos. Through Lindemuth, Gerdova arranged to visit Ann Eilert's tenth grade class at Los Alamos High School. A number of the students wrote pen-pal letters, and Gerdova returned to Russia with the letters in her suitcase. Lindemuth came back from Arzamas-16 in March 1993 with the first replies. Additionally, in December 1993, some two-hundred Los Alamos students contributed artwork to a Bradbury-Science-Museum-sponsored "Friendship Book" on the theme of peaceful relations between the two nations, a book that in January 1994 was presented to Arzamas-16 Director Vladimir Belugin.

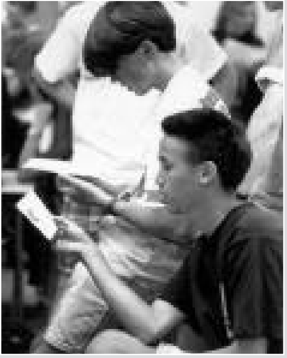
The pen-pals relationship spread to Gallup, NM when scientists from Arzamas -16 came to New Mexico in November 1993 for a joint experimental campaign in Los Alamos' Ancho Canyon. During a side trip to the Grand Canyon, Jim Goforth, a member of the pulsed-power group, and his sister, Marge Spurlin, a high school teacher from Gallup, arranged for the visitors to be welcomed into the homes of Gallup residents. That visit combined with Spurlin's enthusiasm led students in Gallup to join the letter-writing campaign.

Ultimately, the letter writing spread throughout the Los Alamos school system and to several schools in Arzamas-16. Several hundred students from both sides of the Atlantic have participated.

Earlier that year,when the Los Alamos pulsed-power group was in Arzamas-16 for the first joint scientific experiment, they were taken to visit the local hospital. There, they learned from Dr. Valentina Ponomaryova, the director of the childhood and maternity center, that essential medical supplies

We would like to thank the Los Alamos Monitor for allowing us to use information from articles written by Steve Shankland and Chairman Schaller.

> *“The idea of sister-city relationships is one of “people-to-people,” of citizen diplomacy “from heart-to-heart.” Only in this way will the ice left from the cold war be melted.…We would like to believe that if all Americans are like the “citizens” that visited Arzamas-16, then you and I will not perish on this fragile planet.”* *From a report in the Arzamas-16 Courier covering the May 1995 visit of the Los Alamos civic delegation.*



Above: Russian students and teachers from Arzamas-16 at the athletic field of Los Alamos high school n October 1995. Right: Los Alamos students Tony Maggiore and Chih-Cheng Peng open pen-pal letters from fellow students in Arzamas-16. Bottom: Bob Reinovsky (left) greets Russian high school teacher during visit to Arzamas-16.

were available in Russia but were priced beyond the reach of the citizens of Arzamas-16, who were regularly going unpaid as the Russian government struggled financially.

When the Los Alamos scientists returned home and reported what they had seen, the Los Alamos community expressed a desire to help. Upon the advice from the U.S. Embassy in Moscow that cash donations to the Arzamas-16 hospital would be the most expedient and effective way to help, Lindemuth and John Eilert of the Laboratory’s Environmental Safety and Health Group opened a bank account in December 1993 to launch the Arzamas-16 Children’s Medical fund. Donations from Los Alamos, the surrounding communities, and even from Colorado and Pennsylvania began to arrive. When Arzamas-16 Director Vladimir Belugin visited Los Alamos in January 1994, he was given more than six hundred dollars to take to Dr. Ponomaryova. Later, Cari Zocco took over as Chairwoman of the Medical Fund, and over the years, additional cash donations have been forwarded to Dr. Ponomaryova.

Soon thereafter, Ken Bower, a member of the Laboratory’s Community Involvement and Outreach Office, and then Treasurer of the American Chemical Society Central New Mexico Chapter, told Lindemuth that his Chapter had accumulated a cash surplus and would like to distribute the money in Russia. Lindemuth and Bower first located a charitable medical organization (MAP International) that had access to surplus medical supplies and then a U.S.-State-Department-supported shipping organization that would ship to Russia at no cost to the donor. Bower leveraged ten thousand dollars in Medical Funds and American Chemical Society fund donations into a twenty-foot shipping container full of medical supplies that arrived in Arzamas-16 in early 1995. The medical supplies had a U.S. wholesale value of five-hundred thousand dollars.

The sister cities relationship was consummated in May 1994 with the visit to Los Alamos by eight students and two teachers from Arzamas-16 and their participation in the first New Mexico High School Critical Issues Forum, a series sponsored by the Laboratory's Science Education and Outreach Group. The topic of the first forum was to be nuclear dismantlement; the format would involve teams of students from New Mexico high schools researching dismantlement and then developing proposed policies for U.S. assistance to Russia. When Lindemuth heard about the forum he called Judith Kaye, leader of the Outreach group, who agreed that Russian students could participate. Frantic phone calls to Arzamas-16 and hours of paperwork on the part of the Russians produced two teams of Arzamas-16 students to present their ideas on the dismantlement issue. The combined plan of the participating teams produced the clever acronym “TRUST, ”The Russian-United States Transition. After the forum, the plan was presented to U.S. Department of State personnel Joe Dethomas and Ann Harrington in Washington, D.C. Some pen-pals were able to meet face-to-face during this visit.

In February 1995, two gifts were presented to Bob Reinovsky and Lindemuth by Gennadi Karatayev, the Arzamas-16 City Administrator. A cast bronze bell and an invitation for a Los Alamos civic delegation to visit Arzamas-16 to participate in the May 9 Victory Day celebration commemorating the end of World War II in Europe. A seven-member delegation accepted the invitation and became the first U.S. civic visitors permitted into Arzamas-16 by the Russian government. Among the delegation was Steve Shankland of

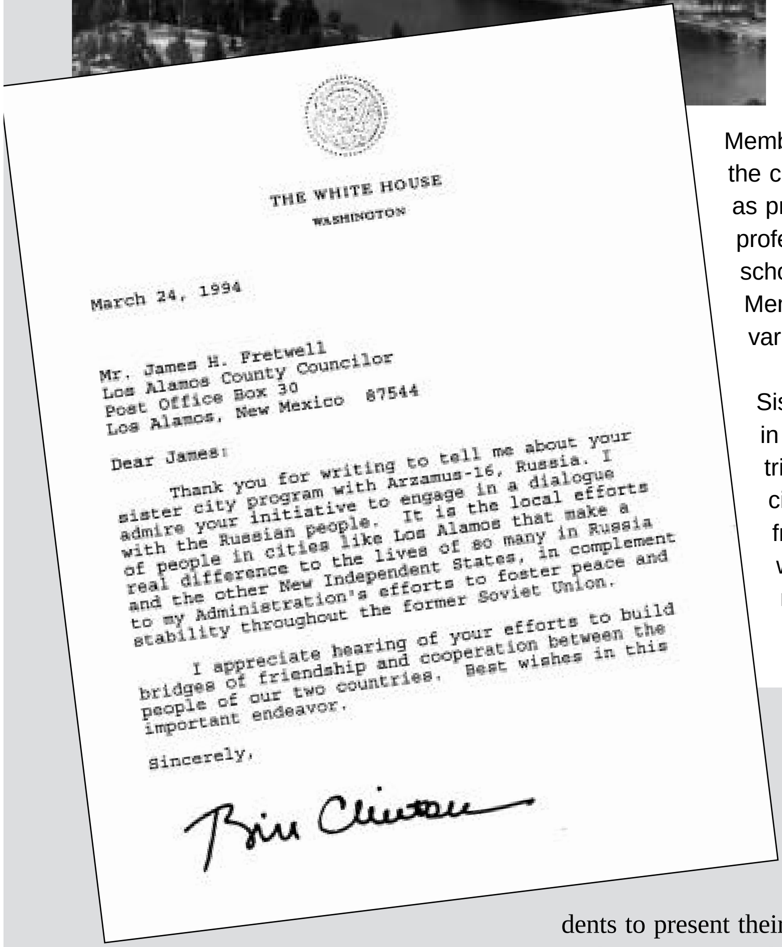
Sister Cities International

Sister Cities International is a national, non-profit, volunteer-membership organization joining United States and foreign communities. Sister city affiliations lead the national movement for volunteer participation and community development in the international arena.

The Sister City Program began shortly after World War II and developed into a national initiative when President Dwight D. Eisenhower proposed the people-to-people program at a White House Conference in 1956. He hoped that involving citizens internationally might lessen the chance of future world conflicts. Initially grouped with the National League of Cities, Sister Cities International became a separate, not-for-profit organization in 1967. The procedure for establishing an official Sister City affiliation requires that an agreement be signed by the respective mayor of each city and ratified by each city council, or its equivalent.

Membership in Sister Cities International is designed to improve the cultural understanding of people of different nations as well as provide new prospects for trade and business. Student and professional exchanges and other learning experiences in schools may be initiated through direct inter-school contracts. Membership in Sister Cities International provides eligibility for various grant programs.

Sister Cities International represents 125 million Americans in 1,200 U.S. cities and their 1,900 partners in 120 countries worldwide. Since 1986, partnerships between U.S. cities and those in the Former Soviet Union have grown from six to one hundred and fifty-two. Today, partnerships with Japanese and German cities represent the largest number of sister-city affiliations by country.



THE WHITE HOUSE

WASHINGTON

March 24, 1994

Mr. James H. Pretwell
Los Alamos County Councilor
Post Office Box 30
Los Alamos, New Mexico 87544

Dear James:

Thank you for writing to tell me about your sister city program with Arzamus-16, Russia. I admire your initiative to engage in a dialogue with the Russian people. It is the local efforts of people in cities like Los Alamos that make a real difference to the lives of so many in Russia and the other New Independent States, in complement to my Administration's efforts to foster peace and stability throughout the former Soviet Union.

I appreciate hearing of your efforts to build bridges of friendship and cooperation between the people of our two countries. Best wishes in this important endeavor.

Sincerely,

Bill Clinton

Like Los Alamos, modern Arzamas-16 (upper photo) is situated in a region of great natural beauty. The Sarovka and Satis Rivers flow into the Volga River separating the city into distinct sections.

the Los Alamos Monitor, the first non-Russian media representative ever permitted into the city.

The May 1995 visit to Arzamas-16 set the stage for an October visit to Los Alamos by a 15-member Arzamas-16 delegation. In January of this year, Los Alamos Middle School teacher Jeanne Allen was notified that she had been awarded a twenty-nine thousand dollar thematic exchange grant from Sister Cities International. Through this grant, five students and a teacher from Los Alamos and San Ildefonso Pueblo will visit Arzamas-16, and five Arzamas-16 students and a teacher will come to Los Alamos. The students will research water-quality issues, using New Mexico's Rio Grande and tributaries of Russia's Moksha River. The Laboratory will participate in this project by providing tours, lectures, and analytical assistance.

From the beginning of their modern existence, the people of Los Alamos and Arzamas-16 have been committed to the security of their respective nations. When the changing global political climate made it possible to work together to reduce the nuclear danger, the two cities embraced the opportunity. ■

Arzamas-16 Changes Name

A formal request by the people of Arzamas-16 in August 1995 led Boris Yeltsin to officially change the name of the city back to its historic name of Sarov.

Originally a provincial center, the town was the site of the Sarova monastery next to the Sarovka River. Before the Communist revolution, thousands of Russians, including the czar, made pilgrimages to the site to benefit from the pure water of the Sarovka River. The water is said to have healing powers and is a marketable commodity of the city today. In 1923, the monastery was closed by the communists and many priests were executed. Many of the buildings, including a spectacular cathedral, were destroyed, and the remaining buildings were converted to secular use. The high bell tower visible from much of the city stands as a monument to the earlier times.

The city disappeared from unclassified maps in 1946, the same year the All-Russian Scientific Research Institute of Experimental Physics, the weapons design facility, was built. The village was then given status as a city and, over the years, labeled with a series of classified code names. In 1990, the Soviet government first acknowledged the city's existence openly. Most in Sarov support the name change, but others feel that Arzamas-16 more correctly reflects the city's greatest achievements–nuclear weapons.

The city of Sarov remains a "closed" city with entrances and exits carefully monitored by armed guards at the periphery. Mr. Gennadi Karatayev, the City Administrator, recognizes that considerable time and money will be required to separate the necessarily classified technical areas from the remainder of the Institute and from the community. Nevertheless, Karatayev has expressed the hope that within ten years his city and much of the Institute will be "open," not unlike Los Alamos. Once again, members of the Russian Orthodox Church may now make pilgrimages to the sacred shrines of St. Serafim, the monastery's most famous resident.

The Patriarch of the Russian Orthodox Church visits the monastery of St. Serafim. Academician Yuli Khariton, the "Soviet Oppenheimer," is on the right.

In the midst of a cold Russian winter, these Russian and American experimentalists attempted to produce a plasma that was one hundred times hotter than the surface of the sun.

Lab-to-Lab

Scientific Collaborations Between Los Alamos and Arzamas-16 Using Explosive-Driven Flux Compression Generators

Stephen Younger, Irvin Lindemuth, Robert Reinovsky, C. Maxwell Fowler, James Goforth, and Carl Ekdahl

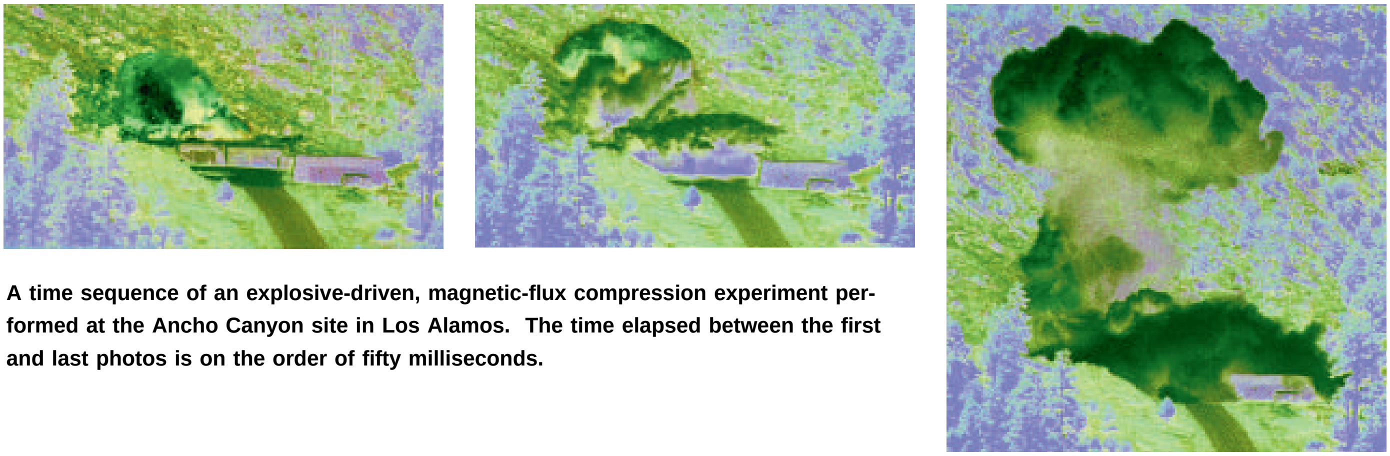
The first international conference on Megagauss Magnetic Field Generation and Related Topics was held in 1965 in Frascati, Italy. By then, Max Fowler, Wray Garn, and Bob Caird had already spent the better part of eight years producing megagauss magnetic fields. The small group of Los Alamos scientists had pioneered a technique called magnetic-flux compression, which takes the energy stored in the chemical bonds of high explosives and converts it to magnetic field energy. The energy is then delivered to an experiment as a pulse of either extremely strong magnetic field or extremely large electrical current. Although the Los Alamos magnetic-flux compression effort was relatively modest, Fowler and his team had achieved considerable success at building flux compression generators and had already produced magnetic fields above 10 megagauss (mega = 10^6). By comparison, the Earth's magnetic field is about 0.5 gauss, and that of an ordinary refrigerator magnet about 10 gauss.

A smiling Steve Younger congratulates Russian delegation leader Alexander Bykov after the success of the first, collaborative, nonweapons-related scientific experiment to be carried out on U.S. soil. The experiment, performed by Russian nuclear-weapon scientists and their Los Alamos counterparts, occurred in December 1993. On the left is Russian translator Elena Gerdova.

One of Fowler's motivations for building these devices was to use the enormous field to contain or compress a plasma. This compression could be a means of achieving thermonuclear fusion (the process by which the sun produces energy), which might make available to the world an unlimited energy source. Even without that exceptionally practical goal, Fowler and his team recognized that ultrahigh magnetic fields and intense electrical currents could find application in the study of phenomena ranging from material properties to x-ray generation.

While thumbing through the abstracts submitted to that 1965 conference, Fowler, to his surprise, noticed that some were from the Soviet Union. Nineteen scientists were represented in eight abstracts, and the Soviets were going to discuss the generation of megagauss fields by the technique of magnetic-flux compression.

"That was the first time I had seen anything of their work." said Fowler. "We had certainly never met any of



A time sequence of an explosive-driven, magnetic-flux compression experiment performed at the Ancho Canyon site in Los Alamos. The time elapsed between the first and last photos is on the order of fifty milliseconds.

them. It was strange, because their work seemed to be of the same scope as ours, and they were alluding to the same problems and the same solutions."

But the papers referenced by those abstracts were never submitted to the conference. No Soviet scientists attended, and the international community was left with only a tantalizing glimpse of the Soviet research program.

The Russian Magnetic-Flux Compression Program

We now know that the Soviet work had begun as early as 1951 when Andrei Sakharov, one of the premier scientists of the Soviet nuclear weapons program and winner of the 1975 Nobel Prize for peace, had sketched out an idea for compressing magnetic flux and generating high fields or currents. Like Fowler, Sakharov was seeking a means to achieve thermonuclear fusion, and he helped identify several schemes in which high magnetic fields could potentially help the fusion process. Some of the schemes were purely for research purposes, whereas others could potentially be used for weapons work.

Sakharov's ideas initiated a program involving some of the best Soviet weapons scientists, and an intense effort was devoted to the development of the high-field and high-current generators required to implement those ideas. The work was performed at Arzamas-16, the secret city that harbored the All-Russian (formerly the All-Union) Scientific Research Institute of Experimental Physics (VNIIEF), the Soviet Union's first nuclear weapons laboratory. Initially, much of the experimental flux compression work was carried out by Robert Lyudaev, who in 1952 succeeded in producing a magnetic pulse of approximately 1.5 megagauss. (In these explosive-driven flux compression schemes, the entire experiment is over in less than a millisecond. The field or current pulse rises "slowly," then quickly reaches peak value in the few microseconds before the generator is destroyed. In general, this research is referred to as high-explosive, pulsed-power research.)

Lyudaev's work was extended and advanced by scores of skilled Russian scientists, including Alexander Ivanovich Pavlovskii and Vladimir Konstantinovich Chernyshev, scientists who more than three decades later would play pivotal roles in establishing scientific collaborations between the Russian Federation and the United States. Pavlovskii eventually refined a generator, called the MC-1, to the point that it could reliably and predictably produce magnetic fields in excess of 10 megagauss. This was about the same field magnitude produced by Fowler's generators, but it was established in a larger and therefore more useful volume. Chernyshev's team developed a flux compression generator, called the DEMG, that could produce currents exceeding 200 megamperes. The Russian investigation into magnetic-flux compression continues to this day.

The Russian-American Pulsed-Power Collaborations

The independent development of the Los Alamos and Soviet pulsed-power programs represented something of an anomaly within the framework of modern science. Basic research is difficult and success often elusive, and the free exchange of ideas is vital. Yet here were two groups that were unable to communicate, much less exchange ideas. Despite the fact that flux compression generators were primarily used for pure scientific research, these devices could potentially aid in weapons development.† In the suspicion-charged atmosphere of the cold war, potential threats to national security superseded the desire for scientific exchange.

But times and situations change, and when the second Megagauss conference was held in Washington, D.C. in 1979, some fourteen years after the first conference, Soviet research papers were actually presented. However, neither Pavlovskii nor Chernyshev nor their team members were allowed to attend. Instead, a close colleague of theirs read

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† A ten-megagauss magnetic field can exert an enormous pressure on a conducting material, one that is exceeded only by the pressures achieved in a nuclear explosion. The generators can therefore be used to study weapons materials and evaluate diagnostics without detonating a nuclear device.

a number of papers that were of interest the non-Soviet scientists in attendance.

Communication and interactions between the Los Alamos and Arzamas-16 pulsed-power groups gradually increased during informal meetings at subsequent conferences. Fowler first met Pavlovskii in 1982 at the third Megagauss conference in Novosibirsk, U.S.S.R. The two scientists had been indirectly influencing each other's work for more than a decade, but now a personal relationship developed between the two men. With Fowler's assistance, Pavlovskii visited both the United States and Los Alamos for the first time in 1989.

Megagauss-V was held later in 1989 in Novosibirsk. Pavlovskii, who was not in attendance due to health problems, had a letter delivered to Fowler that raised the issue of a joint research program for producing fields in the 20 to 30 megagauss range. The suggestion, though informal, was a recognition of the obvious. Faster progress would be achieved by both groups through a collaborative effort, and both groups would benefit.

Megagauss-V was also where Bob Reinovsky and Irv Lindemuth of Los Alamos met Vladimir Chernyshev for the first time. The Los Alamos and Soviet teams were by then well acquainted with each other's publications, and the meeting led to several speculative discussions about the possibility of future collaborations. The talk became more serious at the 1991 International Pulsed Power Conference, held in San Diego, and culminated in September of that same year when Chernyshev and Vladislav N. Mokhov met with Lindemuth in Moscow and presented a written proposal for a formal collaboration on thermonuclear fusion research using flux compression generators.

The Soviet proposal called for a generator to create a large magnetic field that would be used to implode a liner, which is a hollow metal cylinder. The liner would surround a dense, hot, plasma that would be created in a second magnetic field. This method of preparing a "magnetized" plasma was not akin to any method then being pursued in the United States. Imploding the liner would potentially compress the plasma to the very high densities and temperatures needed to initiate thermonuclear fusion. This speculative fusion scheme is known as MAGO in the Soviet Union. The collaboration proposal was signed by VNIIEF Director Vladimir Belugin and, evidently, had the support of Yuli Khariton—the "Soviet Oppenheimer"—as well as high-ranking officials from the Soviet Ministry of Atomic Energy. However, although the Soviets were willing to share with the Americans the results of their pulsed-power program, including their MAGO thermonuclear fusion research, the global political climate was changing so abruptly in the latter part of 1991 that the formal proposal went unanswered by the United States government.

In fact, the political climate turned severe with the collapse of the Soviet Union in December of 1991 and the Russian Federation's subsequent rapid decline towards economic chaos. Within the nuclear cities, the formerly elite nuclear weapons scientists were suddenly facing food-distribution problems and shortages of medical supplies. It was perceived by many in the West that the situation was becoming unstable and could potentially result in breakdowns in the security that safeguarded nuclear weapons and materials. Many feared that weapons of mass destruction or fissile materials could be stolen or sold to rogue nations or terrorists. President Bush himself was deeply concerned about the possibility of the so-called "brain drain," wherein nuclear weapons scientists would migrate to and work for other countries.

Los Alamos Laboratory Director Sig Hecker, aware of the various overtures extended to Los Alamos scientists by the Arzamas-16 scientists, pointed out to then Secretary of Energy Admiral Watkins that perhaps the Russian laboratory leaders themselves knew the best way to keep their scientists at home. That simple acknowledgment, and Watkins quick approval, led directly to the Laboratory Directors' exchange visits in February of 1992.

The Directors' exchanges would form the beginnings of the "lab-to-lab" collaborations between the United States and Russian nuclear laboratories. Scientifically, this program was for the purpose of conducting pure research, and was not directed towards the development of any weapon, fusion or otherwise. The Americans, and presumably the Russians, came to recognize that the technical advances that could emerge from the research would have a minimal and remote risk of being applied to weapons that posed a threat to either country.

Instead, the collaborations would have the positive effect of infusing a small amount of money into the Russian complex. This would help stabilize the financial situation and help keep the Russians scientists working. The United States would also reap the benefits of scientific exchange with world-class research institutions. It is interesting to note, however, that although the Directors' exchange formally cut the ribbon, the bridge that spanned the East-West political gulf had been built by scientists reaching out to one other. A friendly handshake between Max Fowler and Alexander Pavlovskii was transformed into a tangible link between Russian and American scientists.

Irv Lindemuth, Bob Reinovsky, Max Fowler, and Stephen Younger visited Arzamas-16 in June of 1992. During that visit, Younger, then the Program Director for Above-Ground Experiments, suddenly found himself elevated to the role of negotiations point man. Younger succeeded in forging an agreement that laid out the rules for the lab-to-lab program. The Russians would provide manpower, expertise, and equipment for joint experiments. Los Alamos would finance part of the experiments and would complement the Arzamas-16 devices with its significant expertise in fast diagnostics, recording instrumentation, and supercomputer modeling.

It was agreed that two experimental campaigns would initially be conducted, the first to take place at Arzamas-16. That experiment would test Chernyshev's DEMG high-current flux compression generator. The Russian scientists would then come to Los Alamos and help conduct an experimental series in superconductivity using Pavlovskii's MC-1 generators that had been purchased by Los Alamos. The contract establishing the lab-to-lab collaborations was signed at Los Alamos in November 1992.

That initial contract and the diverse collaborations that developed from it (including an on-going exploration of the MAGO fusion scheme) signified a manifest thawing of Cold War relations and a true shift in the respective roles of the labs. But another, more personal thawing took place as well. After more than forty years of mutual distrust and enmity, Russian and American weapon scientists were going to work together as collaborators and "side-by-side as equals."

The remainder of this article describes some of the experiments that were performed between 1993 and 1995. All of those experiments needed megagauss magnetic fields or megampere electrical currents to achieve their objectives. There will be a brief overview of the principle of magnetic-flux compression that is the basis for ultrahigh magnetic field or current generation, followed by a cursory description of several types of flux compression generators. The article will then proceed to describe five different series of experiments that used those generators.

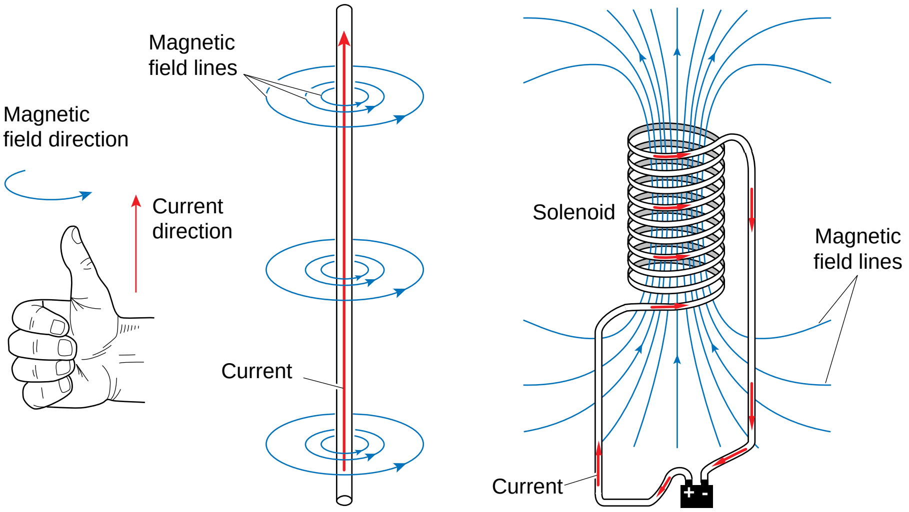


Figure 1. Magnetic Fields and Electrical Currents

Current (red) flowing through a straight wire creates circular magnetic field lines (blue). The field lines are drawn such that the field strength is indicated by the density of the lines (number of lines per unit area). Thus, the magnetic field strength decreases with distance from the wire. The direction of the magnetic field can be found by the "right hand rule." If the thumb of your right hand points in the direction of current flow, the magnetic field lines will point in the direction that your fingers curl. The magnetic field created by a current-carrying solenoid exits from one end of the coil and circles around to enter the other end. The field on the inside of the solenoid is relatively strong and uniform (equally spaced, dense field lines), whereas the field decreases in strength and is nonuniform outside of the coil.

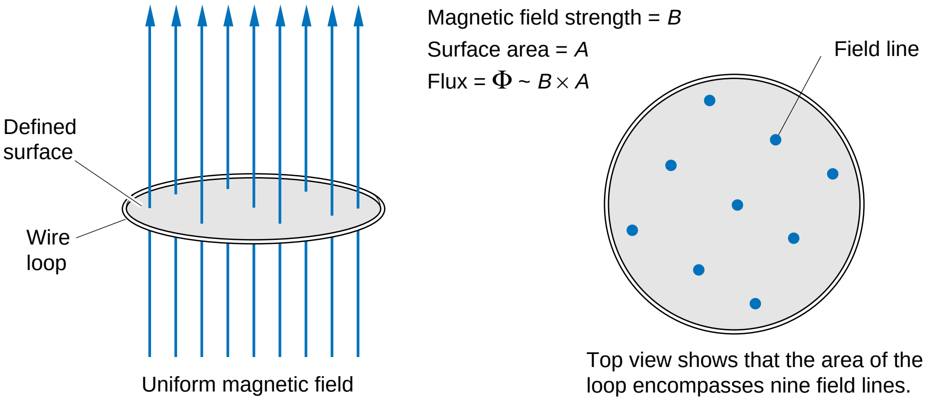


Figure 2. Magnetic Flux

In general, magnetic flux is calculated by integrating the perpendicular component of a magnetic field passing through a surface over the area of that surface. For the uniform magnetic field shown in the figure, the calculation is greatly simplified. The surface is the inside of the circular loop of wire, and the flux is simply the field strength times the area of the loop. Because the field strength is represented by the density of magnetic field lines, the flux is represented by the number of field lines. (Flux = number of lines per unit area × area = number of lines.)

The Principles of Magnetic-Flux Compression

Early in the nineteenth century, through the work of Oersted, Ampere, and others, it was recognized that an electrical current always generated a magnetic field. The size of the current determined the field strength, and the field always pointed in a direction that was at right angles to the direction of current flow (Figure 1).

Although many physicists during the 1820s were aware that currents were the source of magnetic fields, it wasn't until 1831 that Michael Faraday showed the converse to be true; a *changing* magnetic field generates an electric field that causes a current to circulate in a conductor. Faraday summarized his observations by stating that a change in the “magnetic flux” that threaded a loop of wire would generate an electromotive force, that is, a voltage, which would induce current to flow.

Figure 2 illustrates the concept of magnetic flux. Although the flux can be defined and calculated for any arbitrary configuration of field and conductors, a simple case is shown in the figure. There, a uniform magnetic field passes straight through a circular loop of wire. The flux in this case is simply the field strength times the area of the loop.

As described at the start of this section, a current is the source of a magnetic field, so that if the flux that threads a loop changes, and the change induces a current to flow in the wire, a new magnetic field is also induced. Faraday demonstrated that the direction of that new field counteracts the change in the flux (a phenomenon that had been described, but not quantified, by Lenz’s law). In other words, attempts to change the flux through a conducting loop are counteracted by the induction of currents and fields. The induced field points in a direction that negates the flux change.

Suppose our loop is made from a perfectly conducting material, meaning that currents can circulate around that loop without losing energy. For a perfectly conducting loop, a change in the flux will induce a current that will be of sufficient strength to exactly counteract the change. As illustrated in Figure 3, the flux before and after will be the same, and the flux is said to be conserved.

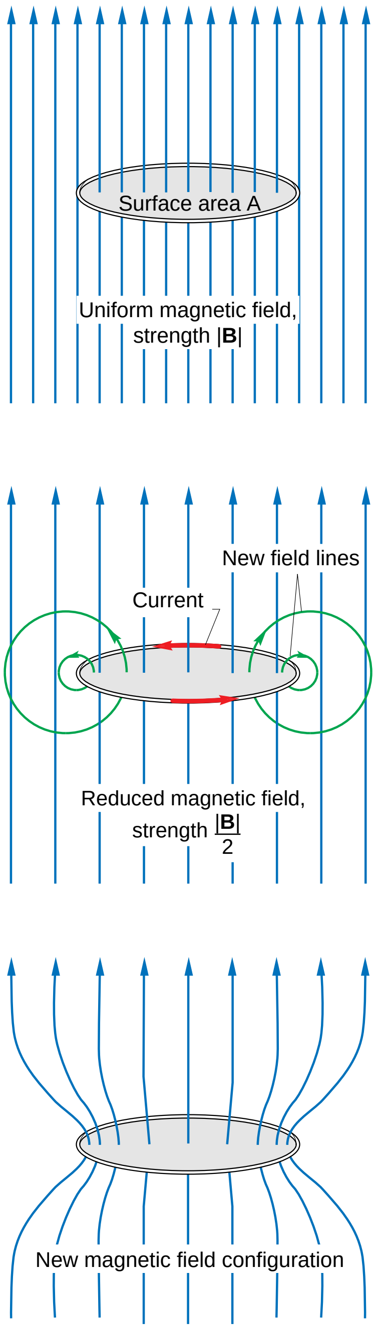


Figure 3. Faraday’s Law and Flux Conservation

An external magnetic field (blue lines) threads a closed, perfectly conducting loop. Nine field lines, which represent the flux, thread the loop.

The external magnetic field is reduced to half its value, such that only five external field lines pass through the loop and contribute to the flux. This change in flux induces a current in the loop, which generates a new magnetic field (green lines). The current flows in such a direction that the induced magnetic field adds to the external field. The induced field negates the flux change, and the total flux through the loop is maintained (four green field lines plus five blue equals nine field lines).

Summing the external field and the induced field gives the final field configuration. The distribution of the magnetic field through the loop has changed, but the total amount of flux is conserved.

Most materials are not perfect conductors but have some resistance. Current flowing through a copper or aluminum wire loses energy, which is dissipated as heat. An induced current will continuously decay at some characteristic rate (which depends on both the resistivity of the material and the “inductance” of the loop), and therefore, the induced magnetic field also decays. It becomes unable to counteract the flux change. A loop made of one-millimeter thick copper wire at room temperature and a few centimeters in diameter will maintain a constant flux for less than a millisecond. On the time scale of an explosion, however, which may last only a few microseconds, that loop maintains flux quite well. Thus, on short time scales, shorter than the characteristic decay time, even normal materials approximate perfect conductors, and flux is approximately conserved.

Suppose that instead of changing the magnetic field through the loop, the loop itself is changed and shrinks in size. The flux, which is proportional to both the field and the area, should decrease, but again, currents are generated in the conducting loop that create a new magnetic field. The induced field points in the same direction as the original field to counter the flux change, and the total strength of the field threading the loop increases.

This is the way ultrahigh fields and

ultrahigh currents are created. A flux compression generator may use a hollow metal pipe instead of a loop, and a portion of an external field will go down the center of the pipe. High explosives, arranged symmetrically around the pipe, are detonated, and the pipe is rapidly compressed by the pressure of the explosion. The pipe wall collapses towards the axis. On the short time scale of the explosion, the flux is approximately conserved and remains relatively constant as the pipe cross section shrinks (Figure 4). The flux is “compressed” because the same amount of flux now occupies a significantly smaller area. To maintain the total flux, the magnetic field strength gets greatly enhanced, and that increasing magnetic field, in turn, generates a large current in the collapsing wall.

The high explosive plays a dual role in this scheme. First, it collapses the conductor so quickly that flux conservation is approximately true. Second, it is a source of energy. Energy is stored in a magnetic field and the amount of energy is proportional to the square of the field magnitude (B^2). Because the field magnitude increases, the energy content must also grow. That energy comes from the chemical energy stored in the molecular bonds that make up the explosive material. When the explosives are detonated, energy is released and does work on the conducting surface, so that it collapses. The conductor, in turn, does work on the field by compressing the flux, and the ultimate repository for the released chemical energy is the magnetic field itself.

Regions of high energy density want to expand and equilibrate with regions of lower energy density. A magnetic field of high energy density will, therefore, exert a physical pressure against any barrier that is trying to contain or exclude that field. The magnetic pressure also scales as B^2, and for the huge fields created by these flux compression generators, that pressure is enormous. A 1-megagauss field exerts a pressure of about 40,000 bar (a bar is about

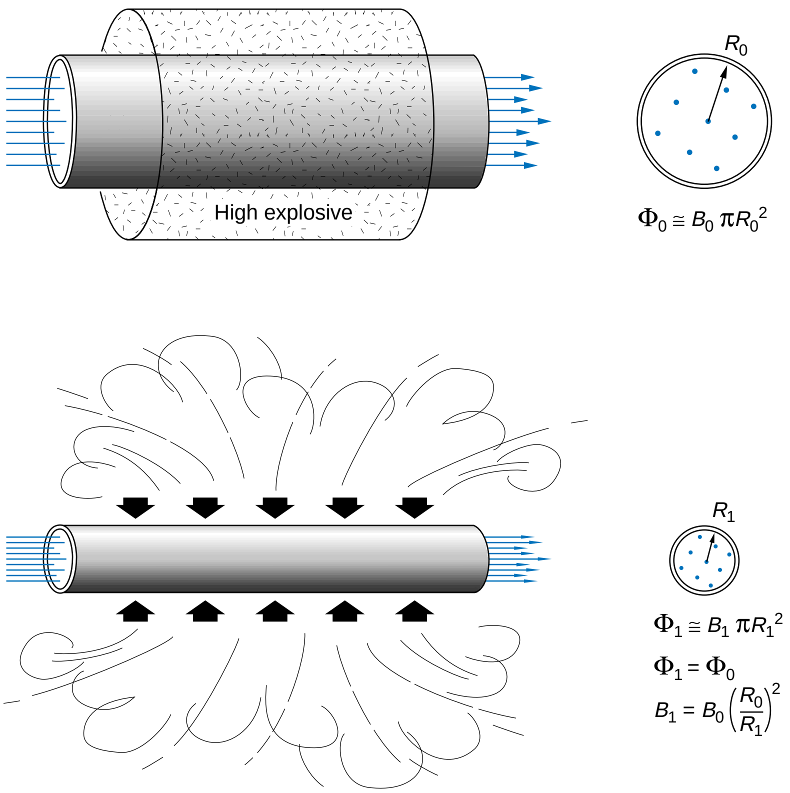


Figure 4. Explosive-Driven Flux Compression

A magnetic field is established within the interior of a metal pipe. The boundary for the flux is the pipe wall, and the surface that defines the flux is the cross-sectional area of the pipe. On short time scales, magnetic flux is conserved so that rapidly imploding the pipe and reducing the interior area compresses the flux (the density of field lines increases). Thus, although (ideally) the flux stays the same, the total magnetic field strength increases.

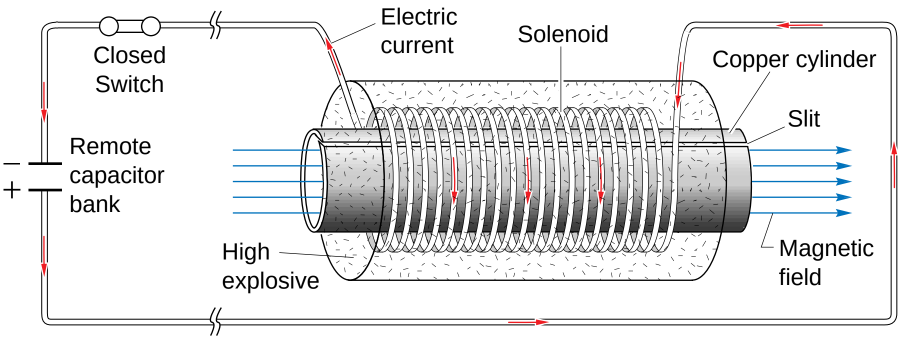


Figure 5. An Early Flux Compression Generator

The central copper cylinder is cut by a long slit, so that it is not initially a closed conducting surface and currents cannot circulate around its circumference. Flux cannot be conserved. When the remote capacitor bank is discharged and current runs through the solenoid, an initial magnetic field is easily established inside of the cylinder. Detonating the high explosives compresses the cylinder, and the slit closes. It is now a closed surface that conserves the flux. As described in the text, the magnitude of magnetic field inside the cylinder increases rapidly.

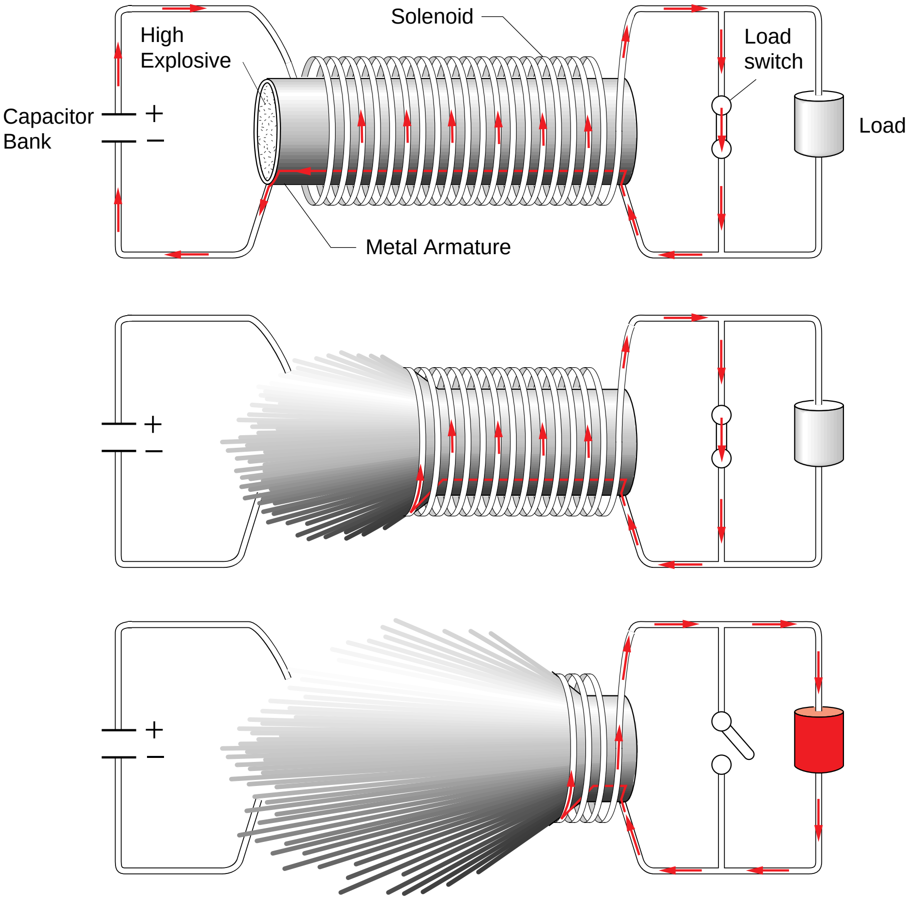


Figure 6. Helical generator

A helical generator has a long metal armature that is packed with high explosive and placed within a solenoid. As the capacitor bank discharges, the current generates a magnetic field in the space between the solenoid and the armature. The load switch is initially in the closed position, preventing the current from flowing through the load.

The explosive is detonated at one end, and the armature expands—like inflating a long balloon. The volume between the solenoid and the armature decreases in both the radial and longitudinal directions. This causes the magnetic flux to be compressed. Flux conservation results in an enhanced magnetic field, which induces a large current in the remaining loops of the solenoid.

At peak flux compression, the load switch is opened, and a greatly enhanced current is delivered to the load.

14.7 pounds per square inch), which will easily cause metals to buckle and deform. Between 1 and 2 megagauss, the pressure will cause the surface of a conductor to liquefy and vaporize. Above 2 megagauss, the vaporization occurs so rapidly and violently that the surface of a conductor is blasted off and shock waves penetrate into the material. A 10-megagauss magnetic field exerts on a conducting surface a pressure of 4 megabars, or 60 million pounds per square inch! This is larger than the pressure values existing in the center of the Earth (3.7 megabars).

Figure 5 shows the type of flux compression generator built by Robert Lyudaev. This device is very similar to a design published by Fowler and his Los Alamos team in the proceedings of a 1961 conference on high magnetic fields (see Further Readings, page 66, third reference). The device used a solenoid to establish an initial magnetic field inside a copper cylinder, and the cylinder was then imploded. The flux was compressed inside the metal cylinder, and the initial field was amplified by a factor of 10 or more. The peak value of the resulting transient magnetic field was estimated to be about 1.5 megagauss.

Fowler's and Lyudaev's early generators, as well as Pavlovskii's MC-1 generator, were intended to use the high magnetic field directly on an experiment that was placed within the central cylinder of the device. But as previously mentioned, the high magnetic field induces a large current in the collapsing conductor, and that current can be the intended output of the generator. In general, the design of a generator will differ depending on whether it is to deliver a high magnetic field or high current to the experiment. A helical generator, shown in Figure 6, is designed to deliver high current to a load located outside of the explosive region of the device. Often, helical generators are used as the first stage in a multistage flux compression scheme. The high output current is used to establish a new, very high initial magnetic field in a second generator.

Before leaving this section to discuss the various experiments, there is one final point to be made. These experiments are true one-shots deals. The generators work because high explosives are detonated, and therefore, the entire experiment must be completed in substantially less than a millisecond, after which time the generator and most of the experimental apparatus is completely destroyed. This places stringent conditions not only on the type of phenomena that can be investigated, but also on the reliability and predictability of the generator and experiment diagnostics. One does not have a second chance.

Figure 7. The Disk Explosive Magnetic Generator (DEMG)

The DEMG consists of pairs of concave conducting disks that are stacked together. A device of 15 disks is shown. It has cylindrical symmetry about the labeled axis. Current flows as indicated by the red line, and an azimuthal magnetic field is established within each toroidal disk cavity. When the DEMG is detonated, the explosion begins on axis and proceeds radially outward. As the disk cavity collapses, the magnetic flux within it is compressed and pushed into the thin region at the outer circumference of the device. That region is bounded by conducting surfaces, so when the flux density within that space rapidly increases, a huge current is induced to flow. When a fuse opening switch is used, the current causes the fuse to melt and open. At the same time, the load switch is forced shut. The current is then delivered to the load, which is often a liner (see below).

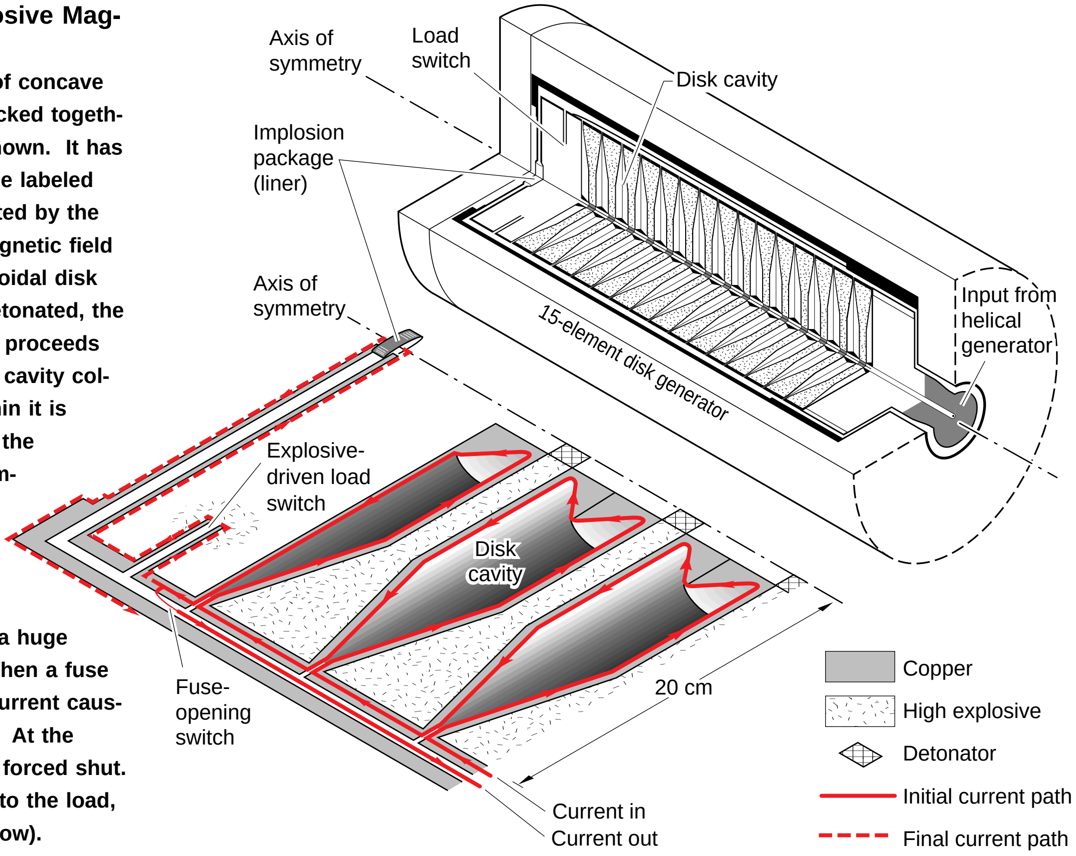
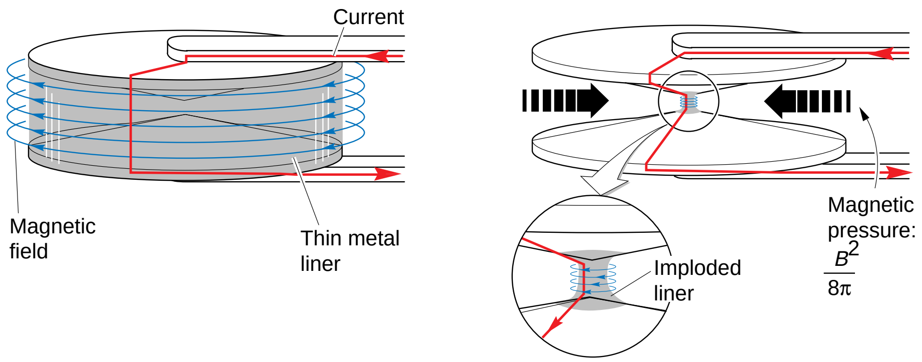


Figure 8. Implosion of a Liner

A liner is a hollow cylinder made of metal. Initially, there is no magnetic flux inside the cylinder. When an intense current pulse from a generator (represented by the single red line) passes down the walls of the liner, a large magnetic field is created. The inside of the liner remains at zero field due to flux conservation and field exists only on the outside. The magnetic pressure drives the liner inward.



The DEMG

The first scientific experiment conducted jointly by the nuclear-weapons laboratories of the United States and the Russian Federation occurred at a high-explosive facility at Arzamas-16 on September 22, 1993—the day after President Yeltsin sent tanks to surround the Russian White House. (The Los Alamos contingent, consisting of all the authors except Max Fowler, plus Lynn Veeser, Pat Rodriguez, and Jim King, tried to ignore the growing political crisis as they completed the final preparations for the experiment.) The objective of the experiment was to verify the performance of the unique high-current generator, the Disk-Explosive Magnetic Generator (DEMG) developed by Chernyshev, that could potentially be used for the MAGO plasma compression experiments, as well as other high-energy-density physics experiments.

The DEMG has no counterpart in the United States, and its properties and operation were unknown. Although small models of the DEMG had been briefly described at the Megagauss-III conference (1983), it was not until Megagauss-V (1989) that the full power of the DEMG was revealed.

The device, shown in Figure 7, has cylindrical symmetry and consists of a series of concave conducting disks that are stacked together in pairs, like opposing pie pans. Magnetic flux is trapped in the space between two disks. Detonating the DEMG collapses the disks, and the magnetic flux is compressed into a thin region bounded by a conducting cylinder. The enormously compressed magnetic flux generates a huge current in that conducting surface, and this current can be delivered directly to the experiment or "stored" for subsequent, rapid delivery to the experiment using a fast-opening switch.

For the 1993 DEMG test, a capacitor bank provided the initial current to create a magnetic field in a helical generator. The helical generator amplified the capacitor's output current of approximately 20 kiloamperes to the 6-megampere current required to power the main DEMG. That device had fifteen disks of 0.2 meter radius. It was to generate some 60 megamperes and deliver as much as 35 megamperes to a cylindrical aluminum liner, 2 centimeters long and 6 centimeters in diameter.

A high current pulse sent down the liner creates a large magnetic field that, for a short time only, exists on the outside of the liner wall (Figure 8). The large magnetic pressure drives the liner inward at huge velocities (up to hundreds of kilometers per second for very light liners). Diagnostics placed inside the liner at different azimuthal angles or different axial positions can detect the liner's arrival, and hence, measure the symmetry of the implosion. The liner can be in a solid, liquid, or plasma state as it implodes, depending on the amount of heat generated by the current and field. Shock wave phenomena, hydrodynamics, and material properties can all be studied with this type of electrical load. For this experiment, the liner was simply a well-understood and convenient diagnostic.

To improve the timing of the current delivery, a thin metal fuse was added that initially allowed the DEMG output current to be diverted away from the liner. When the current reached a critical value, the fuse melted. The high current was then delivered to the liner in less than 1 microsecond.

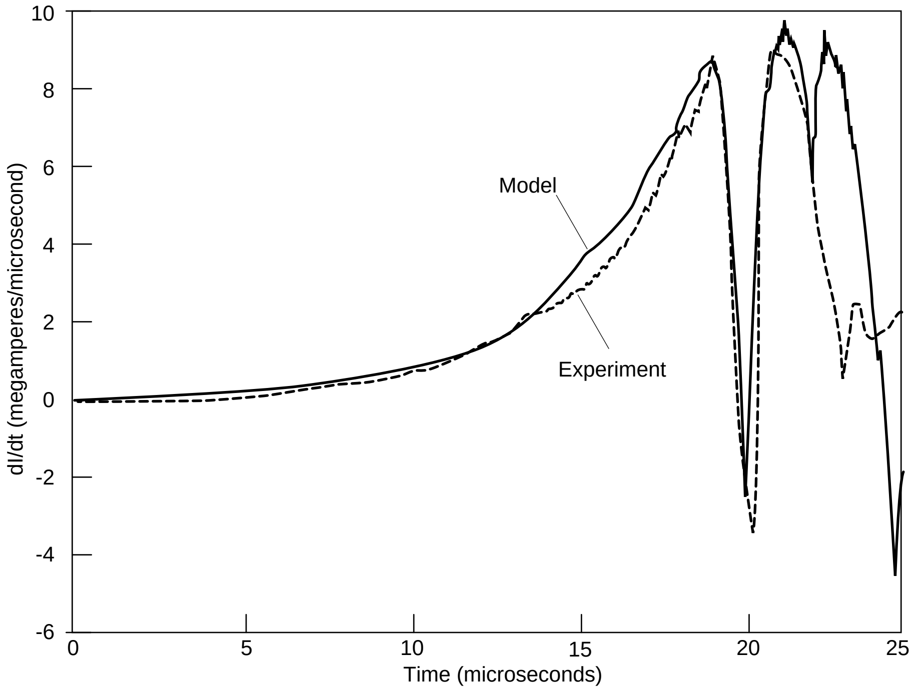


Figure 9. Output from the DEMG

The rate of change of current was measured by a probe that was located near the transmission line that led to the load. Although there are some discrepancies in the late time behavior, clearly the DEMG worked as predicted. The theoretical curve is from a Los Alamos computer model developed by Bob Reinovsky, which was run using input parameters provided by the Russian pulsed-power group.

The rate of change of the current and pulse shape were measured at various points along the DEMG using VNIIEF-built probes (mostly tiny pickup coils called B-dots, which measure the rate of change of the magnetic flux produced by the current). Los Alamos fielded two current probes (Faraday rotation probes, described in the following section) that allowed a more precise measurement of the DEMG's performance than had been previously achieved. The result of the experiment, shown in Figure 9, agrees with model predictions calculated using Los Alamos codes and parameters provided by the Russian scientists. But a probe located near the liner indicated that there was a partial failure in a transmission line, so that only 20 megamperes of the DEMG output was delivered to the load.

Still, the disk generator worked as the Russians had described in the literature, and this first collaborative experiment helped allay many lingering suspicions that existed within both camps. What remained was an atmosphere of enthusiasm, for it was clear that after years of parallel but separate research, scientists with similar backgrounds, interests, and goals were working together.

Measurement of the Critical Field of YBCO Superconductor

At the end of 1993 and two months after the DEMG experiment was performed at Arzamas-16, a group of eight Russians came to Los Alamos, bringing with them five MC-1 generators that had been purchased by Los Alamos as part of the November 1992 agreement. The MC-1s (Figure 10) were used in a series of experiments to measure a key parameter of high-temperature superconductors. Unfortunately, the principal developer of the MC-1, Alexander Pavlovskii, had died in February of 1993 and did not live to see come to fruition the collaboration for which he had worked so hard.

A superconductor is a material that

when cooled below a certain critical temperature, T_c, experiences a sudden drop in its electrical resistance to immeasurably low values, and a direct current moving through a superconductor flows with no energy dissipation. How and why superconductivity occurs was described by Bardeen, Cooper, and Schrieffer in 1957 when they published a detailed microscopic theory of superconductivity.

The cornerstone of the BCS theory is that, below T_c, electrons with equal but opposite momentum and opposite spin form what is called a Cooper pair. By forming a pair, the two electrons lower the sum of their total energy, and thus, pair formation is energetically favorable.

Below T_c, a macroscopic number of electrons condense into paired states with total spin zero. This means that the pairs obey Bose statistics, and the entire ensemble of Cooper pairs can occupy the same quantum state and exhibit collective behavior. It is the collective behavior of the Cooper pairs that leads to resistanceless current flow, often called supercurrent flow.

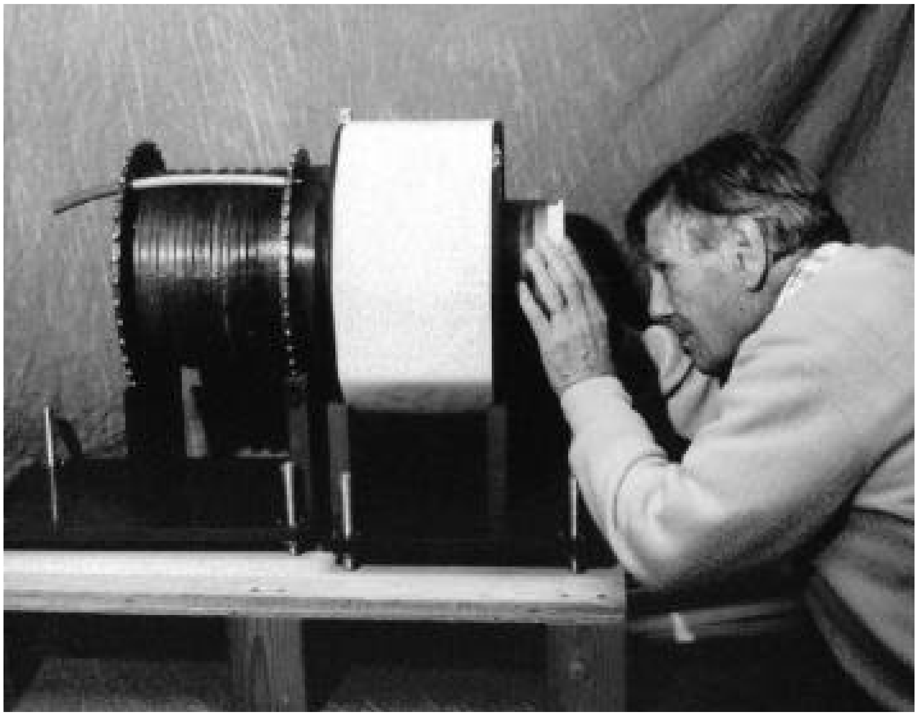


Figure 10. The MC-1 Flux Compression Generator

Max Fowler peers into the central region of an MC-1. The white ring is a mock-up of the high explosive that surrounds the central solenoid. Current is carried to and from the solenoid along numerous cables, although only a single cable is shown.

To understand the supercurrent, first consider the normal current flow due to unpaired electrons moving through a material's crystal lattice. The electrons will scatter from atomic defects in the lattice and lose energy. An analogy is to consider the defects as bumps in an otherwise smooth road, and to consider the free electrons that make up the normal current as cars driving down the road. Each time a car encounters a bump, it slows down or changes direction. The cars encounter "resistance" to their movement.

In the collective state, the cars are all jammed together, front-to-back and side-to-side, forming a pack. Within the pack, cars are linked together as "Cooper pairs" (although the cars forming the pairs are not necessarily right next to each other). The entire pack speeds down the road, each car moving with the exact same velocity as all the others. Small bumps cannot affect the momentum of this single, collective "state," and the cars move down the road without resistance.

Analogies not withstanding, the collective state can be broken. The attractive interaction binding Cooper pairs together is very weak, and above the temperature of absolute zero, thermal energy is often sufficient to cause pairs to break. As the temperature of the material rises, the number of Cooper pairs decreases, until above $T_{c,}$ all Cooper pairs are broken and a normal current flows through a resistive material.

A magnetic field can also destroy the superconducting state. Above a few hundred gauss, magnetic fields will penetrate most superconductors in the form of quantized vortices, which are circular tubes of circulating supercurrent. At the core of the vortex, superconductivity is suppressed over a radius termed the "coherence length," which is roughly equal to the size of the Cooper pair. As the applied magnetic field increases, the density of vortices increases proportionally.

At an external field value referred to as H_{c_2}, the cores overlap and the superconducting state is destroyed throughout the entire sample. Thus, H_{c_2} establishes the highest field in which a superconducting device can be operated without reverting to the "normal" resistive state. From an engineering standpoint, establishing the magnetic field dependence of a superconductor is extremely important. From a research standpoint, H_{c2} is related to the size of the vortex core or the coherence length, and knowing its value and temperature dependence, $H_{c_2}(T)$, is of great theoretical interest.

Prior to 1986, all of the conventional superconductors had to be operated at or near liquid helium temperature (4.2 kelvins), and that required expensive refrigeration technology. The highest T_c that had been observed in any superconductor was 23 kelvins for the compound Nb_3Ge, which has an H_{c_2} of 0.4 megagauss.

In 1986, a new class of superconductors, the "cuprates," was discovered that were based on a layered structure

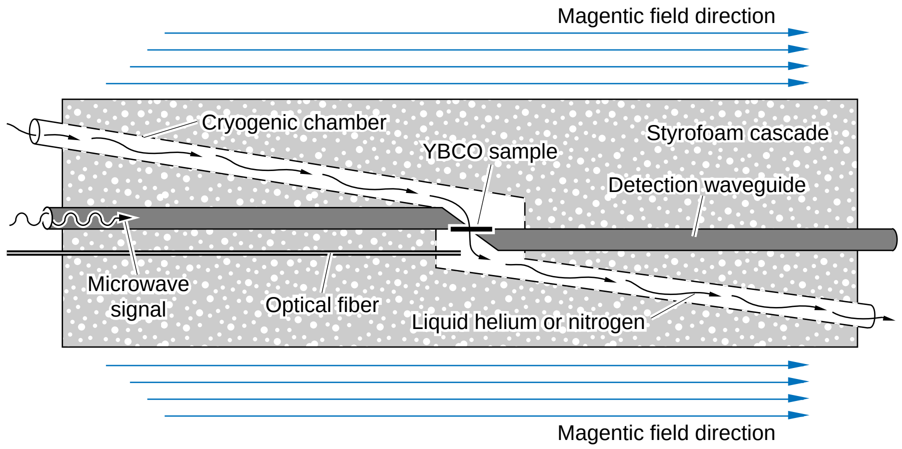


Figure 11. Schematic of the Critical-Field Experimental Setup

A styrofoam cylinder, placed within the center of the MC-1, held the entire experiment. A channel cut into the styrofoam formed a conduit for the delivery of cryogenic fluids that cooled the sample. The temperature was adjusted by changing the particular cryogen. The plastic waveguides directed a millimeter-wave signal to the YBCO sample for the detection of the superconducting to normal phase transition. The field was measured by both optical (Faraday rotation) and inductive (B-dot) probes.

of copper-oxide sheets separated by non-superconducting layers. The cuprates exhibit T_c's extending far above liquid nitrogen temperature (77 kelvins), a much easier temperature to maintain. The present record T_c of 135 kelvins is held by a mercury-cuprate compound. The potential for application of these high temperature superconductors in motors, generators, and high-field solenoids that can operate more economically at liquid nitrogen temperature is enormous.

Naturally, there is a great interest in measuring the critical field for these new cuprate superconductors. However, for compounds with critical temperatures above 90 kelvins, critical magnetic fields have been observed to exceed 0.3 megagauss at temperatures near 70 kelvins. That magnetic field is approximately at the limit of presently available direct current magnet technology. Since H_{c_2} only increases as the temperature plunges towards absolute zero, a measurement of the critical field at lower temperature values has not been possible.

Thus, the value of $H_{c_2}(T)$ was more than just idle curiosity. The model outlined above for how a magnetic field destroys superconductivity is quite general and has been experimentally verified in detail for the conventional superconductors and, in many respects, for the new cuprates. However, there is yet no established theory for the microscopic mechanism of superconductivity in the cuprates, and there is growing evidence to support the idea that there are fundamental differences with low temperature superconductivity. Recent experiments indicate, for instance, that Cooper pairs in the cuprates may have nonzero orbital angular momentum, in contrast to the BCS model and to the established behavior of conventional compounds. This difference could affect the detailed functional form of $H_{c_2}(T)$ at high fields. In addition, there have been predictions of novel magnetic structures developing at high fields that differ from the usual vortex lattice structure. It is clear that a determination of $H_{c_2}(T)$ over the range from T_c to low temperatures and in fields of several megagauss will be important in answering these questions.

The Los Alamos-Arzamas-16 collaboration was interested in directly measuring $H_{c_2}(T)$ for a YBCO (Yttrium-Barium-Copper-Oxygen) high-temperature superconductor as a function of temperature, data that previously could not be measured because of the high critical field value. A sample of the YBCO material was placed along the axis of the MC-1 generator. A flow-through cryogenic system maintained the sample at a predetermined temperature between 4 and 80 kelvins. For a given fixed temperature, the state of the material would be monitored while the magnetic field strength was continuously measured as it increased. At the critical field, the superconducting sample went normal.

The transition to a normal state was heralded by the appearance of a millimeter-wave signal at a receiver. When superconducting, the ceramic YBCO sample reflects electromagnetic radiation at millimeter wavelengths, but the radiation passes straight through the material when it is normal. As seen in Figure 11, the sample was sandwiched between two plastic dielectric waveguides. The probe waveguide brought a 4-millimeter wavelength (75 GHz) signal to the 0.15-micron thick YBCO sample. When the sample went normal, the radiation passed through the material, entered the detection waveguide, and was detected by a receiver.

Magnetic field values were measured with both B-dot pickup coils and with optical probes. An optical probe makes use of the Faraday effect, in which the plane of polarization of polarized light is rotated as it passes through an optical element situated in a magnetic field. The amount of rotation is proportional to the field strength. A polarized laser beam was transported to and from a cylinder of flint glass (the optical element) by fiber optic cables, and a comparison of the plane of polarization between the outgoing and the incoming laser beams measured the magnetic field.

To complement the high field, low temperature measurements, two additional experiments were performed at higher temperatures using low field generators built by Los Alamos. Figure 12 shows the four data points that were generated. At the lowest temperature, about 4 kelvins, the criti-

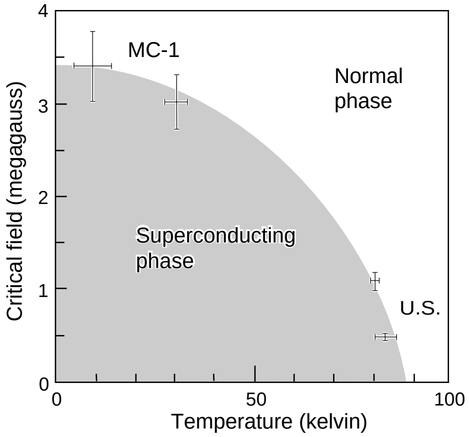


Figure 12. Critical Field of the YBCO Superconductor

The critical field, H_{c_2}, for the YBCO superconductor is plotted versus temperature. The critical temperature, T_c, for this material is about 90 kelvins. The border of the shaded region was drawn by hand to help guide the eye and is not a fit to the data. The temperature dependence roughly follows that of metallic, low temperature superconductors: $H_{c_2}(T) = H_{c_2}(0)[1-(T/T_c)^2]$, where $H_{c_2}(0)$ is the critical field at absolute zero.

cal field was over three megagauss, more than six times the peak field achievable in prior laboratory experiments. The seven collaborative experiments mapped out the curve of the critical field over the full temperature range. The data provides valuable information for theorists and experimentalists studying this material.

Fowler and Bruce Freeman of Los Alamos led the American team of more than two dozen scientists in these challenging experiments. This effort was the first time that Russians—let alone Russians from a nuclear weapons institute—had worked "behind the fence" at Los Alamos. Although most of the generators were Russian (Pavlovskii's MC-1 generator), the high explosives that powered them were American, and Los Alamos explosives engineers had to learn how to load the special "Russian initiator blocks" that served to detonate uniformly the exterior of the main explosive charge.

Hot Magnetized Plasmas

The third series of experiments, which were initiated at Arzamas-16 in April 1994, was the start of our collaboration on the MAGO thermonuclear fusion scheme. This was the topic that was originally proposed by Chernyshev and Mokhov in September of 1991. The goal of this series was to investigate the first step of the MAGO scheme, that is, the production of a hot, magnetized plasma that could potentially be imploded to thermonuclear fusion ignition conditions.

Fusion is the process by which two light atomic nuclei combine to form a heavier nucleus. But fusion does not normally occur under the conditions found here on Earth. All nuclei are positively charged, and as the familiar maxim states, like charges repel. Each nucleus is surrounded by a Coulomb barrier that normally prevents the nuclei from coming too close to each other.

But in the same way that a speedy bullet can pass right through a thick wall, nuclei moving at extreme speeds have sufficient energy to penetrate through the Coulomb barrier. A collision between intensely energetic nuclei will bring them so close that they feel the strong attractive nuclear force. The two nuclei will come together, fuse, and form a heavier composite nucleus.

As illustrated in Figure 13, a deuterium (D) nucleus and a tritium nucleus (T), two of the lightest nuclei available, will fuse to form an isotope of helium (^{5}He). That composite nucleus quickly decays into a neutron and an alpha particle (a ^{4}He nucleus). There is a large net energy release from the reaction, and both the alpha particle and the neutron fly off with a considerable amount of kinetic energy.

Because energy is released, scientists have long recognized the potential of fusion to be the basis for a commercial energy source. But realizing that potential has proven to be remarkably difficult. For decades, scientists have been frustrated in their attempts to advance beyond even the first critical step in energy production, which is achieving a self-sustaining, thermonuclear fusion reaction.

In thermonuclear fusion, the "fuel" for the reaction is a plasma (a state of matter consisting almost entirely of ions and electrons) that is heated to millions of degrees. That plasma temperature is a measure of the average kinetic energy of the ions and electrons. Because the particle energies are distributed according to a Maxwell-Boltzman distribution, a tiny fraction of the ions have energies that are much higher than the average energy. For all present day thermonuclear fusion schemes, the initial plasma temperature is such that only those few nuclei at the extreme high energy tail of the thermal distribution are sufficiently energetic to overcome the Coulomb barrier and fuse.

Energy is released by those early fusion events in the form of fast moving particles. If those particles are captured

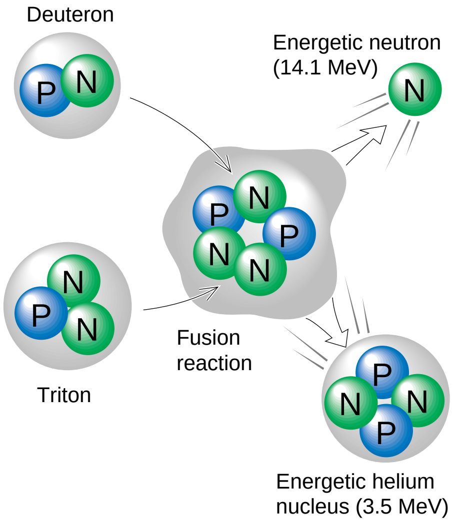
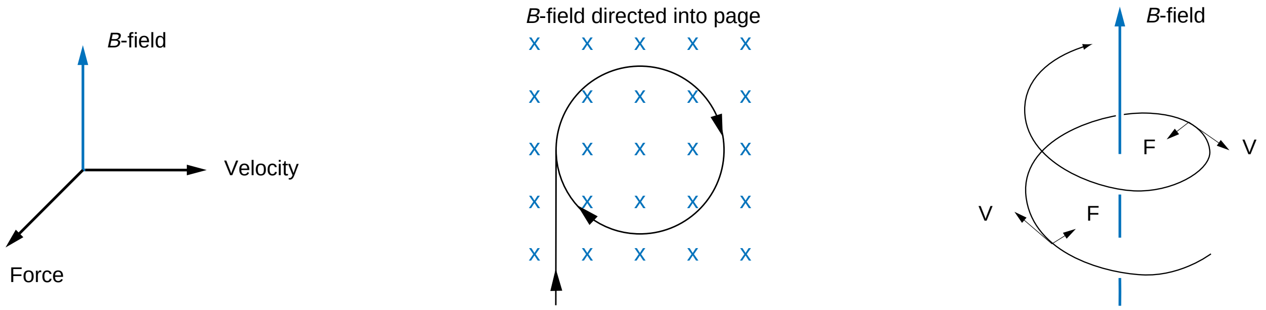


Figure 13. Thermonuclear Fusion

Einstein's famous equation, $E = mc^2$, relates mass to energy. The sum of the deuteron and triton rest masses at the start of the fusion reaction is actually more than the sum of the alpha particle and neutron rest masses after the reaction has finished. As a result of fusion, some mass is converted into energy, and that energy is imparted to the reaction products. Both the alpha particle and the neutron emerge from the fusion event with a significant amount of kinetic energy.



The magnetic force on a charged particle is directed at right angles to both the magnetic field and the particle's velocity.

A charged particle with a velocity that is entirely in the plane perpendicular to a uniform magnetic field moves in a circle.

A particle with a velocity component that is parallel to a uniform magnetic field spirals along the field line, which acts as a guiding center for the particle motion.

Figure 14. Motion of a Charged Particle in a Magnetic Field

When a plasma consisting of bare atomic nuclei and electrons is subjected to a magnetic field, the individual particles will spiral about the field lines. Stronger fields exert more force and the motion is a tighter spiral. Because the particles follow the field lines, magnetic fields can be used to contain a plasma and increase the particle confinement time.

and become part of the plasma, the energy released by early fusion events will go into increasing the plasma temperature. The number of energetic nuclei will increase, and the probability that two nuclei fuse will go up. The fusion reaction can become self-sustaining.

Unfortunately, there are always energy losses that cool the plasma and kill the fusion reaction. Plasma particles are in constant motion, and each time an electron scatters and gets accelerated by an ion, energy is radiated away (as continuum radiation, also known as bremsstrahlung). The plasma cools. To maintain the temperature, enough energy must be pumped into the plasma, either by initial fusion events or externally, to counteract those losses.

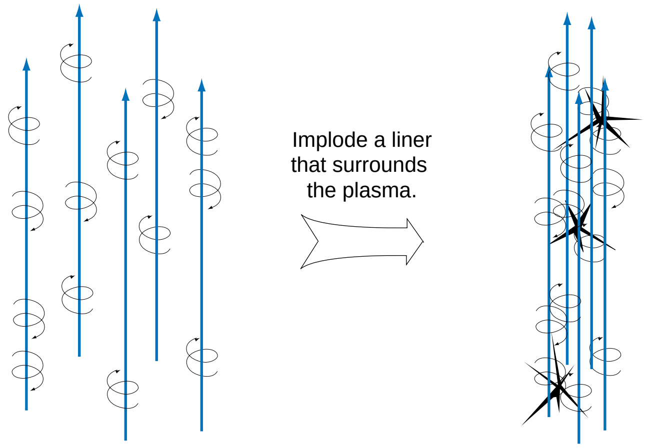
Because the energy gained by fusion and the energy lost through bremsstrahlung both have a temperature dependence, equating the two allows calculation of an "ignition" temperature, above which the plasma temperature is maintained and the fusion reaction becomes self-sustaining. For the DT reaction, the ignition temperature is about 4000 electron volts, or about 45 million degrees (one electron volt corresponds to about 11,600 kelvins).

Other loss mechanisms cool the plasma, but they are more amenable to experimental control. One is the loss of ions or electrons from the hot plasma. These carry energy away and the plasma cools. A second loss mechanism involves contaminants of "heavy" impurity ions, such as aluminum or iron, that increase the rate of bremsstrahlung, and again the plasma cools. If enough impurities are present, one can never win in the energy balance equation, and ignition can never be reached. Because impurities are nearly always present due to the outgassing of walls and insulator materials that comprise the plasma chamber, minimizing impurities has been a major challenge to all fusion schemes.

Even in this simplified picture of thermonuclear fusion, it is clear that constructing a system that is designed for getting useful power from fusion is a difficult undertaking. One wants a system that sustains a high particle collision rate for a long a period of time. But in any real system, these are often conflicting demands. For any given temperature, the collision rate can be increased by increasing the plasma density. But a high-temperature, high-density plasma exerts an outward pressure, and the higher the density, the more difficult it is to keep the plasma confined.

By making general assumptions about how much energy will be produced by a plasma and how much energy will be lost by that plasma, one can arrive at minimum conditions for achieving useful power. The product of the density, n, and the plasma confinement time, τ, that is, $n\tau$, is the relevant parameter, and the Lawson criterion states that a minimum value for $n\tau$ be approximately 10^{14} sec-cm^{-3}. There is little hope of achieving power from fusion unless the criterion is satisfied.

In the United States, fusion research has proceeded mostly along two paths. The first approach involves using a toroidal, or donut-shaped, reaction vessel, called a tokamak, to confine a low density ($n \sim 10^{14}$ cm^{-3}) plasma. High currents are sustained within the plasma that heat it to ignition temperatures. As shown in Figure 14, a charged particle will spiral around a magnetic field line. Within the tokamak, magnetic fields are created that twist around the interior of the torus. The field lines form closed surfaces, which the plasma particles are constrained to follow. In principle, the plasma is confined forever. Dynamical instabilities actually limit the confinement time τ to 0.1 to 1 second, but this is sufficiently long to balance the low particle density and bring $n\tau$ to within the range of the Lawson criterion. Generally, the tokamak is considered to be the most promising method for achieving fusion, and worldwide, billions of



① A high temperature plasma in the presence of a magnetic field. Charged nuclei spiral around the field lines.

② Fusion reactions take place in the hot, highly compressed plasma.

Figure 15. The MAGO Two Step Process

In the first step of MAGO, a DT gas inside of a thin liner is heated and ionized to a plasma in the presence of a magnetic field. The plasma particles are constrained to follow the magnetic field lines. In the second step, the liner surrounding this “magnetized” plasma is imploded, and the plasma gets compressed. The higher particle density results in an increased collision rate, which leads to more fusion events. The magnetic field reduces thermal energy losses and potentially helps capture the 3-MeV alpha particles that are released from D-T fusion events. If other thermal losses can be minimized, the plasma temperature may increase and reach ignition.

dollars have been invested in building, understanding, and developing these large and highly complex reactors.

The other mainline approach to thermonuclear fusion, vigorously pursued in the United States, is inertial confinement fusion (ICF). In an ICF scheme, a sphere of solid deuterium and tritium is subjected on all sides to an imploding force that drives the DT fuel inward. The severe compression creates a hot, high-density plasma and results in fusion reactions. However, there is no way to confine the plasma once it is created, and the heat of the initial fusion events tend to expand the sphere and cool the plasma before ignition temperature is reached. It is only because the implosion occurs so quickly (in billionths of a second) that the inertia of the inwardly moving fuel is able to hold the sphere together and maintain the temperature. The confinement time, τ, is on the order of only 10^{-11} seconds, which is balanced by the very high particle density ($n \sim 10^{24}$ to 10^{25} cm^{-3}).

So far, the most successful imploding force has been created by using laser pulses generated by the huge NOVA laser located at Lawrence Livermore Laboratory, or by the OMEGA laser located at the University of Rochester. However, an even more powerful implosion is needed to bring the plasma to ignition. It is hoped that the next-generation laser, to be built at the National Ignition Facility, will produce the required power.

An alternative approach to thermonuclear fusion, one that used elements of both the tokamak and the ICF approaches, was proposed by Andrei Sakharov (who incidentally helped elucidate the principles of the tokamak). He considered creating a high-temperature, DT plasma in a strong magnetic field so that the charged ions and electrons were “stuck” to magnetic field lines, as in a tokamak. The field would prevent energetic electrons from leaving the plasma and thus help reduce themal losses.

The hot, “magnetized” plasma would then be imploded by an external force as in an ICF scheme (Figure 15). The implosion would heat and compress the relatively dense plasma, and the strong field would help capture the energetic alpha particles produced during the fusion events. The approach could potentially simplify the apparatus required to bring about ignition.

The Russian scientists call this fusion concept MAGnitnoye Obzhatiye, or magnetic compression (MAGO), whereas the U.S. researchers refer to it as Magnetized Target Fusion (MTF). To implement the scheme, VNIIEF invented a novel, two-section chamber that produced a hot magnetized plasma by means of hypersonic flow (Figure 16). A gas mixture of DT is introduced into both sections of the chamber. Two current pulses sent through the chamber cause a portion of the DT gas in one section to become ionized and then propelled through a nozzle so that it enters the second section at a very high velocity. The effect of the abrupt collision between this plasma, moving at hypersonic speeds, and the relatively static gas in front of it is to raise the temperature of the gas rapidly to several thousand electron volts. This newly formed, extremely hot plasma quickly equilibrates to a temperature of several hundred electron volts, at which point it is a large volume, relatively dense, hot plasma, referred to as the target plasma in Figure 16.

In a full MAGO fusion scheme, the target plasma would be surrounded by a thin liner. Another current pulse, sent down the walls of the liner, would create a magnetic field that implodes the liner. This action would compress the plasma and potentially bring it to ignition conditions. (Figure 16 shows the chamber that was used for the plasma formation tests. In compression experiments, the chamber would be modified by replacing the thick, stationary outer wall with a thin liner.)

Producing the target plasma is the

intriguing aspect of the MAGO scheme, and the Arzamas-16 scientists presented some neutron data as evidence that the plasma had been created. The initial plasma temperature of several thousand electron volts is sufficient to initiate a burst of thermonuclear reactions, so that even without further compression, a small fraction of the plasma produced on the order of 10^{13} neutrons. Although those neutrons were simply a by-product of the plasma formation method, ironically, this neutron production was comparable to the highest ever achieved in the United States in pulsed-power or ICF experiments.

The objective of the first MAGO experiment, held in April of 1994, was to produce and diagnose the hot, magnetized plasma. The Chernyshev team provided a unique two-pulse helical generator to power the plasma chamber, and Los Alamos brought to Arzamas-16 more than a ton of advanced diagnostics equipment, which included spectrometers, plasma interferometers, and precision current probes. Excellent data were obtained with the U.S. instruments, and the experiment greatly improved our understanding of plasma flow through the nozzle as well as the final temperature and density distribution of the hot, dense plasma.

Still, the effectiveness of a magnetic field in reducing electron losses could not be deduced from that initial experiment. Thus, four more experiments were done by a team of Russian and American scientists at Los Alamos in October 1994. VNIIEF sent two of their two-pulse helical generators and two test armatures to Los Alamos. The first two experiments tested the performance of American explosives in driving the armature of the complex Russian generator. The third was a full MAGO plasma formation shot using the same Russian generator, but pure deuterium was used in the chamber instead of a deuterium-tritium mix. The purpose of that shot was to confirm the electrical performance of the device using Los Alamos explosives and our capacitor bank. The experiment served also to verify the operation of new diagnostics that would be used on the fourth shot.

Fourteen VNIIEF scientists and more than fifty Americans participated in the final experiment. Chernyshev and Mokhov led the Russians, and Reinovsky and Goforth were the Los Alamos shot coordinators. The experiment again used a Russian helical generator along with as complete an array of diagnostics as Los Alamos could provide. Two major neutron diagnostics were fielded. One, based on measurements of the time of flight of the neutrons to the detectors, attempted to obtain an indication of the plasma temperature. The second, based on neutron imaging, attempted to define the precise region from which the neutrons were produced. An array of optical and x-ray spectrometers were designed to provide critical information on the time dependence of plasma temperature as well as the presence of heavy ion impurities in the plasma.

The results of the experiment were very encouraging. The data analysis suggested that a hot, dense plasma had indeed been produced. Significantly, there were also indications that impurities generated in the first plasma chamber were delayed by several microseconds before arriving in the second

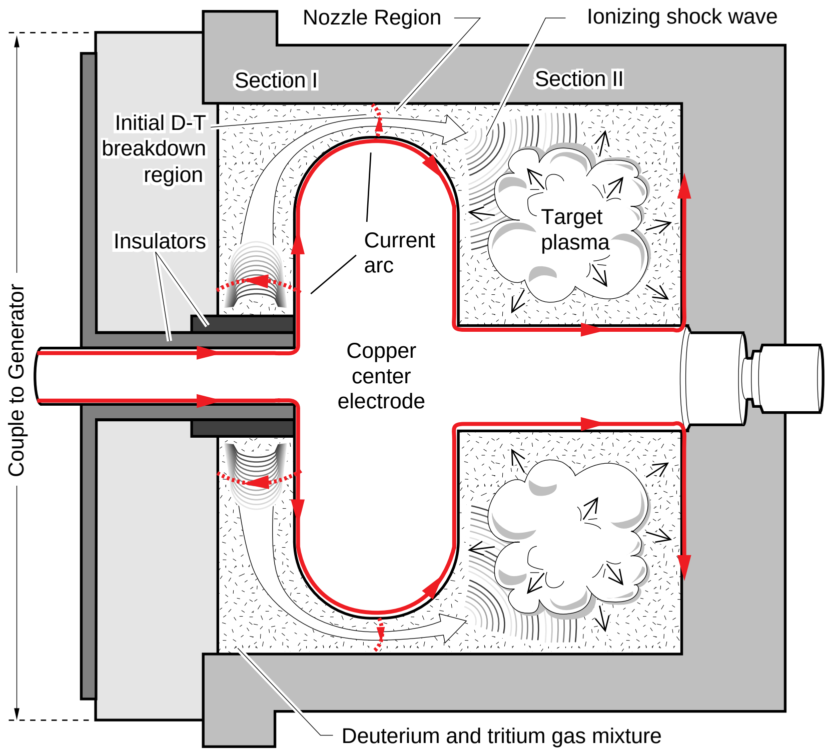


Figure 16. MAGO Two-Section Chamber and Target Plasma Formation

A cross section of the cylindrically symmetric, two-section MAGO chamber. The two sections are joined by a narrow opening that acts as a nozzle. Initially, a DT gas fills both sections. A current pulse of about 2 megamperes sent through the electrode creates a complex magnetic field pattern throughout the entire chamber. A second current pulse, reaching 6 to 8 megamperes, arcs through both section I and the nozzle region and creates a weak plasma. Due to the Lorentz force, this plasma is propelled through the nozzle. When the high-velocity plasma collides with the relatively static gas filling section II, shock waves are produced. These shock waves ionize the bulk of the gas and create a large volume, relatively dense plasma at a temperature of 100 to 300 electron volts. Such a plasma could possibly be compressed to thermonuclear ignition conditions in future experiments. (Figure courtesy of N. Shea, Defense Science)

chamber. This meant that the DT plasma in the second chamber would remain relatively free of harmful impurities and was likely to remain sufficiently hot for the 5 to 10 microseconds required to compress it to ignition conditions.

Another series of experiments at Arzamas-16 are planned to test MAGO/MTF concept. Ultimately, once a plasma has been judged suitable in terms of temperature, density ($n \sim 10^{18}$ cm^{-3}), and purity, the experiments will attempt an implosion using the same type of plasma formation chamber as before and a DEMG to provide the roughly 65 megajoules of energy estimated to bring about ignition. A joint experiment at Arzamas-16, planned for the summer of 1996, will be the first developmental test of the “high-energy” liner that will implode the hot plasma.

Isentropic Compression

The behavior of matter under extreme compression is of interest in terms of understanding phenomena as diverse as the atmospheres of gaseous planets and the structural mechanics of rock deep within the Earth. For example, the properties of materials under extreme pressures is important to geophysicists studying the origin and dynamics of earthquakes. Because many earthquakes occur deep beneath the surface, knowing the shear strength of rock at conditions found there could be important for developing predictive models of earthquakes.

One of the most successful techniques for compressing materials to high pressures is to use a diamond anvil press, which can currently achieve pressures up to about 2 megabars. Above that, a standard technique is to use high explosives to drive shock waves directly through the material. Although ultrahigh densities can be achieved via this technique, the shock waves abruptly jar the material and generate heat as they propagate. Strong gradients and transient effects often complicate the interpretation of data obtained by this method.

An alternative technique for achieving pressures above 2 megabars is to use magnetic pressure to implode a conducting surface that surrounds the sample of interest. The implosion can subject the sample to even higher pressures than are possible with shock wave methods. Because a flux compression generator produces a magnetic field that builds slowly and reaches its peak value after a few microseconds, the pressure increases in a relatively smooth and steady fashion. Thus, shock wave production and sample heating are minimized, and materials can be compressed with a minimum change of entropy (isentropic compression). This simplifies not only the data interpretation, it also opens up the possibility of studying the low-temperature behavior of materials.

Our Russian colleagues at Arzamas-16 had employed isentropic compression to study many different materials at pressures of many megabars. Hydrogen was of particular interest in the early Russian work. At very high pressures, this gaseous element was predicted to undergo a transition to an atomic, metallic phase. It proved to be very difficult to identify unambiguously the atomic phase, because under extreme pressure, hydrogen can form many different molecular phases that tend to obscure the interpretation of the data.

In 1994, we began discussions with the Russians to perform an isentropic compression experiment. Eventually, it was decided that we would attempt to measure the electrical conductivity of solid argon as it was compressed under a peak pressure of over 6 megabars.

Argon solidifies at liquid nitrogen temperatures. Because it is a closed-shell atom, argon is insulating under normal conditions, and even when solidified, the atoms of the crystal retain their monatomic character. Under extreme pressure, however, the atomic orbitals of adjacent atoms are predicted to overlap, which would allow electrons greater mobility, effectively increasing the electrical conductivity. The solid argon is predicted to undergo a transition to a conducting state at about 5 megabars. Any change in the electrical properties of the sample could be attributed to quasi-molecular or many-body behavior.

A preliminary attempt to measure electrical conductivity of the sample failed, however, due to the premature destruction of the current probes. A second experiment, conducted in August 1995, used a simpler current-probe design and very clearly demonstrated a conducting state for argon at pressures between 5 and 6 megabars.

This experiment was the first demonstration of the transition of argon from an insulator to a conductor at high pressure, and it held some surprises. The conductivity was remarkably low, indicating that rather than creating a conduction band of current carrying free electrons, the electrons were tending to “hop” from one atomic site to another. This behavior was unexpected, and thus the experiment has generated some theoretical interest. Future experiments will attempt to achieve even higher pressures, so that the crossover to the metallic phase should be more apparent.

Soft X Rays

Another topic of mutual interest to Arzamas-16 and Los Alamos is the creation of a soft x-ray source. Most pulsed-power sources of x rays are based on the fast implosion of a cylindrical liner. As described earlier, a very light liner driven inward by magnetic pressures can reach fantastic speeds of hundreds of kilometers per second. The interaction with the magnetic field heats the imploding liner and turns it into a moving wall of plasma. When this cylindrical wall of plasma reaches the implosion axis, it collides with itself, stops moving, and converts its kinetic energy into internal heat energy. That hot, stagnated plasma radiates x rays as it cools.

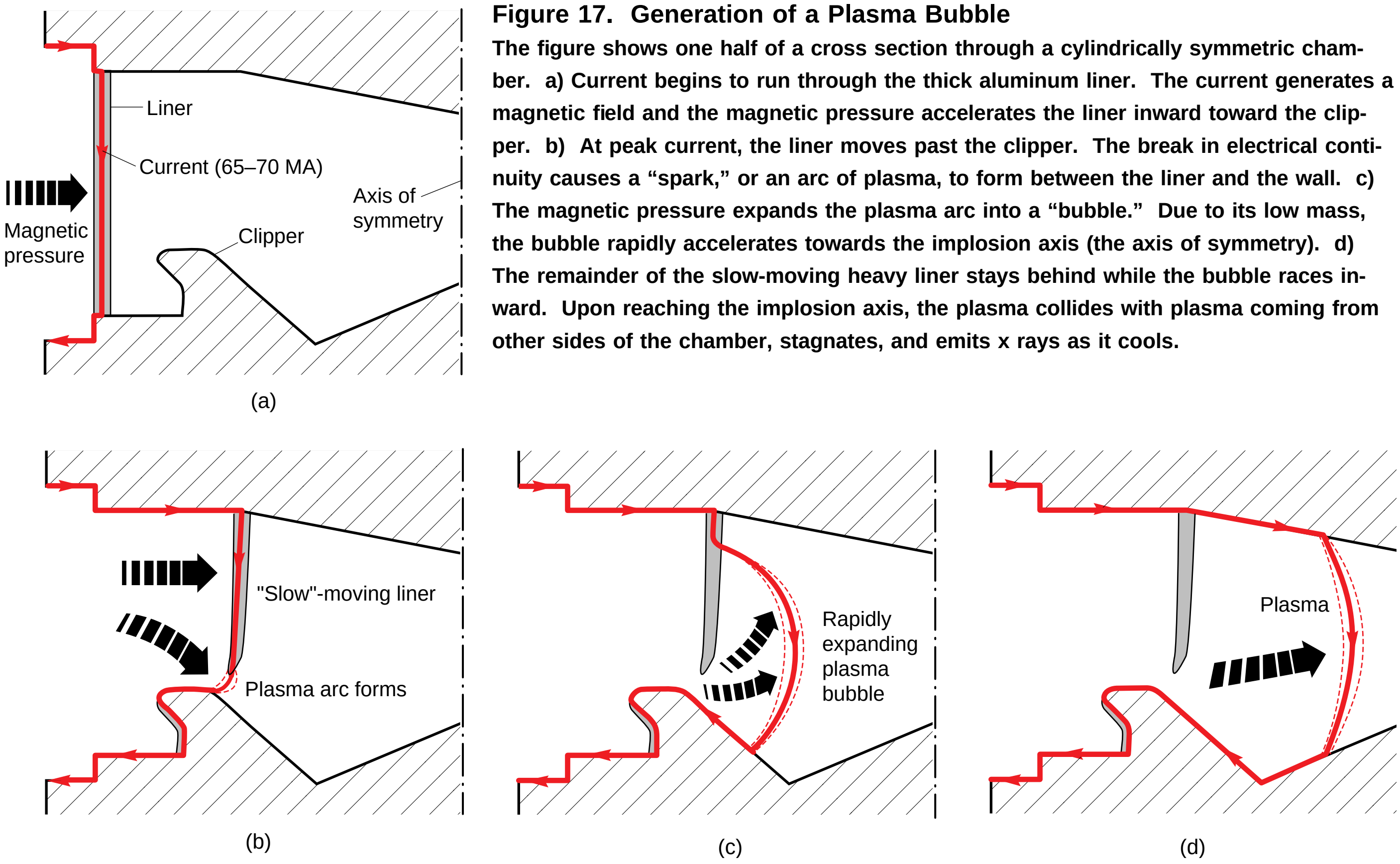


Figure 17. Generation of a Plasma Bubble

The figure shows one half of a cross section through a cylindrically symmetric chamber. a) Current begins to run through the thick aluminum liner. The current generates a magnetic field and the magnetic pressure accelerates the liner inward toward the clipper. b) At peak current, the liner moves past the clipper. The break in electrical continuity causes a "spark," or an arc of plasma, to form between the liner and the wall. c) The magnetic pressure expands the plasma arc into a "bubble." Due to its low mass, the bubble rapidly accelerates towards the implosion axis (the axis of symmetry). d) The remainder of the slow-moving heavy liner stays behind while the bubble races inward. Upon reaching the implosion axis, the plasma collides with plasma coming from other sides of the chamber, stagnates, and emits x rays as it cools.

For the above concept to work, the liner must reach a very high velocity. Otherwise, the total energy in the system is below what is necessary to create an intense thermal x-ray source. In addition, the implosion must proceed with a high degree of symmetry. If some section of the liner is moving faster than the rest, it will prematurely arrive at the implosion axis. Stagnation will occur somewhere off-axis, and the hot plasma will be distributed over a broad, indeterminate region.

Although many ideas have been tried, almost all of them have fallen short of the two criteria mentioned above. More often than not, the limiting factor is the growth of dynamical instabilities that cause the liner to break apart prematurely, so that the implosion is severely asymmetric. But obtaining a very rapidly rising current pulse is also problematic. The current source must deliver all of its energy in the tenths of microseconds before the rapidly moving plasma shell reaches the implosion axis. Designing a fast switch represents a significant challenge for any pulsed-power system.

The Chernyshev-Mokhov team conceived a novel approach to solve these problems. Rather than accelerating a low-mass liner, a magnetic field implodes a large-radius (19 centimeters), "heavy" (0.5-millimeter thick) aluminum liner. The acceleration occurs during the several tens of microseconds that the generator is powering up. When the generator has reached peak current, the liner, now in a liquid state, is cut by a knife-like protrusion called a "clipper." In a manner similar to running a wire through a film of soapy water, the break in the liquid liner causes a "bubble" to form between the clipper and the remaining liner, as shown in the Figure 17.

The bubble is really a section of the liner that is "thinned" to the point that the magnetic forces can ionize it and turn it into a plasma. The magnetic field that was driving the heavy liner now rapidly accelerates this plasma bubble so that it converges upon the axis of the device. The hot plasma stagnates and produces x rays.

The advantage of this scheme is that while the generator is powering up, the heavy aluminum liner is moving relatively slowly, so the opportunity for the growth of instabilities is greatly reduced. After the bubble is formed, its low mass can be accelerated rapidly by the peak field. There are no switches involved. In addition, the surface density of the bubble is much lower than that of the liner, which also helps in the suppression of hydrodynamic instabilities.

After a detailed analysis of the Russian's two-dimensional calculations, we defined a set of Los Alamos diagnostics that would test the key elements of the concept. A microwave interferometer was designed to measure the initial motion of the heavy liner. A set of fiber-optic and magnetic probes measured the progress of the plasma bubble during the fast phase of the implosion. A

DEMG was used to provide the current to drive the heavy liner. This ambitious experiment was conducted in February 1995 at the same firing point where the previous DEMG and magnetized plasma experiments had been conducted.

The results of the experiment were mixed. Los Alamos and VNIIEF analyses suggest that a bubble was indeed formed, although some significant asymmetries appear to have occurred during its implosion. The implosion axis was shifted approximately one centimeter off-center of the DEMG symmetry axis, probably because of a significant azimuthal asymmetry in the density of the plasma bubble that formed. The reason for the density asymmetry is not clear. One possible explanation is that the heavy liner may have had a nonuniform electrical connection to the current source, resulting in nonuniform acceleration. In any case, unless the unpredictable shift can be controlled, the scheme in its present configuration is unusable as an x-ray source because the x rays would be generated from an unknown location.

This experiment highlights the difficult nature of explosive-driven pulsed power research. The results of months of effort culminated in one irreproducible experiment that lasted but a few microseconds. The outcome was not all that had been hoped for, although analyses showed that the imploding plasma may well have had more implosion kinetic energy than presently available in any other concept. Ways of improving the technique and removing the asymmetries may therefore be explored in the future.

The Future

The unprecedented collaboration between the nuclear weapons laboratories at Arzamas-16 and Los Alamos reflects the changes that have occurred in the post-Cold War period. Scientists who were previously intense competitors in the design of weapons of mass destruction are now working together to apply their skills to problems of general scientific interest. In just over two years, Los Alamos and VNIIEF have performed experiments on ultrahigh current generation, the properties of high-temperature superconductors, the properties of magnetized plasmas, the compression of materials under megabar pressures, and the creation of a soft x-ray source. These experiments were conducted at the very sites previously used for weapons development.

Both sides are enthusiastic about continuing and expanding the collaboration. There is much to be learned about the promising MAGO/MTF fusion scheme first suggested by Andrei Sakharov. In forthcoming experiments, we hope to compress helium to the same conditions found in the gas-giant planets and thereby gain a better understanding of these remarkable bodies. A Los Alamos proposal that involves flying an explosive generator on a high-altitude balloon to stimulate lightning artificially has been accepted by the Russians. Several experiments to explore quantum field effects at high magnetic fields using the MC-1 generator have already been performed at Los Alamos (see “The Dirac Series—A New International Pulsed-Power Collaboration” on page 68). A DEMG experiment to drive the most energetic solid liner ever will be conducted this summer. In short, there seems to be no end to the possibilities for collaborations on scientific endeavors. ■

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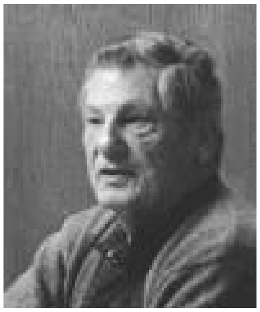
Carl Ekdahl earned his Ph.D. in Physics at the University of California, San Diego, in 1971. He first joined the Laboratory in 1975 to carry out experiments in controlled thermonuclear fusion, then again in 1982 to lead experiments to heat a high-density plasma with electron beams and to launch a high-power microwave-source development program. In 1983, he joined Sandia National Laboratories to continue with beam-propagation experiments and became Supervisor of the High-Energy Beam Physics Division. He rejoined the Laboratory in 1986 to design, execute, and analyze experiments using the radiation from underground nuclear-weapon tests. As leader of a nuclear-test diagnostics group, he directed their transition into above-ground experimental activities, including the first lab-to-lab experiments with VNIIEF. He is currently Program Manager for high-energy-density physics in the Nuclear Weapon Technology Directorate. Prior to joining the laboratory, Ekdahl held positions with Scripps Institute of Oceanography, the Laboratory of Plasma Physics at Cornell University, and Mission Research Corporation.



C. M. (Max) Fowler joined the Laboratory permanently in 1957 with the responsibility of assembling a team to develop and apply explosive-driven magnetic-flux-compression devices. The early work of this team influenced subsequent megagauss solid state research, liner implosion of plasmas, and was instrumental in starting the “Megagauss” Conferences. Through his career, Max and his colleagues have used the explosive-driven magnetic-flux-compression technique to generate energy sources to power a number of plasma-producing devices, lasers, imploding foils, electron-beam accelerators, and railguns. This energy source was also used to power high-magnetic-field generators to study materials in megagauss fields, including high-temperature superconductors. Fowler received his B.S. in chemical engineering from the University of Illinois and his Ph.D. in physics from the University of Michigan. He was recently awarded an Honorary Doctorate from Novosibirsk State University for his work in high-energy-density physics and for furthering scientific relations between the United Sates and Russia. Fowler is active as a Los Alamos Laboratory Fellow and a Fellow of the American Physical Society.

James H. Goforth received his M.S. in physics from New Mexico State University in 1973. During a tour of duty at the Air Force Weapons Laboratories in Kirkland, NM, he directed the operation of a state of the art, 250-kilojoule capacitor bank for driving plasma z-pinch experiments. Also at the Air Force Weapons Laboratories, he participated in z-pinch and fuse opening switch experiments powered by flux compression generators at Los Alamos National Laboratory. He joined the Laboratory in August, 1976, as head of the detonator exploratory development unit. In 1981, he joined the Shock-Wave Physics Group, where he continues to do explosive pulsed-power research and development . His major contribution is the development of the explosively formed fuse opening switch that is in current use as the primary pulse compression stage of the Procyon explosive pulsed-power system. He has also played a substantial part in the development of all explosive pulsed power systems for the High Energy Density Physics Program. Goforth is currently project leader for the development of driver systems to be used for high-energy liner experiments.

Irvin R. Lindemuth received his B.S. in electrical engineering from Lehigh University in 1965, and his M.S. and Ph.D. in engineering-applied science in 1967 and 1971, respectively, from the University of California, Davis/Livermore. Prior to joining the Laboratory in 1978, Lindemuth was a technical staff member at the Lawrence Livermore National Laboratory. His areas of research include thermonuclear fusion, advanced numerical methods for computer simulation of fusion plasmas, and related pulsed power-technology. He currently is Project Leader for the International Collaboration in Pulsed Power Applications at LANL and has responsibility to provide technical leadership for the pulsed-power/magnetized-target fusion collaboration between Los Alamos and VNIIEF at Arzamas-16. Lindemuth is credited with establishing a Sister City relationship between the two nuclear cities and actively continues his participation and support of the program. In 1992, he was the recipient of a Distinguished Performance Award for his work in the formative stages of the LANL/VNIIEF collaboration.

Robert E. Reinovsky received his M.E. and Ph.D. degrees in physics from Rensselaer Polytechnic Institute in 1971 and 1973, respectively. From 1974 through 1986, he worked at the Air Force Weapons Laboratory (now Air Force Phillips Laboratory) in plasma and pulse-power physics. His principle interests were high-density plasma implosions, radiation processes, plasma diagnostics, and pulse-power physics. Reinovsky was responsible for developing and building four generations of the world-class SHIVA family of high-current, low-impedance pulse-power systems. Techniques in ultrahigh-current, high-explosive pulse power that were developed in Los Alamos in the1950s caught Reinovsky’s interest. He joined the Laboratory in 1986 to continue work applying these techniques to ultrahigh-current plasma systems for applications to high-energy-density physics. Reinovsky led the explosive pulse group from 1990 to 1993 and later joined the program in high-energy-density physics as project leader for the Athena pulse-power project. He is currently Chief Scientist for that program.

Stephen M. Younger received his Ph.D. in theoretical physics from the University of Maryland in 1978. Prior to employment with the Laboratory, Younger worked at the National Bureau of Standards in Washington D. C., on related topics in theoretical atomic physics and was a member of the Nuclear Design Department at Lawrence Livermore Laboratory. His research at Livermore included advanced nuclear weapons designs and supervising design groups for the nuclear-driven x-ray laser and other nuclear-explosive concepts. He came to Los Alamos in 1989 and has directed programs in inertial-confinement fusion and above-ground experiments. In 1994, he was named Deputy Program Director for Nuclear Weapons Technology and was responsible for the physics associated with nuclear weapons. Younger currently is the Director of the Center for International Security Affairs at the Laboratory. His responsibilities include oversight for interactions involving Los Alamos and the Newly Independent States.

The Dirac Series

This April, scientists from seven laboratories under four flags gathered at Los Alamos to conduct a campaign of pioneering experiments using ultrahigh magnetic fields. This collaboration among Americans, Russians, Australians, and Japanese is without precedent. This series of experiments was named after the great physicist P.A.M. Dirac because his monumental contributions to quantum theory touch on all aspects of the physics and chemistry we intend to explore. We are sure Dirac would have appreciated the unification of world scientific efforts represented by this collaboration, as the world appreciated the unification he brought to science.

Some of the participants in this collaboration are Florida State University, the University of New South Wales, Louisiana State University, the University of Tokyo, the National Institute of Materials and Chemical Research (Tsukuba, Japan), Bechtel Nevada, and the All-Russian Institute of Experimental Physics (Arzamas-16). The Los Alamos contingent consists of program manager Johndale Solem, shot coordinator Jeff Goettee, and local staff members Max Fowler, Will Lewis, Dwight Rickel, Murry Sheppard, and Bill Zerwekh.

The International Group of Scientists and Technicians that Carried Out the Dirac Series. More than seven universities and institutes, representing four countries, participated in the experiments that were conducted in Ancho Canyon at Los Alamos. The large white tubing seen in front was a vacuum line that was eventually connected to a cryostat located inside an explosive-driven flux compression generator.

The Dirac series included four 1.5-megagauss experiments, using an explosive-driven generator designed at Los Alamos, and three 10-megagauss experiments, using the MC-1 explosive-driven generator designed at Arzamas-16. A brief outline of the goals of each experiment is given.

The Quantum Hall Effect at High Electron Density. The Hall effect describes the development of a transverse electric field in a current-carrying conductor placed in a magnetic field, and it was discovered nearly a century ago by Edwin Hall. The *quantum* Hall effect was discovered in 1980 by Klaus von Klitzing using the two-dimensional electron gas formed in a metal-oxide, silicon, field-effect transistor. At low temperatures, the degenerate electron ground state breaks up into energy levels called, “Landau levels.” As von Klitzing adjusted the gate voltage to raise the Fermi energy level, he observed a quantized sequence of plateaus in the Hall conductivity at integral multiples of e^2/h, suggesting a fundamental unit of electrical conductivity. These plateaus were accompanied by near-vanishing resistivity in the electric-field direction. Von Klitzing won the Nobel Prize for his discovery of this “integer quantum Hall effect.”

But the story was far from over. Using much higher fields and lower temperatures, researchers in 1982 reported a fractional quantum Hall effect; plateaus occurred in fractions of e^2/h. At first, only odd denominators were reported (1/3, 2/5, 3/5, 2/3, and so forth). These were quickly attributed to the interaction between electrons, that is, collective effects or quasiparticles. Sensible theories were propounded as to why the denominators were all odd, but in 1993 many re-

A New International Pulsed-Power Collaboration

searchers reported even denominators. At present, many theorists believe the fractional quantum Hall states are actually integral quantum Hall states of composite Fermions. For example, the 2/5 state has 5 flux quanta for every 2 electrons (that is, 2 filled Landau levels of composite electrons).

Although many experiments have been performed, precision experiments on the quantum Hall effect are often limited by imperfections in the sample. Fortunately, samples with higher electron densities are less sensitive to imperfections, and higher magnetic fields allow observation of the quantum Hall effect in samples with large electron densities. Ultrahigh magnetic fields are required to observe the effect. The object of this experiment is to explore integer and fractional quantum Hall effects in a high electron density, two-dimensional electron gas in a semiconductor heterostructure device. Clean data from this experiment will supply a stronger experimental basis for building a complete understanding of magneto-quantum electronic effects in solid state physics.

Waiting for Dirac. **Program manager Johndale Solem and Max Fowler (foreground) have done their jobs. On the day of the shot, responsibility for the experiment falls to the technicians and the shot coordinator, and to the individual researchers. In the background are Andy Maverick from Louisiana State University and Hiroyuki Yokoi from the National Institute of Materials and Chemical Research, Tsukuba, Japan.**

Quantum Hall Effect and Quantum Limit Phenomena in Two-Dimensional Organic Metals. Two-dimensional metals may be several orders of magnitude more conducting in the *x* and *y* directions than in the *z* direction. Their anisotropic conductivity suggests that these metals should behave somewhat like a composite of two-dimensional electron gases. The integer quantum Hall effect has been observed in preliminary laboratory experiments up to about 5 megagauss. At extremely high fields, the magnetic and Fermi energies are comparable, and we enter the realm called the quantum limit.

What happens to the two-dimensional metals in the quantum limit is simply unknown. If they retain their Fermi-liquid character, we expect something akin to the fractional quantum Hall effect, although we may see entirely new collective electronic configurations. On the other hand, the field may localize the conduction mechanisms and cause the material to behave more like a semiconductor or an insulator. The results will certainly lead to a deeper understanding of these very interesting materials as well as conduction mechanisms in general. Curiously, these two-dimensional metals have many aspects in common with biological materials, so the implications may transcend the domain of solid state physics.

Magnetic-Field Induced Superconductivity. Superconductivity derives from a net attractive interaction between electrons in the neighborhood of the Fermi surface. In conventional superconductors the interaction is the sum of a repulsion due to the Coulomb force and an attraction due to ionic overscreening.

As described in the main article, a magnetic field can break the superconducting state, although how it does so depends on the type of superconductor. Formally, there are two types of superconductors. Type I superconductors exhibit perfect diamagnetism: the magnetic field is abruptly expelled at the superconducting transition, and once above a critical magnetic field, the entire specimen reverts to the normal state. In a Type II superconductor, there is no flux penetration below a first critical field, but there is partial flux penetration in the form of evenly spaced thin filaments below a second critical field. In both Type I and

Type II superconductors, the critical field is a function of temperature.

Theoretical work at Los Alamos and elsewhere has suggested that in the quantum limit (the lowest Landau level), the temperature for a transition to the superconducting state can actually increase with field. The electron-electron repulsion is screened by the Debye length, and it can be shown that above some ultrahigh magnetic field values, the Debye length increases with field. The electron-electron repulsion can be reduced until attraction dominates.

This new kind of superconductivity has never been observed, and in principle, it can be observed only at ultrahigh fields. Besides leading to a deeper understanding of superconductivity, this research could result in a new kind of superconductor that thrives, rather than quenches, in a magnetic field.

Preparing for the experiment. **Mikhail Dolotenko of Arzamas-16 (kneeling), oversees the installation of his samples and diagnostics into the bore of the MC-1 flux compression generator (oriented vertically for this experiment). Lying down are Los Alamos technicians Tommy Herrera (facing) and Dave Torres.**

Zeeman-Driven Bond Breaking in $Re_2Cl_8^{--}$. Quadruply bonded metal complexes are a relatively new discovery in physical chemistry. Four bonds are formed between two metal atoms, and that two-atom core is free to interact with a variety of ligands. These complexes are of considerable interest, and they enjoy symmetry properties that make them simple to describe.

The lowest excited state of the rhenium-chloride complex consists of a singlet state (no spin) and triplet state (one unit of spin). The singlet is readily accessible by photoexcitation, and hence its energy level has been measured and is well-known. Little is known about the triplet other than it has an electron in an antibonding orbital. Thus, two rhenium atoms can form only three bonds when excited to the triplet state.

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Conclusion. The Dirac series of experiments will explore fundamental physics in the ultrahigh magnetic field regime of several different disciplines. These are extremely difficult experiments, and new measurement techniques are already being developed in the course of designing and performing these investigations. This international effort is a fitting extension to the Russian-American pulsed-power collaboration initiated under the lab-to-lab program. ■

The Dirac Series

This April, scientists from seven laboratories under four flags gathered at Los Alamos to conduct a campaign of pioneering experiments using ultrahigh magnetic fields. This collaboration among Americans, Russians, Australians, and Japanese is without precedent. This series of experiments was named after the great physicist P.A.M. Dirac because his monumental contributions to quantum theory touch on all aspects of the physics and chemistry we intend to explore. We are sure Dirac would have appreciated the unification of world scientific efforts represented by this collaboration, as the world appreciated the unification he brought to science.

The International Group of Scientists and Technicians that Carried Out the Dirac Series. **More than seven universities and institutes, representing four countries, participated in the experiments that were conducted in Ancho Canyon at Los Alamos. The large white tubing seen in front was a vacuum line that was eventually connected to a cryostat located inside an explosive-driven flux compression generator.**

Some of the participants in this collaboration are Florida State University, the University of New South Wales, Louisiana State University, the University of Tokyo, the National Institute of Materials and Chemical Research (Tsukuba, Japan), Bechtel Nevada, and the All-Russian Institute of Experimental Physics (Arzamas-16). The Los Alamos contingent consists of program manager Johndale Solem, shot coordinator Jeff Goettee, and local staff members Max Fowler, Will Lewis, Dwight Rickel, Murry Sheppard, and Bill Zerwekh.

The Dirac series included four 1.5-megagauss experiments, using an explosive-driven generator designed at Los Alamos, and three 10-megagauss experiments, using the MC-1 explosive-driven generator designed at Arzamas-16. A brief outline of the goals of each experiment is given.

The Quantum Hall Effect at High Electron Density. The Hall effect describes the development of a transverse electric field in a current-carrying conductor placed in a magnetic field, and it was discovered nearly a century ago by Edwin Hall. The *quantum* Hall effect was discovered in 1980 by Klaus von Klitzing using the two-dimensional electron gas formed in a metal-oxide, silicon, field-effect transistor. At low temperatures, the degenerate electron ground state breaks up into energy levels called, “Landau levels.” As von Klitzing adjusted the gate voltage to raise the Fermi energy level, he observed a quantized sequence of plateaus in the Hall conductivity at integral multiples of e^2/h, suggesting a fundamental unit of electrical conductivity. These plateaus were accompanied by near-vanishing resistivity in the electric-field direction. Von Klitzing won the Nobel Prize for his discovery of this “integer quantum Hall effect.”

But the story was far from over. Using much higher fields and lower temperatures, researchers in 1982 reported a fractional quantum Hall effect; plateaus occurred in fractions of e^2/h. At first, only odd denominators were reported (1/3, 2/5, 3/5, 2/3, and so forth). These were quickly attributed to the interaction between electrons, that is, collective effects or quasiparticles. Sensible theories were propounded as to why the denominators were all odd, but in 1993 many re-

A New International Pulsed-Power Collaboration

searchers reported even denominators. At present, many theorists believe the fractional quantum Hall states are actually integral quantum Hall states of composite Fermions. For example, the 2/5 state has 5 flux quanta for every 2 electrons (that is, 2 filled Landau levels of composite electrons).

Although many experiments have been performed, precision experiments on the quantum Hall effect are often limited by imperfections in the sample. Fortunately, samples with higher electron densities are less sensitive to imperfections, and higher magnetic fields allow observation of the quantum Hall effect in samples with large electron densities. Ultrahigh magnetic fields are required to observe the effect. The object of this experiment is to explore integer and fractional quantum Hall effects in a high electron density, two-dimensional electron gas in a semiconductor heterostructure device. Clean data from this experiment will supply a stronger experimental basis for building a complete understanding of magneto-quantum electronic effects in solid state physics.

Quantum Hall Effect and Quantum Limit Phenomena in Two-Dimensional Organic Metals. Two-dimensional metals may be several orders of magnitude more conducting in the *x* and *y* directions than in the *z* direction. Their anisotropic conductivity suggests that these metals should behave somewhat like a composite of two-dimensional electron gases. The integer quantum Hall effect has been observed in preliminary laboratory experiments up to about 5 megagauss. At extremely high fields, the magnetic and Fermi energies are comparable, and we enter the realm called the quantum limit.

What happens to the two-dimensional metals in the quantum limit is simply unknown. If they retain their Fermi-liquid character, we expect something akin to the fractional quantum Hall effect, although we may see entirely new collective electronic configurations. On the other hand, the field may localize the conduction mechanisms and cause the material to behave more like a semiconductor or an insulator. The results will certainly lead to a deeper understanding of these very interesting materials as well as conduction mechanisms in general. Curiously, these two-dimensional metals have many aspects in common with biological materials, so the implications may transcend the domain of solid state physics.

Waiting for Dirac. **Program manager Johndale Solem and Max Fowler (foreground) have done their jobs. On the day of the shot, responsibility for the experiment falls to the technicians and the shot coordinator, and to the individual researchers. In the background are Andy Maverick from Louisiana State University and Hiroyuki Yokoi from the National Institute of Materials and Chemical Research, Tsukuba, Japan.**

Magnetic-Field Induced Superconductivity. Superconductivity derives from a net attractive interaction between electrons in the neighborhood of the Fermi surface. In conventional superconductors the interaction is the sum of a repulsion due to the Coulomb force and an attraction due to ionic overscreening.

As described in the main article, a magnetic field can break the superconducting state, although how it does so depends on the type of superconductor. Formally, there are two types of superconductors. Type I superconductors exhibit perfect diamagnetism: the magnetic field is abruptly expelled at the superconducting transition, and once above a critical magnetic field, the entire specimen reverts to the normal state. In a Type II superconductor, there is no flux penetration below a first critical field, but there is partial flux penetration in the form of evenly spaced thin filaments below a second critical field. In both Type I and

Type II superconductors, the critical field is a function of temperature.

Theoretical work at Los Alamos and elsewhere has suggested that in the quantum limit (the lowest Landau level), the temperature for a transition to the superconducting state can actually increase with field. The electron-electron repulsion is screened by the Debye length, and it can be shown that above some ultrahigh magnetic field values, the Debye length increases with field. The electron-electron repulsion can be reduced until attraction dominates.

This new kind of superconductivity has never been observed, and in principle, it can be observed only at ultrahigh fields. Besides leading to a deeper understanding of superconductivity, this research could result in a new kind of superconductor that thrives, rather than quenches, in a magnetic field.

Preparing for the experiment. Mikhail Dolotenko of Arzamas-16 (kneeling), oversees the installation of his samples and diagnostics into the bore of the MC-1 flux compression generator (oriented vertically for this experiment). Lying down are Los Alamos technicians Tommy Herrera (facing) and Dave Torres.

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Russian-American MPC&A

Nuclear Materials Protection, Control, and Accounting in the Russian Federation

Ronald H. Augustson and John R. Phillips
as told to Debra A. Daugherty

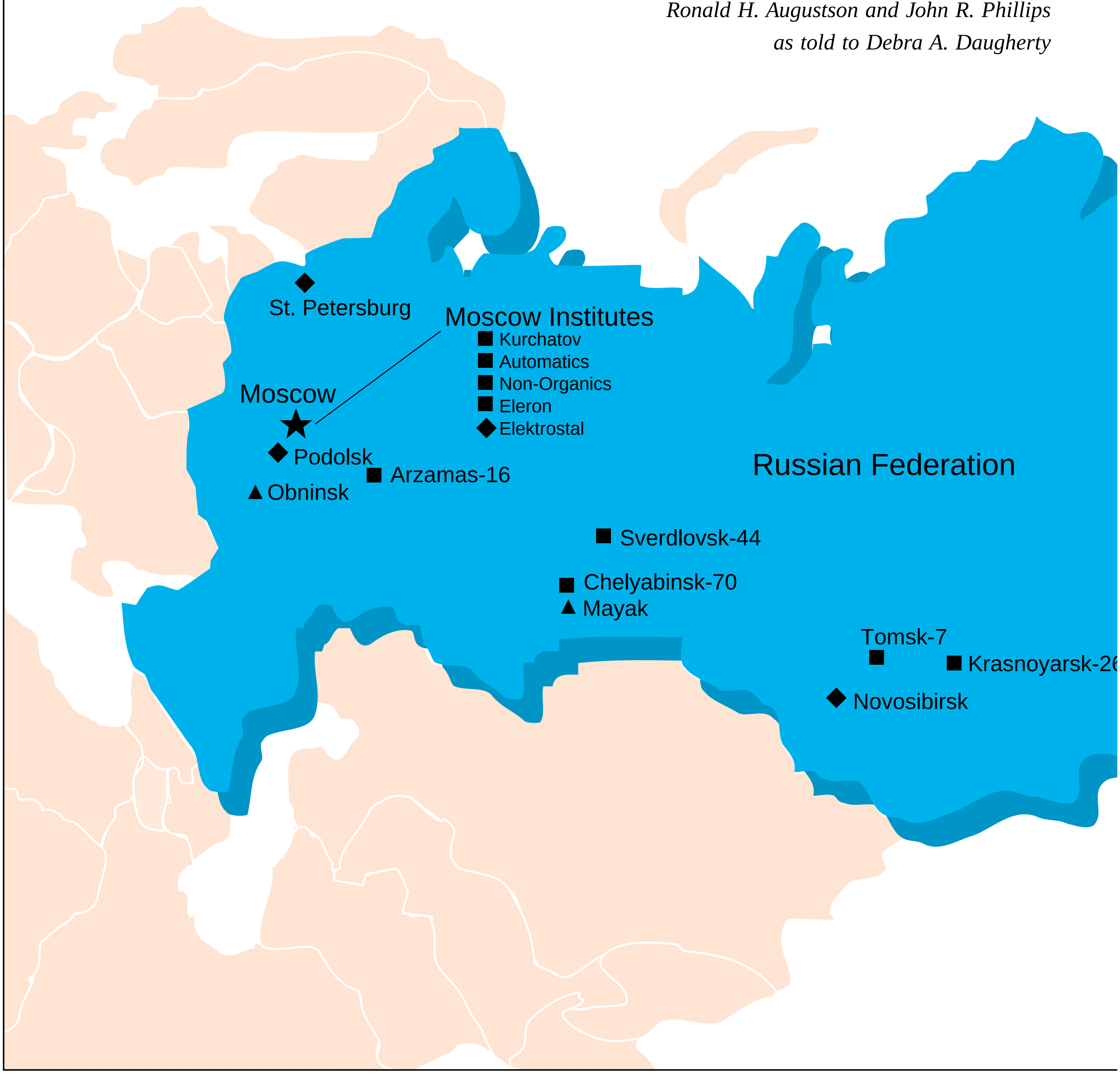

Figure 1. The map of the Russian Federation below shows the nuclear facilities where the United States and Russia have begun to collaborate on the once forbidden subject of nuclear materials protection, control, and accounting. In the photograph on the right, Russian workers transport nuclear materials to storage.

Nuclear proliferation and terrorism pose serious threats to the United States. Fortunately for us and the world at large, nuclear weapons are difficult to obtain whether by theft or by one's own labor. The five recognized nuclear weapons states (United States, Russia, Britain, France, and China) guard their nuclear weapons very tightly, and undeclared nuclear states, compelled by their own secrecy, probably also protect their weapons well. Furthermore, most nations have formally agreed to forego the development of nuclear weapons and to submit all their nuclear activities to international inspection by signing the Nuclear Nonproliferation Treaty (NPT).

However, a number of states, as well as certain terrorist groups, have shown interest in constructing their own weapons. Their greatest challenge is not designing the weapon but rather obtaining weapons-grade "fissile materials," either highly enriched uranium or plutonium, neither of which exist in nature. Because the production of those nuclear explosives requires a significant expenditure of time and money, potential nuclear weapons states may prefer the alternative—obtaining the materials by theft.

Since the dissolution of the Soviet Union in December 1991, that prospect has become even more worrisome. Economic decline and political unrest within the former Soviet Union have raised concern about the security of nuclear materials there, and reports of small amounts of weapons-grade material found in Germany and other places during the past five years have fed that concern. As a result the United States has taken an active role in helping the Russians maintain the security of their nuclear materials.

Los Alamos scientists became involved in that effort in 1992 as part of the Nunn-Lugar-sponsored "government-to-government" programs initiated immediately following the collapse of the Soviet Union. But, through an outgrowth of the "lab-to-lab" scientific conversion program between Los Alamos and Arzamas-16, its sister city in Russia, the program in nuclear materials protection, control, and accounting—or MPC&A—has been able to make substantial progress. This article traces the development and accomplishments of lab-to-lab MPC&A and discusses the impact of that program on the larger government-to-government program.

From left to right, Vladimir Belugin, Sigfried Hecker, Radi Il'kaev, and Steven Younger form the group that initiated the lab-to-lab MPC&A program.

The History Behind MPC&A

During the Cold War, both the United States and the Soviet Union accumulated enough weapons-grade fissile material to build tens of thousands of nuclear weapons. Both countries have also been acutely aware of the various threats of theft, which range from armed attack by commandos to the more insidious threat from insiders, and both have implemented safeguards to defend their fissile materials. Yet, their approaches have been very different.

In the United States, an external threat—for example, an overt armed attack on a nuclear facility or the hijacking of a nuclear shipment in transit—is countered by physical protection, such as armed guards and high fences. The more subtle internal threat—covert diversion or theft of nuclear materials—is countered by internal control systems, for example, computerized materials control and accounting systems. Those consist of sophisticated radiation sensors integrated with a network of computers that monitor nuclear materials from the moment they enter a facility to the time they leave again. Together, the United States refers to those safeguards against external and internal threats as MPC&A.

In the Soviet Union, however, both external and internal threats have historically been handled by physical protection combined with strong "people control." Whereas most Soviet nuclear facilities were surrounded by physical security to deter and defend against external attackers, it was the "people control" that prevented theft by insiders. The omnipresence of the KGB and the threat of harsh penalties made clandestine behavior among insiders unlikely. That system, under the Soviets, was considered virtually impenetrable.

In recent years, however, fundamental economic, political, and social changes in Russia have put that system into question. When the Soviet Union collapsed in 1991, weapons funding plummeted drastically as the economy, rather than the military, came to the forefront of Russia's concerns. Likewise, the welfare of the formerly honored Soviet defense workers was suddenly in serious jeopardy. Their salaries were frozen by the government and eroded by inflation such that, today, a typical weapons scientist is paid about 30 to 50 dollars per month. Financial need and possible disillusionment among Russian nuclear workers might make the surreptitious diversion of even a small amount of weapons-grade fissile material all too tempting.

Yet, thankfully, there have not been any violations of Russian nuclear safeguards that resulted in the loss of enough nuclear material for a weapon. Although confident that their system remains relatively secure, the Russians want to add controls and accounting to their existing physical protection to bring their nuclear safeguards into line with their new socio-political order. Russian weapons scientists and government officials alike have expressed interest in adopting controls and accounting techniques like those used in the United States.

In November 1991, the Nunn-Lugar bill redirected four hundred million dollars of Department of Defense (DOD) funds to assist with the "transportation, storage, safeguarding, and destruction of nuclear and other weapons [and] the prevention of weapons proliferation." Two Nunn-Lugar programs specifically funded MPC&A. Under one program, a storage facility for fissile materials from nuclear weapons dismantled under the Strategic Arms Reduction Treaties (START I and II) would be constructed and equipped with MPC&A systems. Under the other, MPC&A improvements would be implemented at civilian Russian nuclear institutes. Unfortunately, both of those programs initially moved relatively slowly.

Fortunately, at the same time, some of us from Los Alamos had the chance to informally discuss many aspects of MPC&A theory and design with the Russian scientists from Arzamas-16. Although the Russians were not familiar with computerized controls and accounting, they learned quickly, and our conversations with the Arzamas-16 scientists, especially Sergei Zykov and Vladimir Yuferev, later formed the basis of our joint work with Arzamas-16 under the auspices of the lab-to-lab MC&A program.

While our relationship with those scientists was forming, numerous reports of nuclear materials theft in 1992 and 1993 prompted the Senate Armed Services Committee to address nuclear materials safeguards in the former Soviet Union and the potential for nuclear proliferation. Under Secretary of Energy Charles Curtis attended those hearings and was urged to accelerate efforts being made through government-to-government channels. Two days later Sigfried Hecker, the Director of Los Alamos National Laboratory, had an introductory meeting with the newly appointed Curtis, and Curtis asked him if anything could be done to help the Russians safeguard their nuclear materials. Hecker had a ready answer. He suggested that the lab-to-lab scientific collaborations with Arzamas-16 (see "Lab-to-Lab Scientific Collaborations Between Los Alamos and Arzamas-16 Using Explosive-Driven Flux-Compression Generators") be extended to include MPC&A. Curtis made sure that two million dollars from the Department of Energy (DOE) 1994 budget were allocated to get the program started, and Mark Mullen, Gene Kutyreff, and I (Ron Augustson) began to develop a plan.

We designed the lab-to-lab MPC&A program to be a joint effort like the scientific program. Money would be divided into three roughly equal parts: Russian salaries, American salaries, and equipment. Our initial effort would focus on creating a demonstration of MPC&A for the officials at nuclear institutions that would show them what could be done. In June 1994, a small delegation from Los Alamos went to Russia to negotiate and sign contracts, and our first stop was Arzamas-16. In two days, we signed six contracts with Arzamas. Under the first five, we would produce specific products for computerized controls and accounting. Under the sixth, we would combine the products of the first five contracts into a demonstration that could be used to raise interest in materials control and accounting among the leaders of the Russian nuclear institutes.

That summer we also signed contracts with scientists from the Kurchatov Institute, Chelyabinsk-70, and in November, the Institute of Physics and Power Engineering at Obninsk. We teamed up with five other U.S. national laboratories—Brookhaven, Lawrence Livermore, Oak Ridge, Pacific Northwest, and Sandia—and since then, progress has been rapid at Arzamas-16, IPPE, and the Kurchatov Institute. In the following sections, we describe the work done at those three nuclear institutes, and using the demonstration at Arzamas-16 as a guide, we elaborate on the various features and procedures of MPC&A.

Arzamas-16

Arzamas-16, a city located about 250 miles east of Moscow, existed in complete secrecy throughout the cold war, unheard of to all Soviet citizens outside the Soviet defense complex. Although its name and location are now public knowledge, Arzamas-16 remains a closed city to this day. Forty miles of double fence surround the city and armed guards from the Interior Ministry patrol the perimeter. Visitors to the city are scrutinized and subjected to severe restrictions.[1] Physical protection against outside threats is formidable.

To protect against insiders, however, the scientists at Arzamas-16 wanted to develop a materials controls and accounting (MC&A) system like the one we discussed during work on the Nunn-Lugar storage facility. For a start, we decided to develop a realistic demonstration that would not only arouse the interest of officials at other facilities, but would also serve as a starting point within Arzamas-16 from which the MC&A could spread. The demonstration was a very ambitious prototype with many different components (see Figure 2) that provides a test bed for instruments and systems elements. Although it was designed as if it were to be applied at a storage facility, the demonstration was equipped with instruments that are useful for all sorts of nuclear facilities. (The demonstration does not duplicate any system that will actually be installed.) In all, thirty-nine integrated systems were installed, about half of which were Russian. We Americans contributed financial support, advice, and equipment, but the demonstration was designed and constructed entirely by the Russians.

Nuclear facilities in general are run by four different groups of people who perform four different tasks: protection, management, security, and materials

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[1] Not only are visitors required to apply for permission from MinAtom a month and a half in advance of their visit, but all cameras, computers, and listening devices are taken away from them as they enter the city.

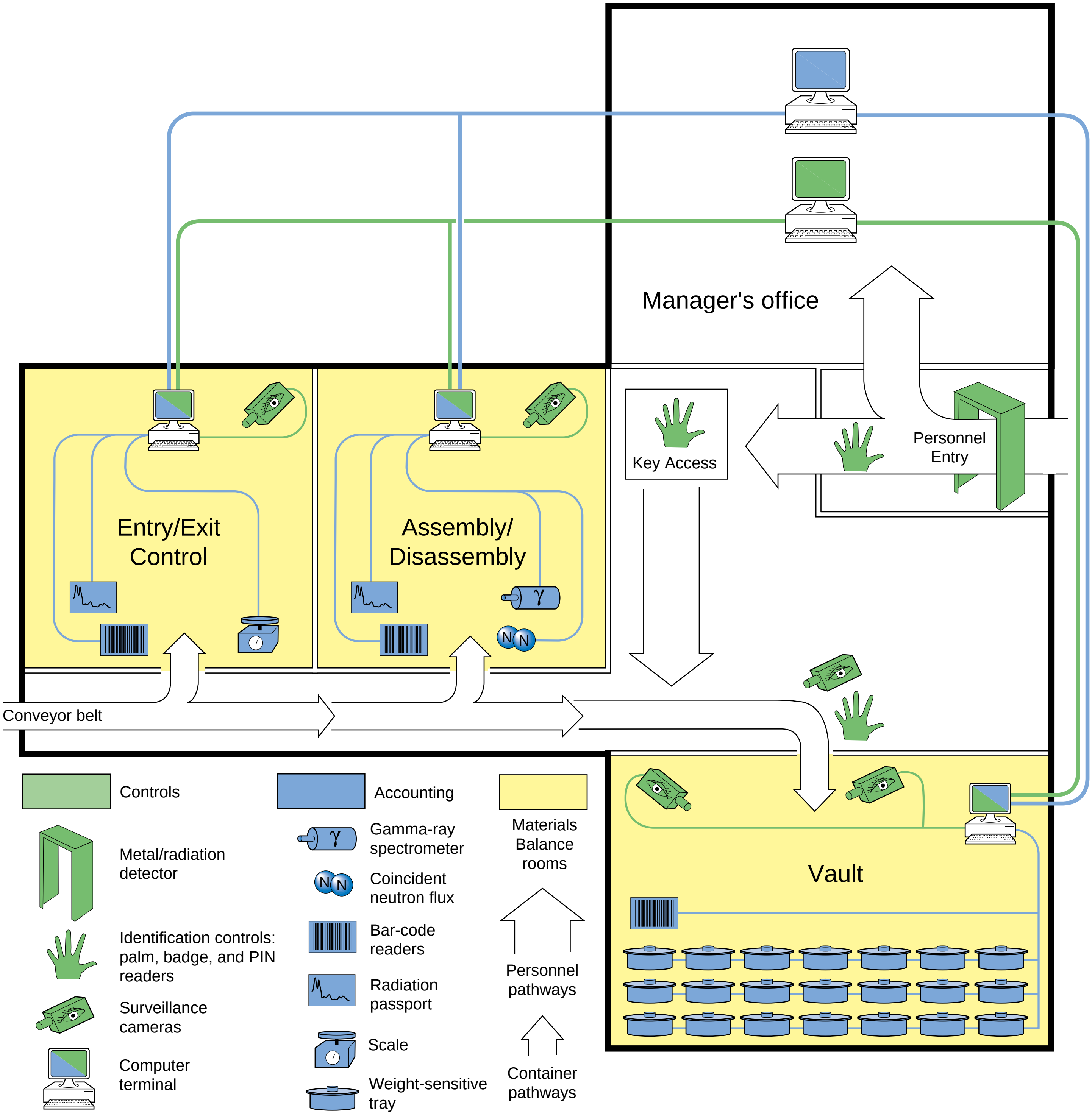

Figure 2. The Arzamas-16 Demonstration

This is a conceptual diagram of the Arzamas-16 demonstration MC&A system. Controls, which limit and monitor access to materials, are shown in green, instruments for accounting in blue, and the three Materials Balance rooms in yellow. All controls and accounting equipment are connected to a computer terminal in each Materials Balance room, and the terminal is connected to the central controls and accounting computers in the Manager's office. Bar code readers play a dual-role between controls and accounting. Not only are they used to identify containers, they also track the movement of materials through the facility.

handling. To promote control, the workers are typically separated on the basis of the task they perform. The protection forces work outside the facility. Inside, managers are limited to the Manager's Office, while security officers and materials handlers work in the Materials Balance rooms (shown in yellow in Figure 2). That separation of functions helps prevent theft.

Figure 3. Access Controls
The palm reader on the left determines a worker's identity on the basis of the size and shape of their hand. The size and shape are calculated from the capacitance between the hand and a grid of plates inside the palm reader. The palm, badge, and personal identification number readers (below) are used to identify workers throughout a nuclear facility. On the basis of a worker's identity, access to nuclear materials may be allowed or denied.

The demonstration was designed such that managers, security officers, and materials handlers all enter the facility through a single entrance, called Personnel Entry, that is separate from the entrance for materials. As they enter, workers pass through radiation and metal detectors, and their identity is determined by a palm reader, badge reader, and personal identification number (see Figure 3). The computerized MC&A system then unlocks the appropriate door at the end of the Personnel Entry to let managers into the Manager's Office and security officers and materials handlers to the Key Access area. After passing through the Entry, managers no longer interact with security officers and materials handlers directly.

Instead, managers "oversee" the operation of the facility via two central computers. The central computers are connected to computer terminals in each of the Materials Balance rooms, which, in turn, are connected to the controls and accounting instruments in those rooms. One of the central computers, the "accounting" computer, keeps an inventory of the material in every room that is updated in real time as containers of nuclear material enter, exit, and move through the facility. The other computer, the "controls" computer, supervises the movement of materials within the facility and restricts access to materials.

Under the watchful eye of the managers, materials handlers and security officers obtain keys to the Materials Balance rooms from the Key Access area. They are required to operate in teams of three that consist of two materials handlers and a security officer. All three must be identified by their palm, badge, and personal identification number. Then, if the team has permission from the Manager's Office, a key to the appropriate room will be released from the keyboard.

To illustrate the operation of the facility, let us assume that a team has obtained a key to the Entry/Exit Control room (on the left in Figure 2), where workers check the contents of incoming and outgoing containers of nuclear material. Newly-arrived containers are brought to the door of the Entry/Exit Control room by a conveyor belt, each with paperwork that lists the container's identification number and contents. Each container also has a bar code, which encodes the same information as the paperwork. At the door to the Entry/Exit Control room, a worker uses a hand-held scanner to read each container's bar code and checks the results with the paperwork. Because the scanner is connected to the accounting computer in the Manager's Office, the new container is automatically registered into the inventory of the facility.

Even if the paperwork and bar code agree, the team weighs the container to make sure its mass is consistent with the alleged contents, and they visually inspect the container's seal to make sure it hasn't been opened. They also verify the identity of the container by measuring its "radiation passport" (see Figure 4). In that way, the team checks and rechecks the validity of the container by independent methods.

When the team has finished inspect-

Figure 4. The Radiation Passport

The "radiation passport," which is a low-resolution measurement of the gamma-ray spectrum and neutron flux emitted by a container of nuclear material, provides a unique and highly reliable method of identifying individual containers. The graph on the right shows two low resolution gamma-ray spectra. Each peak in a given spectrum corresponds to gamma rays of a given energy, and the relative heights of those peaks are unique to a given container.

A record of the radiation passport for each container is stored in the central accounting computer. When a new container arrives at a facility, its identity is checked by measuring its radiation passport and comparing it with the passport on record for that container. If, for example, the two spectra in the figure were the measured and recorded passports, the central accounting computer would reject the alleged identity of the container.

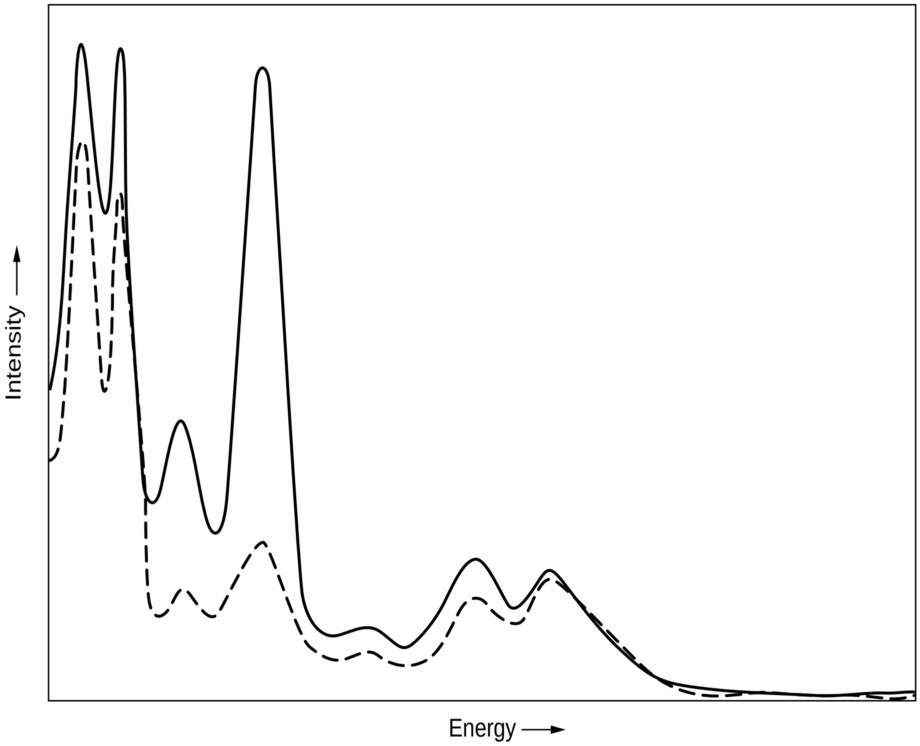

Figure 5. Gamma-ray Detector

In the photograph on the right, Sergei Razinkov and Valeri Belov from Arzamas-16 examines an American-made gamma-ray detector. The high-resolution spectrum produced by that detector can be used to determine the relative masses of the different isotopes of nuclear material inside the container. With a precise count of the fission neutrons emitted by the material, and knowing the decay rates of the isotopes of plutonium and uranium, the total mass of each isotope inside the container can be calculated.

ing the container in the Entry/Exit Control room, it can be taken to the Assembly/Disassembly room or straight to the Vault. Let us assume that, because the material arrived in shipping containers, the team must take the material to the Assembly/Disassembly room to put it in storage containers. Before they leave Entry/Exit Control, one worker must enter the destination of the container into the computer terminal. Another worker reads the container's bar code, which makes the central controls computer start a timer. If the container is not detected in the Assembly/Disassembly room in a certain amount of time, the controls computer will sound an alarm.

When the container's bar code is read at the door to the Assembly/Disassembly room, the timer is stopped.

The shipping container is then opened and the materials are redistributed among storage containers. New bar codes and radiation passports have to be established for each new storage container.

One worker allocates identification numbers for the new storage containers on the computer terminal while another worker measures their radiation passports. The accounting computer records the radiation passport along with the identification number of each container for future identification purposes (see Figure 4). The precise isotopic composition of the contents of each container is then determined from a high-resolution measurement of the container's gamma-ray spectrum and fission neutron flux (see Figure 5). A new bar code listing the container's identification number and the isotopic composition of its contents is printed out for each new storage container.

Now that the material is prepared for storage, one of the workers enters the next destination—the Vault—into the computer terminal. Another reads the bar code on the storage container to start the timer. Like the vault in a bank, the storage vault is barricaded by an extremely heavy door. All three members of the team must be identified by their palm, badge, and personal identification number, and if that team has permission from the Manager's Office, the controls computer unlocks the door. The computer terminal inside the Vault lists the "station" where each container is to be placed. The team then reads the bar code of each container and its station to register them into the inventory stored on the accounting computer (Figure 6).

The Vault, like the hallways of the demonstration, is continuously watched by video cameras, which are monitored by the controls computer. The images from the camera are digitally processed, and unauthorized changes in the images automatically set off an alarm.

Figure 6. The Vault

As many as 20,000 containers can be kept in the vault of a typical storage facility on shelves like the ones above. The bar code reader shown in the bottom center of the photograph is used to register both the container and its station into the accounting computer's inventory. The containers are placed on weight-sensitive trays, which are monitored by the controls computer to make sure that the containers are not moved without permission. Surveillance in the vault is strict. Several cameras are dedicated to watching the Vault door, while a number of others oversee the containers themselves. The video images produced by those cameras are digitally processed by the controls computer to search for unauthorized movement within the vault.

In January 1995, only six months after the contracts with Arzamas-16 had been signed, the demonstration facility was up and running. The successful demonstration spurred interest in the design and possible installation of systems that would meet the specific needs of relevant facilities. Interest was intense in both Russia and the United States. Representatives of the U.S. national laboratories were the first to visit the demonstration, followed by Russian government officials, Russian nuclear facility operators, and American congressmen. In May 1995, the Minister of Atomic Energy Viktor Mikhailov asked Arzamas-16 to transport the demonstration to Moscow and set it up in a conference room next to his office so that it would be accessible to everyone. In a single day, well over one hundred representatives from both Russian and American nuclear facilities and government agencies went through the Arzamas-16 demonstration, including the U.S. Secretary of Energy Hazel O'Leary.

The Institute of Physics and Power Engineering

The Institute of Physics and Power Engineering (IPPE) is located about 100 kilometers southwest of Moscow in the city of Obninsk, Russia. Although IPPE is administered by MINATOM, it is not a defense facility but rather a civilian center for research and development of nuclear technologies. At IPPE's Bystrye Fisicheskie Stendy (BFS) facility, scientists perform research on fast breeder reactors using the two critical assemblies BFS-1 and BFS-2.

In August 1994, not long after we had signed contracts with Arzamas-16, IPPE was brought into the public eye by a front-page article of the *New York Times* called "Russian Nuclear Materials Controls Are Leaky." As described in the article, the eight metric tons of highly enriched uranium and plutonium at BFS are in the form of thousands of small, hockey-puck-sized disks (Figure 7). The disks, which are used in reactor fuel rods, are "clad" in aluminum or stainless steel that absorbs the alpha and beta radiation of the uranium or plutonium in the disks. Therefore, a thief could simply place a few disks in his pockets without fear of being exposed to radiation. The *Times* article highlighted the proliferation risks associated with those disks.

Following up on several preliminary contacts in September and October of 1994, John Phillips from Los Alamos and representatives from five other U.S. national laboratories visited IPPE in November to initiate a lab-to-lab MPC&A program there. With the Russian scientists, we decided to concentrate our efforts on the so-called "Stone Sack," an isolated section within the BFS facility that contains the BFS-1 and BFS-2 reactor rooms, a storage vault, a manager's office, and a large portion of the most attractive nuclear materials at IPPE.

We began by installing a four-tiered system of controls. At the outermost fence surrounding the BFS facility, we installed a vehicle monitor to detect nuclear material in vehicles leaving the site (Figure 8). Inside the fence, at the entrance to the BFS facility, we put a radiation detector that can detect a single disk of highly-enriched uranium or plutonium. A "people trap" developed by the Russian company Technocom,[2] was placed at the entrance to the Stone Sack within BFS. The people trap is a sophisticated system of controls that includes palm, badge, and personal identification number readers, a scale to check the worker's weight, and metal and radiation detectors. Any violation will trigger the people trap to ensnare the offender. Finally, surveillance cameras were installed to monitor any slight changes in the storage areas and the reactor rooms.

Figure 7. Researchers at IPPE

In reactor research, fuel rods of various configurations are built out of large numbers of disks such as the one above. Bar coding the disks that contain nuclear material was the first step in the implementation of computerized accounting at IPPE.

Figure 8. The Vehicle Monitor

The large white posts on either side of the truck contain sensitive gamma-ray and neutron detectors that measure the amount of nuclear material inside the truck. If the measured amount is greater than expected, the vehicle must stop for inspection.

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[2] Tehnocom is a private enterprise formed by former Arzamas-16 weapons scientists that provides a number of technologies to the Russian defense complex.

As a precursor to a total computerized accounting system, we installed "stand-alone" accounting equipment in the Stone Sack. The two reactor rooms and the storage vault were equipped with low-resolution gamma-ray spectrometers to measure the radiation passports of the disks. High-resolution gamma-ray spectrometers and fission neutron counters were installed near both of the reactor rooms to measure the isotopic composition of the disks.

The tens of thousands of disks of nuclear material are in the process of being labeled with bar codes that list the identification number and contents of the disk—that process alone is expected to take three years to complete. A network of computers and bar code readers was installed in the two reactor rooms, the storage vault, and the manager's office, and in the near future, we plan to connect the stand-alone accounting equipment into the network.

The work done at IPPE marked one of the first times the lab-to-lab MPC&A program had implemented a safeguards program that protected real nuclear materials. IPPE also houses the MINATOM training center where workers from other Russian facilities can come to learn about MPC&A.

Figure 9. Building 116

Building 116 at the Kurchatov Institute houses two experimental critical assemblies, the Nartzis and the Astra, and a large amount of nuclear materials.

The Kurchatov Institute

The Kurchatov Institute in Moscow is a leading research center in the design of nuclear reactors for space and naval propulsion. Kurchatov has been independent of MINATOM since 1992. Its accessible location and its advocacy of the importance of improved safeguards made Kurchatov a priority for the lab-to-lab MPC&A program.

We focused our efforts on Building 116 where two critical assemblies, the Nartzis and the Astra, are used for nuclear reactor studies. Like the disks at IPPE, the nuclear material used in Building 116 is in relatively small, and therefore vulnerable, units—tiny "pellets" for the Nartzis and baseball-sized "pebbles" for the Astra. Thousands of such pellets and pebbles, each of which contains a few grams of nuclear material, are kept within the two storage rooms and two reactor rooms in Building 116.

Most of our work at the Kurchatov Institute has addressed the most pressing issue of physical protection. The grounds around Building 116 were cleared of bushes and trees to improve surveillance of the area, and we erected tall, sturdy fences and gates as shown in Figure 10.

We also installed surveillance and certain controls. Video cameras and infrared sensors, which detect the presence of people by the heat they give off, were installed along the perimeter of the facility, and additional cameras were installed inside the building. All windows and all but one entrance to Building 116 were sealed off, and the entrance was equipped with a people trap similar to the one at IPPE.

Lastly, we supported Kurchatov in taking total inventory of the nuclear materials of the two critical assemblies. Computer terminals were placed in each of the critical assembly rooms, and a third was installed in a separate building at the Kurchatov Institute, and the inventory is updated on the computer as it changes.

In December 1994, the Kurchatov Institute was the very first Russian nuclear institute to demonstrate its new safeguards. In February 1996, the Russian Navy[3] visited Building 116. Since then, the Navy has signed contracts through Kurchatov to begin lab-to-lab MPC&A work.

Conclusion

In less than two years, the lab-to-lab MPC&A program has made remarkable progress, and we expect progress to continue. New contracts have been signed to install complete computerized MC&A systems at the Arzamas-16 crit-

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[3] The Kurchatov Institute maintains a close relationship with the Russian Navy because the nuclear reactors for the Navy's submarines and surface ships were originally designed at Kurchatov.

Figure 10. Before and After

The top photograph shows the gate outside Building 116 of the Kurchatov Institute before the lab-to-lab MPC&A program, and the bottom photograph shows the same gate after. Physical protection such as strong fences and secure gates is the focus of our work at the Kurchatov Institute.

ical assembly and processing facility, IPPE's central storage and processing facilities, and the Kurchatov Institute's central storage facility. And progress at Chelyabinsk-70 has been steady. Personnel and vehicle monitors have been installed at the Chelyabinsk critical assembly area, and the vehicle monitor has survived its first Siberian winter. Soon we will install a computerized MC&A system there.

Three other Russian nuclear institutes have recently joined our program. Two of them, the Institutes of Automatics and Non-Organics, will be developing and constructing instruments and developing methods for MPC&A. At the third, Tomsk-7, we will be installing computerized MC&A systems at the spent-fuel reprocessing and uranium processing plants. In January 1996, the Russian Minister of Atomic Energy Viktor Mikhailov and the U.S. Secretary of Energy Hazel O'Leary signed a joint statement to open up Sverdlovsk-44 and Krasnoyarsk-26 to the lab-to-lab MPC&A program.

The trust and confidence that has been built up between the Russians and the Americans under the lab-to-lab MPC&A program has helped the government-to-government MPC&A program make progress. Our work has also inspired collaborations with two new Russian agencies. DOE has been allocated 10 million dollars for a new collaboration with Gosatomnadzor (GAN), the Russian equivalent of the U.S. Nuclear Regulatory Commission, and the U.S. national laboratories have been allocated 5 million dollars for a collaboration with the Russian Navy which involves the Kurchatov Institute as a partner.

Funding for the lab-to-lab program has increased from the two-million-dollar "start-up" fund of 1994 to 15 million dollars in 1995. Forty-five million dollars are budgeted for 1996, and plans are for funding to expand next year and continue until 2002, at which time Russia and its nuclear institutes should have sufficient infrastructure and resources, both human and technological, to carry on the work of MPC&A independently.

Above all, we would like to mention that the commitment of our Russian colleagues has been critical to the success of the lab-to-lab MPC&A program. Without their understanding and vision, we could not have met with such success. On the American side, we would like to acknowledge the contributions of the staff from all six participating DOE laboratories who worked very well together to solve technical, administrative, and cultural problems. The chemistry of the Joint Russian/American team has been tremendous. ■

Acknowledgements

We would especially like to thank all those at Los Alamos who have made exceptional contributions to the lab-to-lab MPC&A program, including Mark Mullen, Gene Kutyreff, Edward Kern, Cheryl Rodriguez, Tom Sampson, Gregory Sheppard, Susan Voss, Rob York, Boris Rosev, and Richard Wallace. Finally, the program could not have happened without the support and personal involvement of DOE management.

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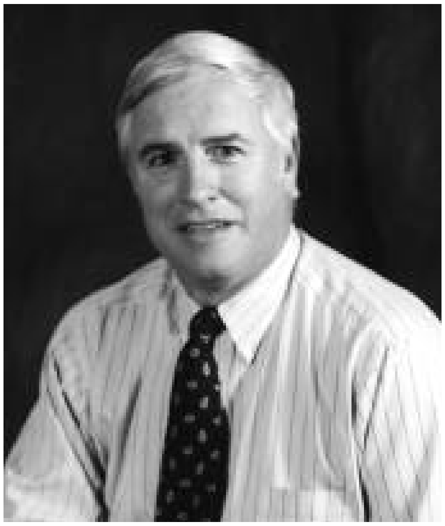
Ronald H. Augustson is the project leader for the Russian/American Lab-to-Lab Nuclear Material Protection, Control, and Accounting program at Los Alamos, and he is a member of that program's steering group.

Ron received his doctorate in physics from Rensselaer Polytechnic Institute in 1967. During the same year, Ron joined the Nuclear Materials Safeguards Program at Los Alamos to work on the development and implementation of neutron and gamma-ray based nondestructive assay techniques. In 1977, he was appointed technical project manager and group leader for the development of a dynamic nuclear-materials control system for the Los Alamos plutonium fabrication facility. In the summer of 1979, Ron took a position with the International Atomic Energy Agency in Vienna for 3 years, work that brought him to Tokai-Mura, Japan. After he returned to Los Alamos in 1982, Ron became the Los Alamos liaison for the U.S. Technical Support Program to the IAEA Safeguards Department. In 1992, he became involved with Russian nuclear safeguards by helping to design the Nunn-Lugar Russian Fissile Material Storage Facility. In the spring of 1994, Ron contributed to the formation of the Russian/American lab-to-lab MPC&A program that led to his present position.

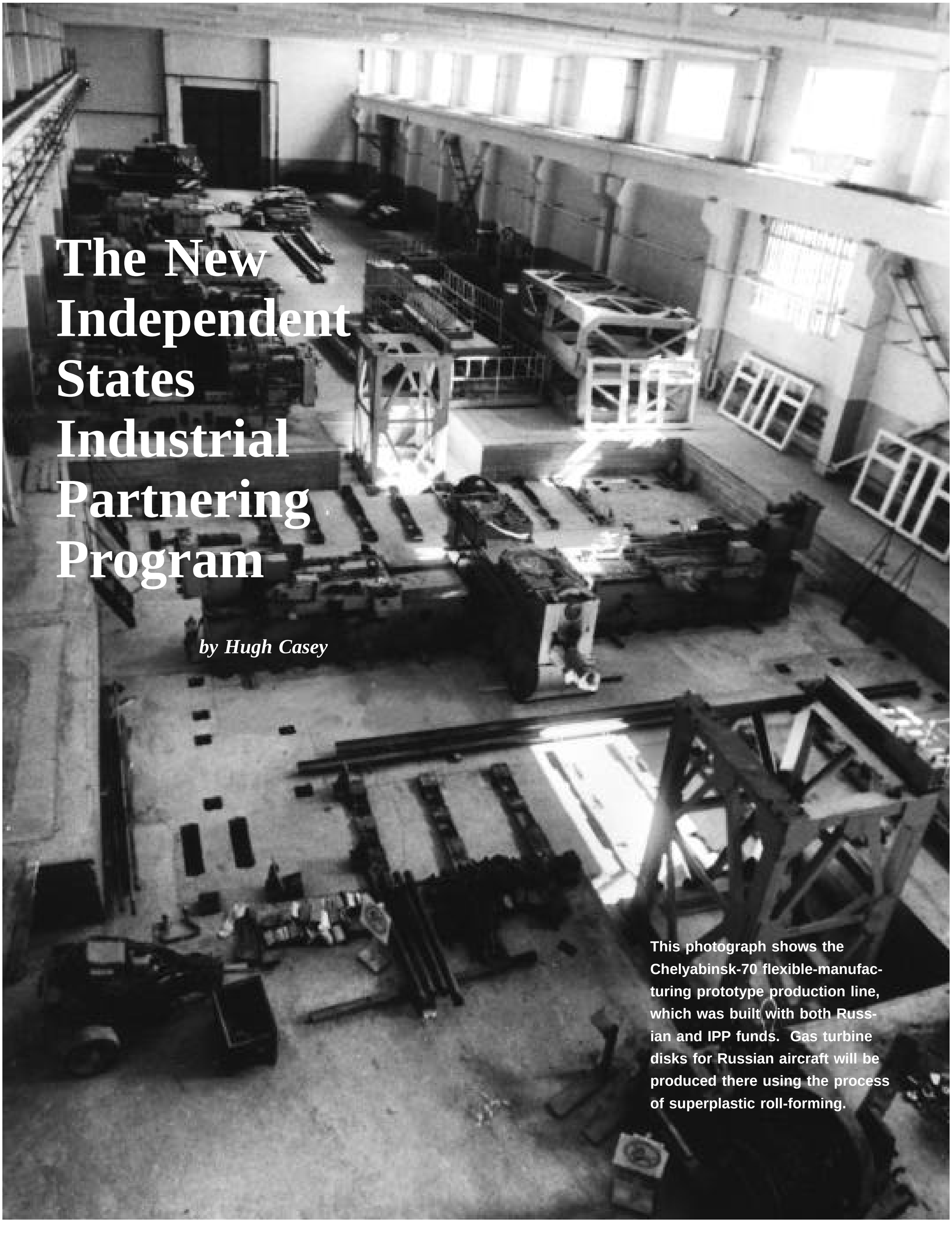


John R. Phillips has served as the team leader for the U.S. multi-laboratory support for the Russian/American MPC&A program at the Institute of Physics and Power Engineering (IPPE) in Obninsk, Russia. He is also a member of a multi-laboratory team developing a program for DOE on Countering Nuclear Smuggling.

John has a Ph.D. in analytical chemistry and an MBA from the University of New Mexico. He has served as a technical expert to the IAEA for the development and implementation of nondestructive assay instrumentation. He has served on a number of advisory groups including the DOE Laboratory Advisory Group on Effluent Research (LAGER). He has served as a member of the UNSCOM inspection team that discovered the calutron and centrifuge enrichment systems in Iraq following the Gulf War. His technical interests include spent-fuel examination, analytical chemistry of actinides, assessment of nuclear capabilities of potential proliferants, and effluent monitoring and analysis.

The New Independent States Industrial Partnering Program

by Hugh Casey



This photograph shows the Chelyabinsk-70 flexible-manufacturing prototype production line, which was built with both Russian and IPP funds. Gas turbine disks for Russian aircraft will be produced there using the process of superplastic roll-forming.

During the Cold War, the Soviet Union developed a vast infrastructure of science and technology to support its defense needs. In contrast with the United States, however, the Soviet Union had no civilian research and development supporting a private sector. Consequently, thousands of scientists skilled in the various aspects of weapons development, including weapons of mass destruction, have found themselves ill-equipped to deal with the economic crisis that accompanied the Soviet Union’s collapse. There are few alternative employment opportunities for those highly skilled specialists, and the possibility exists for defection of personnel or sales of sensitive information to rogue nations.

Figure 1. The New Independent States

On December 25, 1991, the Soviet Union broke up into the 15 New Independent States (NIS) shown above. All members of the NIS are eligible to participate in the Industrial Partnering Program; however, as a nonproliferation program, IPP focuses on the four “nuclear successor states”—Russia, Belarus, Kazakhstan, and Ukraine.

The Industrial Partnering Program (IPP) addresses the threat of “brain drain” by engaging weapons scientists from the New Independent States (NIS) (Figure 1) in cooperative research and development projects. The projects are specifically directed toward the development of non-military applications for the scientists’ skills and technologies. The Department of Energy (DOE) laboratories identify and evaluate the technologies and facilitate the involvement of U.S. industry, which, in turn, shares the cost of the research and development effort and supports the commercialization phase of successful ventures.

The foundations of IPP date back to the late 1980s and President Gorbachev's policy of *glasnost*, or “openness,” when the Soviet Union began overt attempts to market defense-based technology in eastern and western Europe. In 1988, the Soviets sponsored their first MATec conference in Helsinki, Finland, featuring advanced materials and manufacturing technologies from the Soviet defense institutes. Tony Rollett, ‘Krik’ Krikorian, and I, all from Los Alamos, were among the few Americans who attended.

I was specifically interested in the high-powered Soviet gyrotrons, which produce ultrahigh-frequency collimated microwave beams because at Los Alamos we had been experimenting with microwave sintering of ceramics. Our low-power industrial equipment was inadequate, and we were unable to obtain funding to build a more appropriate microwave source. During my conversations with Soviet scientists at MATec, I became convinced of the value of the Soviet gyrotron technology, not only for defense but for industry at large.

Our research on microwave technology continued, but it was not until several years later, following the collapse of the Soviet Union, that we had the opportunity to acquire the Soviet gyrotron technology. John Hnatio, who is the program manager for technology transfer at DOE, and I arranged a partnership between Los Alamos and the National Center for Manufacturing Sciences (NCMS), the United States largest consortium of manufacturing industries. With Hnatio’s help, Los Alamos secured DOE funds from the Advanced Manufacturing Initiative (later called the Technology Transfer Initiative) to evaluate the equipment for NCMS applications. We acquired three gyrotron tubes and associated equipment from the Paton Institute in Kiev, Ukraine. With the help of Ukrainian and Russian engineers, we established a “user facility” at Los Alamos where the experimental work could be performed. Hnatio had also been instrumental in setting up an industrial consortium at Sandia Laboratory, and some of the member companies were interested in acquiring Russian technology.

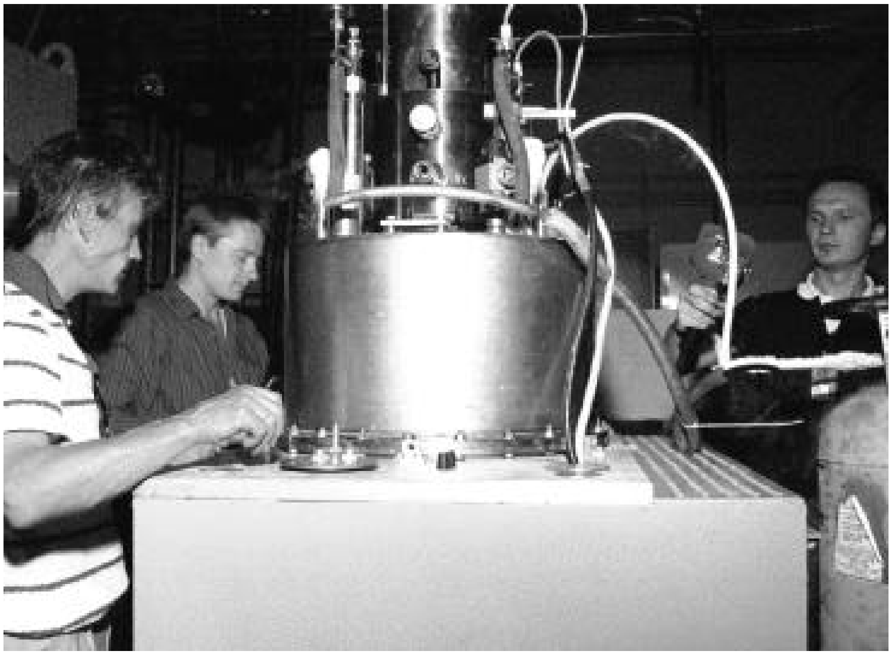


Figure 2. The Gyrotron

Peter Alekseevich Syrovets and Andrey Ivanovich Bunenko from the Paton Institute in Kiev, Ukraine, and Vladimir Ivanovich Irkhin from Gycom in Nizhny-Novogorod, Russia, are shown working on the gyrotron in the Los Alamos "user facility."

When Senator Domenici expressed interest in involving U.S. industry in laboratory partnerships with the Russians, the labs held a series of three meetings to assess the level of interest and commitment on the part of U.S. industry to that concept. With positive response from industry, the Senator moved forward with legislation to provide funding for a program of technology transfer from NIS defense institutes to U.S. industry.

As a result, 35 million dollars were included in the fiscal year 1994 Foreign Operations Act to establish a "program of cooperation between scientific and engineering institutes in the New Independent States of the former Soviet Union and national laboratories and other qualified academic institutes in the United States" that was "designed to stabilize the technology base in the cooperating states" and to "prevent and reduce proliferation of weapons of mass destruction." More specifically, the U.S. national laboratories were to help NIS scientists convert their defense technologies into commercially viable products and to facilitate the transfer of those technologies to U.S. industry.

The Interlaboratory Board was formed between six U.S. national laboratories who prepared the original program plan for IPP. Since then, the board has grown to include all ten DOE multi-program laboratories. Following a long series of interagency negotiations, funds were received at the laboratories in July 1994. Shortly after receipt of funds, we helped establish the U.S. Industrial Coalition, a consortium of private companies with interests in investing in NIS technology.

In April 1994, confident that the funds would come through, I made my first trip to Russia accompanied by John Shaner. We visited Arzamas-16 and Chelyabinsk-70 as well as a number of institutes in the Moscow region, including the Institute for High Pressure Physics, the Bochvar Institute, and the Institute of Solid State Physics in Chernolgolovka. We collected a number of proposals, which we circulated to the technical divisions at Los Alamos. John Shaner and I headed up a committee of technical experts to select proposals for Los Alamos projects. Los Alamos received approximately 4.5 million of the 20 million dollars that were allocated for lab-to-institute projects. Our target was an average of 100,000 dollars per project, at least half of which had to be spent abroad at the Russian institutes. In August 1994, Los Alamos signed its first IPP contract with Arzamas-16, to be followed shortly thereafter by multiple contracts for twenty-four projects with twenty NIS institutes.

IPP projects cover a broad range of technologies that reflect the core competencies of the NIS institutes. The similarity of the NIS institutes' technical base with our own labs is not coincidental. Materials, manufacturing sciences, theory and modeling, lasers and particle beams, and sensors and diagnostics are all represented in the IPP project portfolio. We have a few fairly basic scientific projects, but most of our activities are in the areas of applied science and engineering. There are no military projects, and we have avoided technologies covered by other government programs. The following brief descriptions will illustrate the nature of the project work.

The Gyrotron

Since the days of the Advanced Manufacturing Initiative, the gyrotron project has matured and grown to capture the interest of the automotive, oil, electronics, communications, manufacturing, and aerospace industries. Individual companies participating include Ford Motor Company, AT&T, General Atomics, Tycom, Continental Electronics, Baxter Health Care, and Ferro, a list that indicates the diversity of applications as well as the level of industrial interest. The gyrotron (Figure 2) is being investigated for use in numerous operations, including heat treating auto windshields, sintering ceramic and plastic appliance hardware, coating tool bits, separating and recycling plastics, vitrifying radioactive sludge, and other fascinating applications. At Los Alamos and the Paton Institute, we investigate the interaction of the millimeter-wave radiation produced by the gyrotron with different materials. We then optimize the gyrotron to specific applications.

The first gyrotron-based "production machine" will be installed at Ford Motor Company this year, and we are assisting the scientists at the Paton Institute to set up user facilities in Kiev.

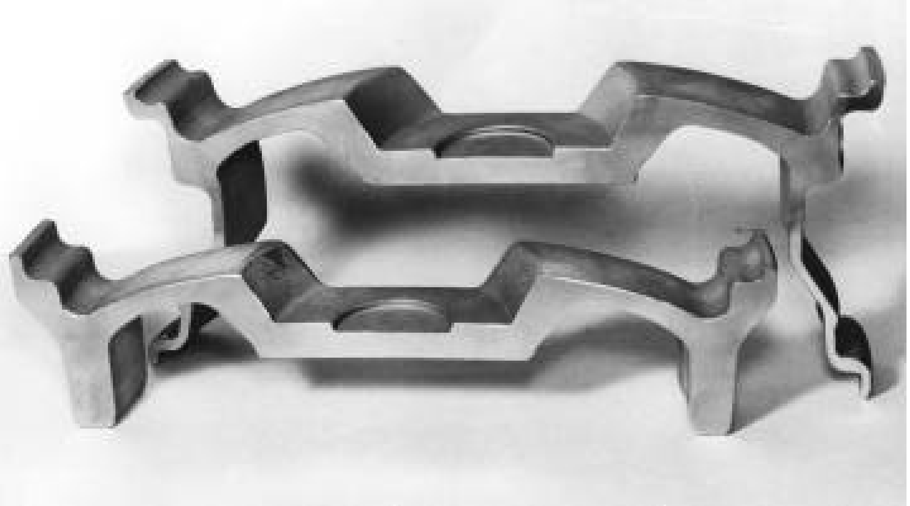


Figure 3. Superplastic Forming
The photograph above shows two cross sections of automobile wheel rims that were produced at the Russian Federal Nuclear Center at Chelyabinsk-70. They were made of ultrafine aluminum which, like most ultrafine and nano materials, exhibits "superplastic" behavior at certain temperatures and certain rates of strain. Under those conditions, superplastic materials are as pliable as paste and can be formed into complicated shapes, such as automobile wheel rims, simply by pushing on them.

Ultrafine and Nano Materials

The size of the grains, or "crystallites," in metals and alloys has a pronounced effect on their physical and mechanical properties. The grain size in engineered materials, such as steels or aluminum alloys, is determined by the manner in which the materials are prepared. Historically, manufacturers of metals and alloys have obtained specific properties by controlling alloy composition or the thermomechanical processing steps used in the production of the material. For most conventional processing methods, grain sizes are typically in the range of tens to hundreds of micrometers.

Recent research in the United States, Russia, and Ukraine has shown that many materials exhibit remarkable properties when their grain-size is refined. Ultrafine materials have grains a few tenths of a micrometer in diameter and exhibit strengths as much as a factor of five times that of their unrefined counterparts while retaining excellent ductility and resistance to fracture. They also show improved corrosion resistance and, in many instances, "superplastic" properties—that is, they can be deformed without any "localized yielding" in a manner similar to heated plastics and glass (Figure 3).

Nano materials have grains as small as hundredths of a micrometer and have the same advantages as ultrafine materials but to an even greater extent. In addition, nano materials have a multitude of unique characteristics, such as their magnetic properties, that are not yet fully understood.

Early efforts to produce ultrafine and nano materials employed conventional methods of powder compaction in which solid shapes were formed by compressing finely ground powders, usually at high temperature. However, that process produced materials with relatively high levels of impurities and numerous defects. Under the IPP project headed by Terry Lowe of Los Alamos, we use the Russian-developed technique called "severe plastic deformation" in which a material is put under severe stresses that breakdown, or "refine," the material's grains. Although there remains considerable work to optimize that process, the Russian technique is the first to produce solid shapes of high enough quality to be considered useful in load-bearing engineered structures.

The Ufa State Aviation Technical University in Ufa, Russia produces all of the ultrafine and nano materials used in this IPP project. Three other Russian institutes in Ekaterinberg and Tomsk study and test those materials for practical applications, and Los Alamos and Northwestern University use them to test theoretical models of material behavior.

Recently, the researchers in Ufa began to produce superplastically formed ultrafine titanium plates for endoprosthetic applications (Figure 4). We expect to establish a U.S. Industrial Coalition partnership before the end of the year that will expand this application to other areas of traumatic medicine and biomedical engineering. Another partnership would apply nano materials to the construction of permanent magnets with "structural integrity"—that is, magnets that can be formed into complex shapes and still retain their strength and resistance to fracture.

IPP also funds two projects related to

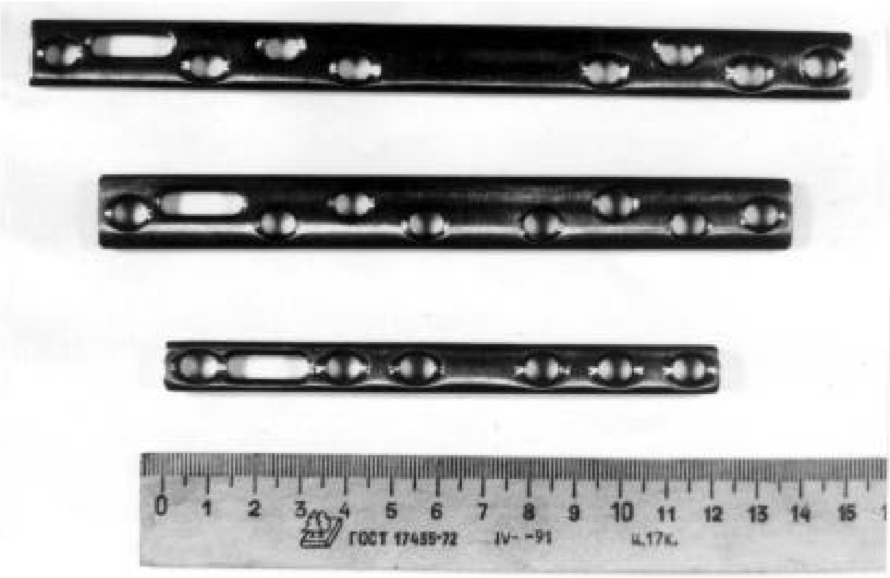


Figure 4. An Application of Ultrafine Materials

The photograph above (taken at the Ufa State Aviation Technical University) shows endoprosthetic appliances produced from ultrafine-grain titanium. The "plates" in the picture are between 1.5 and 2 times stronger than conventional titanium alloys engineered for traumatic medicine applications. Even more importantly, these pure titanium devices will not react with the body's chemistry. They will be undergoing medical certification at the Research Center of the Republic Clinical Hospital in Ufa, Russia.

nano and ultrafine materials. One is geared toward the production of nanocrystalline powders that are commonly used in cosmetics and paints as ultraviolet absorbers. In the other, Los Alamos is helping Russian scientists to convert a weapons facility at Chelyabinsk-70 into a manufacturing facility for superplastic roll-forming of turbine discs (see opening photograph). Industrial partners in that venture include Rockwell International Science Center, United Technologies Research Center, and several members of the U.S. Industrial Coalition.

The Optical Microresonator

About twenty-five years ago, physicists conducting high-precision experiments approached the so-called "standard quantum limit," a theoretical bound on the accuracy of measurements on single objects (for example, a macroscopic oscillator or an electromagnetic wave) imposed by the fundamental principles of quantum mechanics.

Going back to thought experiments due originally to Bohr and Einstein, Vladimir Braginsky developed a theory of measurement called quantum non-demolition (QND) that outlined ways to overcome the standard quantum limit in different kinds of elementary measurements. Not only did QND eliminate any a priori limit on the accuracy of certain measurements, it also provided experimental recipes on how to make measurements without perturbing the quantity to be measured. For example, it indicated how the energy of a photon might be measured without destroying the photon. QND provided the capability to make repeated and predictable measurements on a single quantum system.

During the past decade, the principles of QND, as applied to electromagnetic waves in the optical band, have been demonstrated by researchers at NTT Basic Research Lab (Japan), Institute of Optics (France), and Cal Tech (U.S.). Despite those fine efforts, QND measurements have yet to reach the level of a practical technology because of the expense and labor associated with those experimental techniques.

Vladimir Braginsky and Vladimir Ilchenko of Moscow State University and Salman Habib and Wojciech Zurek of Los Alamos believe that simpler, inexpensive, and higher-resolution QND measurements are not only feasible but can also be the basis for useful applications. They are directing an IPP project to do just that.

A scheme has been proposed to measure the energy of a small number of photons in a resonator. The first and hardest step is to find a way to store photons in isolation for relatively long periods of time. One of the experimental schemes being explored under the IPP program is a new technology invented by the Moscow group called an "optical microsphere resonator." That device is a tiny sphere (30 to 300 micrometers in diameter) made out of very high-purity fused silica, or glass. The microsphere operates as a "photon trap," allowing only photons of very precise energy to enter. Due to total internal reflection, the photons glide continuously along the walls. They circulate inside the microsphere for a few microseconds—

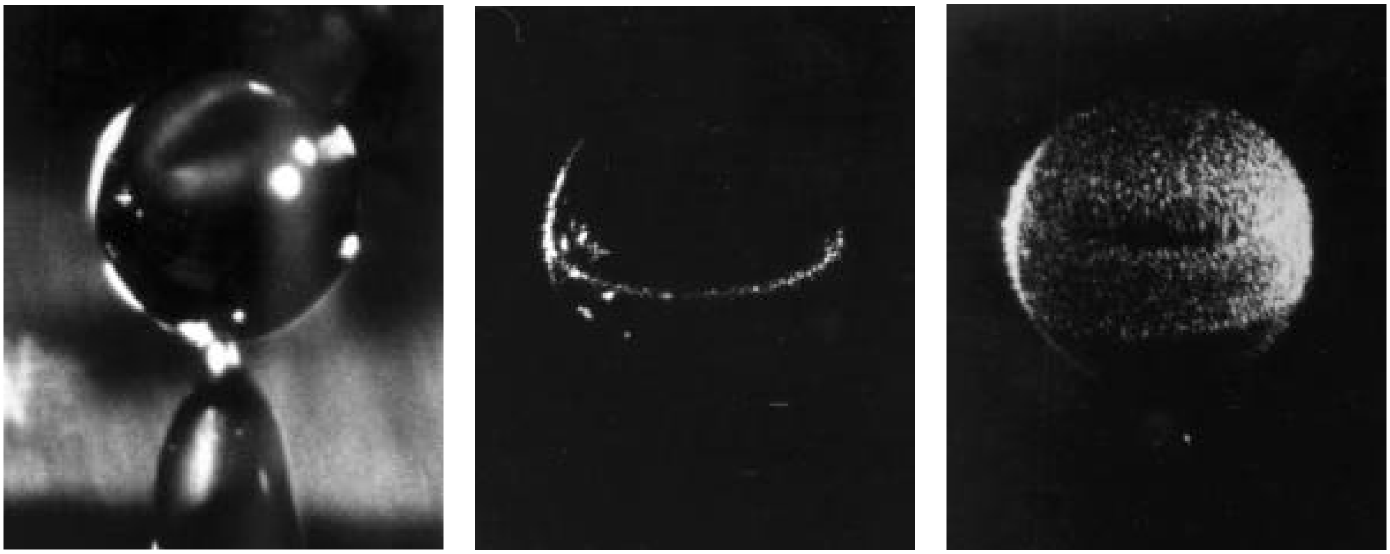


Figure 5. The Optical Microresonator

The black and white photograph on the left shows the optical microresonator under external illumination. The photographs in the middle and on the right show photons trapped in two different modes of the microresonator. (The photons are from a helium-neon laser and are at a wavelength of 633 nanometers (red visible light.) The resonant modes are defined by the difference between two of the photons' quantum numbers, l and m. The middle photograph shows the mode satisfying the relationship $l - m = 0$, and the photograph on the right shows the mode $l - m \approx 70$.

long enough to perform successive measurements on the photons.

The photons occupy a "field mode" (such as the thin annular belt in the equatorial region of the microresonator shown in the middle photograph in Figure 5) of hardly any volume (down to 10^{-10} cubic centimeters). This allows very large electric fields to be established, even with only a small number of photons occupying the mode. For a single photon circulating in the microsphere, the field is larger than 100 volts per centimeter.

The index of refraction of the glass microsphere has a nonlinear component. Large fields produced by a relatively small number of photons in the "signal" mode change the refraction index in the mode area. That change can be monitored by the resulting shift of the resonance frequency of another "probe" mode that overlaps the signal mode. Absolute energy resolution in such a scheme can be made several orders of magnitude better than has been achieved in earlier QND experiments.

Successful QND experiments would allow attainment of the highest possible sensitivity permitted by quantum mechanics. On the way to that ultimate goal, the microsphere QND concept promises a host of less fundamental, yet important, technological spin-offs. The most obvious ones follow naturally from the microsphere's ability to choose photons of very precise wavelength. Relevant applications include high-resolution spectroscopy, investigation of fundamental loss mechanisms in transparent solids and liquids, and frequency stabilization of widely used semiconductor lasers (for which proof-of-principle experiments have already been conducted at Moscow State University).

The realization of QND measurements opens up another set of applications, wholly quantum mechanical, that arise from this new and intriguing ability to manipulate and non-destructively control an object's quantum states. The presently embryonic, but very exciting, areas of quantum computing and quantum communications are two areas where QND measurements will eventually find their natural niche.

The IPP Information System

Early in the development of IPP, we realized that we would need an effective means of communication and a method for storing, tracking, and exchanging technical data. To meet those needs, Molly Cernicek of Los Alamos designed the IPP Information System, a secure and convenient computer-based system that provides information in near real-time to all the participants in the program. The Information System was built using "Lotus Notes Groupware"

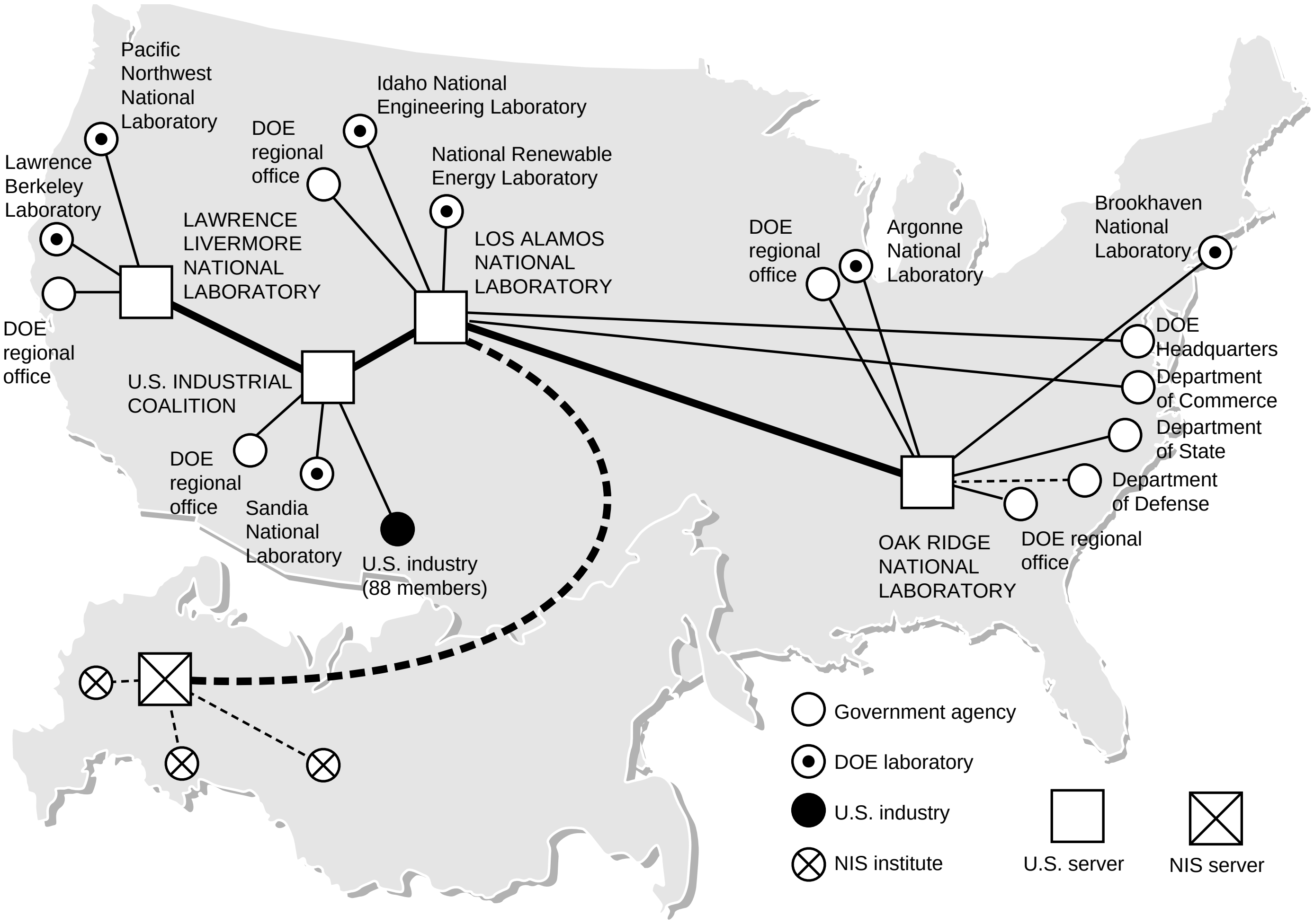


Figure 6. The Net
The IPP Information System is a secure and convenient network of computers that provides effective communication of technical information between the participants in IPP. The current configuration (shown in solid lines) includes the Department of Energy and five of its regional offices, the Department of State, the ten participating DOE laboratories, and over 80 companies from the U.S. Industrial Coalition. Future servers and clients (shown in dashed lines) include the Department of Commerce, the Department of Defense, and most importantly, several nuclear institutes in Russia and other New Independent States.

software. All information exchanged within the network is encrypted to provide security—that is, information can only be decoded by the computer to which it is sent. Furthermore, because the system is based on a single, comprehensive software program, it provides complete compatibility.

By October 1995, the IPP Information System had developed into the nation-wide network shown in solid lines in Figure 6. With few exceptions, the network relies upon existing Internet connections. The five servers in the network (the U.S. Industrial Coalition has two servers) house and share all the databases, which are “replicated,” or copied onto one another, every hour. That way, all IPP participants have access to current IPP information in near real-time. In addition, the system holds dozens of clients representing DOE headquarters and regional offices, the ten participating DOE laboratories, the Department of State, and more than 80 members of the U.S. Industrial Coalition. Future clients in the United States include the Department of Commerce and the Department of Defense as well as both the government-to-government and the lab-to-lab MPC&A programs.

During the summer of 1996, we plan to connect several weapons institutes in Russia (see the inset in Figure 6) to the IPP Information System. Then NIS scientists will be able to use the Information System to electronically submit their own proposals for IPP projects and to rapidly establish relevant contacts with U.S. scientists and engineers. Because the IPP Information System facilitates the movement of NIS scientists from defense to paying peacetime work, it helps keep those scientists in their own countries and serves as a tool against nuclear proliferation.

Lastly, the Information System is used to track the progress of each project in terms of both the general goals of IPP and financial expenditures.

The IPP Information System enables IPP participants to collaborate with one another and to share knowledge and expertise unbounded by factors such as time and distance. Molly Cernicek, Mike Wyman, and their team of students, who put together this system, have introduced us all to what appears to be an interstate on the “information superhighway.”

Conclusion

The Industrial Partnering Program has funded nearly 200 projects involving over 70 NIS institutes and approximately 2000 NIS scientists and technicians since the program began in July 1994.

U.S. industry has shown great enthusiasm for IPP. For every dollar invested by the federal government in NIS-IPP collaborations, two dollars have been invested by members of the U.S. Industrial Coalition. We have received encouraging reviews from many sources, including the John F. Kennedy School of Government at Harvard.

Lastly, IPP has spontaneously integrated with the International Science and Technology Center (ISTC) in Moscow and its equivalent Center in Kiev (see “The International Science and Technology Centers in the Former Soviet Union”). IPP and ISTC are coordinated to avoid redundancy and to promote synergetic interactions among the participants. Several large projects, such as the superplastic forming facility at Chelyabinsk-70, are being funded by both programs, and because of that larger integrated effort, our projects have a greater chance of success.

IPP is a nonproliferation initiative with the added benefit that technology flows back to the United States as a result of the program’s cooperative research and development activities. Programs like IPP have the opportunity to demonstrate the delicate balance between defense and industrial applications of advanced technology as well as promote and facilitate the transfer of NIS defense scientists to peacetime work. ■

Acknowledgements

From a personal point of view, this has been a tremendously exciting and rewarding experience. I would like to take this opportunity to thank all of my Los Alamos colleagues who have provided support and encouragement for this program. Also, I would like to acknowledge the cooperation and support of my colleagues in the Departments of Energy and State who have become members of the team responsible for implementation of this program.

Further Reading

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Hugh Casey is the project leader for IPP. Hugh earned his masters degrees in science and engineering from the University of Glasgow and the University of Strathclyde, Scotland. Upon moving to the United States, he worked in corporate research in the aerospace industry. While employed by United Aircraft corporation (now United Technologies), Hugh’s research and development work with high-energy electron beams and industrial scale lasers included contract research work for Los Alamos and Lawrence Livermore labs. He joined the Chemistry and Materials Division at Los Alamos in 1972.

At Los Alamos, Hugh has worked on translating conceptual designs into engineered systems and developing advanced materials processing and fabrication facilities, particularly electron-beam, plasma, laser, and microwave systems. In his current assignment, Hugh is Chairman of the Interlaboratory Board, which consists of the ten DOE multi-program national laboratories responsible for implementing the cooperative projects with the weapons institutes in the former Soviet Union.

Hugh has numerous personal interests but is best known locally for his association with the Los Alamos Ski School, where he has taught as a certified PSIA instructor since 1978.

The International Science and Technology

Since 1992, the United States has been involved in the establishment and operation of a science and technology center in Russia—the International Science and Technology Center (ISTC)—and a similar center in Ukraine—the Science and Technology Center in Ukraine (STCU). These centers provide funding support—on a government-to-government basis—to scientists and engineers from the defense sector of the former Soviet Union for work in a wide range of civilian science and technology projects.

The concept of an international science and technology center was raised during the Bush-Yeltsin Summit, held in Washington, D.C. in January 1992. The primary role of the center would be to reduce the possibility that personnel with knowledge and expertise in weapons of mass destruction or missile delivery systems would leave the former Soviet Union and offer their services to rogue nations. As stated in the agreement that established the ISTC, weapon scientists would have the opportunity to "…redirect their talents to peaceful activities…and [contribute] to the solutions to national or international technical problems…" This agreement was initialed in May of 1992, with the United States, Russia, the European Union, and Japan as signatories.

Despite the desire of the United States to move quickly on ratification of the agreement, formal operation of the ISTC program proceeded somewhat slowly. Money was not the major stumbling block, because the program, in effect, was an outgrowth of the larger and more encompassing Soviet Nuclear Threat Reduction Act (Nunn-Lugar), and funding initially came from Department of Defense moneys committed under that legislation.

The ISTC agreement was provisionally approved via a decree by President Yeltsin in December 1993. Although the Russian parliament still has not taken formal action on ISTC ratification, Yeltsin's approval allowed the ISTC to became operational in March of 1994.

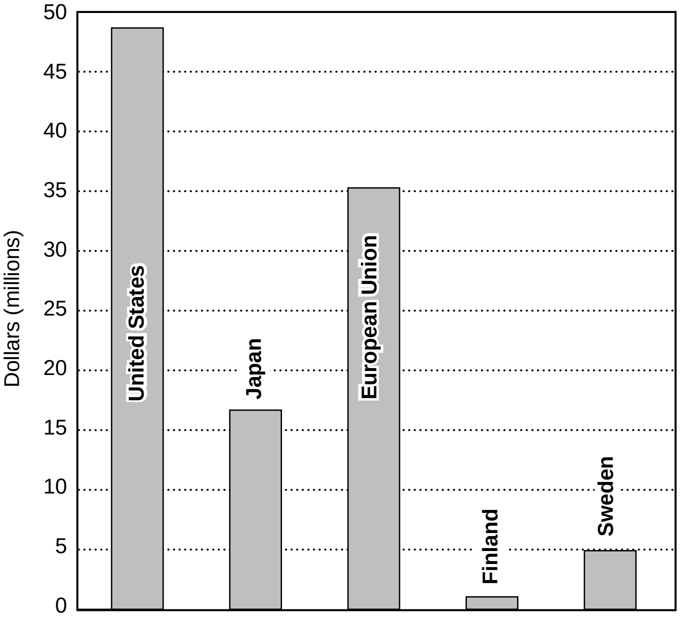


Figure 1. Total Funds Pledged to the International Science and Technology Center by Country (through 1995)

Likewise, there were strong political pressures to create a science center in Ukraine distinct from the one being established in Russia. Ratification for the STCU wasn't finalized by Ukraine's parliament—the Rada—until July 1994.

Regardless of the delays in starting the ISTC and the STCU, both centers are today operating successfully. The ISTC has been funding projects since March 1994, and the STCU since December 1995. To date, nearly 11,500 scientists and engineers with knowledge of weapons of mass destruction have received funding through science-center projects. Approximately 210 projects have been funded at the two centers, amounting to commitments of the funding parties (grown to include Finland and Sweden) of approximately $84 million. United States funding currently falls under the Freedom Support Act, which uses Department of State Foreign Assistance moneys. This source allows project funding in the original nuclear inheritor states (Russia, Kazakhstan, Ukraine and Belarus) as well as additional states of the Former Soviet Union (including Georgia, Armenia, Kyrgyzstan).

The diversity of science and technology areas of the ISTC funded projects is shown in Figure 2. The two largest areas supported by the ISTC—energy and environment—account for over 40 per cent of the 197 funded projects.

Centers in the Former Soviet Union

Steven J. Gitomer

In addition to funding projects, the ISTC has organized a number of symposia to provide opportunities for scientists of the former Soviet Union to present their work to an international audience. The symposia have addressed topics including the environment, conversion in the area of biological weapons, science and technology in Georgia and Kazakhstan, and biotechnology.

Los Alamos was involved with the ISTC from the earliest days and has had a continued influence on the shaping of ISTC throughout its formative period to the present. For example, the author has been involved with the ISTC from 1992 to the present, first serving as a DOE representative, then as a senior scientific advisor to the State Department (1993-1994), and now as a member of the ISTC Scientific Advisory Committee. Boris Rosev served as a senior project manager at the ISTC for over one year (1993-1994), while currently, David Giebink is on a two year assignment at the ISTC.

Los Alamos technical staff members contribute to proposal development and review and monitor various projects. In fact, most of the nearly 500 proposals received from the ISTC and STCU have been reviewed by Los Alamos scientists. Additionally, lab scientists are often committed collaborators in joint research, interacting in quite a wide variety of areas. Many of these research projects were summarized in a series of Los Alamos reports entitled “Los Alamos National Laboratory Interactions with Organizations in the Former Soviet Union” compiled by the author and Jim Kowaczyk.

As this issue of *Los Alamos Science* goes to press, the ISTC has completed another meeting of its Board of Governors at which more than thirty proposals were approved and funds totalling nearly seventeen million dollars were committed. Nearly a thousand additional scientists and engineers, many of whom have knowledge of weapons of mass destruction, will be engaged in projects of a civilian nature. Los Alamos scientists will be involved as collaborators[†] in these projects, which cover areas including seismic monitoring, upward-propagating lightning, and environmental characterization and remediation.

The Western scientific community is having its impact on science and technology in the former Soviet Union in many ways and, specifically through the ISTC and STCU, is becoming a part of their future. As time goes by, I hope more of my colleagues will take advantage of and benefit from the opportunities connected with these centers, and I hope I can help make this so. ■

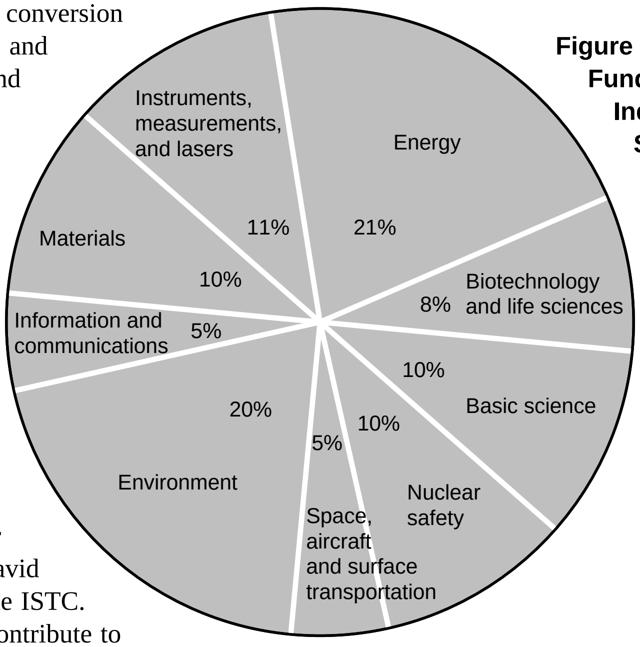
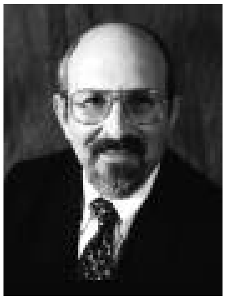


Figure 2. Percentage of ISTC Funds Used to Support the Indicated Areas of Science (through 1995)



Steven J. Gitomer received his Ph.D. in electrical engineering from the University of Wisconsin-Madison. He has been with the Laboratory since 1974. He joined the Center for International Security Affairs in 1995 and has been a member of the Nonproliferation and International Security Division since 1993. His current responsibilities include: U.S. member of the Scientific Advisory Committee of ISTC, Senior Science Advisor to the U. S. Department of State for STCU, and principal Los Alamos point-of-contact for the ISTC, STCU, and lab-to-lab interactions with the Former Soviet Union. From 1991 to 1993, Gitomer served at the U.S. Department of Energy’s Office of Arms Control in Washington D.C., where his work focused on implementation of the Threshold Test Ban Treaty and the establishment of the science and technology centers in Russia and Ukraine.

[†] ISTC/STCU monies only cover salaries, equipment, supplies, travel, and overhead of the project participants from the former Soviet Union. There is no provision for funding collaborators who are not from the former Soviet Union.