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MHD pulsed power for geophysical research

The Cold War produced an array of new military technologies that Russia and the U.S. can now turn into scientific tools. Marsha Freeman reports.

Russian Academician E.P. Velikhov, speaking at a meeting of the American Physical Society in Washington, D.C. on April 20, made an appeal to scientists to apply what he termed "exotic technologies" developed during the Cold War to solve scientific problems. "There are many Cold War technologies which I think have some useful application," Velikhov stated. "I only wish to give you some from my own experiences."

At the end of the 1960s, he said, he was asked to provide an energy source for laser weapons, for the Soviet strategic defense program. "In studying this energy source [requirement], we looked into the MHD [magnetohydrodynamics] generator, which was invented by Michael Faraday very long ago." Faraday had noted in 1832 that an electrical current could be produced directly by the flow of an electrically conducting fluid (such as saltwater in the Thames River) through an external stationary magnetic field (that of the Earth).

Today electricity is produced mainly through the rotational energy produced by huge pieces of equipment such as steam turbine/generator sets. MHD direct conversion of the energy in fossil fuels, along with nuclear fission and thermonuclear fusion, could potentially more than double the 35% efficiency of steam turbine conversion (see **Figure 1**).

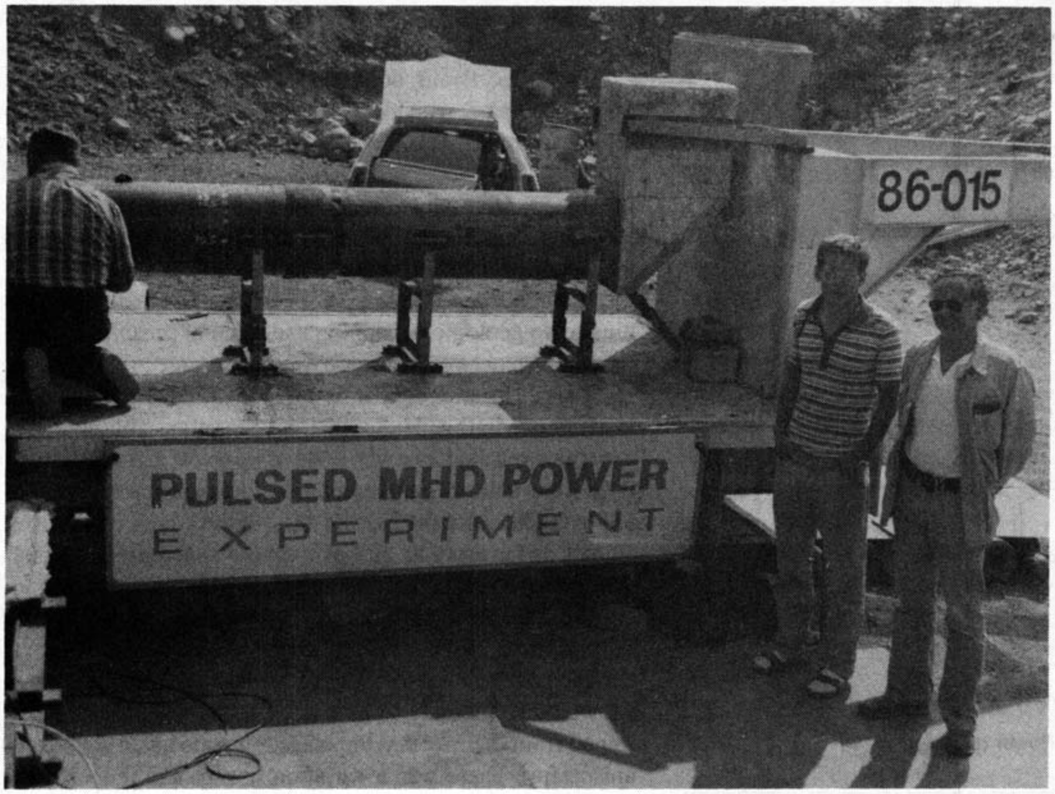
MHD technology is a good match as an energy source for laser weapons, because it can be a stand-alone pulsed-power generator independent of a central power grid, able to be located in remote areas. The electrically conducting fluid for this type of pulsed power generator is produced through the ignition of a solid fuel rocket engine. "It is quite possible to produce the pulse for a few seconds," Velikhov explained, "without any cooling" of the external magnets that surround the MHD channel. "And a few seconds is exactly the time of life of the magnetic fields which you want to have."

"We started with the idea of using this as the energy source" for weapons applications, Velikhov reported. He invited the audience to go to see the combustion chamber used to fuel a portable MHD generator which is in the Smithsonian's National Air and Space Museum in Washington. "It is the first stage of the SS-20 rocket," he said.

When the weapons applications were no longer on the agenda for the Soviet Union, Velikhov reported, "we did not know what to do with this, really." But years before, Soviet scientists had noticed "some sort of a natural coincidence. The same few seconds [needed for energizing a laser weapon] is the time of the propagation of a magnetic signal for a few kilometers through the Earth's crust." Soviet scientists, under Velikhov's guidance, had been experimenting using portable MHD generators for geophysical soundings since 1973.

"For 20 years I tried to convince Americans" to apply MHD technology to geophysics, Velikhov said, as he reviewed the two decades of research carried out in remote areas of the Soviet Union. He said that he was pleased to report that after 20 years, there was now, finally, a Russian Pamir MHD generator in the United States, which he hoped would not be used for weapons applications, "but to be used, as we try, in geophysics."

Although Velikhov's MHD generators have helped produce some impressive experimental results in geophysics over the past 20 years, he complained in his talk that the "geophysical community is extremely conservative" and pre-



In 1986, scientists from the Lawrence Berkeley Laboratory performed some preliminary geophysics experiments using this 5 MW portable MHD generator built by the STD Corp. On the right is the combustor, using a rocket engine. Attached to it, extending to the left, is the MHD channel which is surrounded inside by magnets.

fers to continue to use traditional time-tested techniques, rather than embark on a "new adventure."

The same has been the case, so far, in the United States, American MHD specialists report. Although there is now a Russian Pamir MHD generator in the United States, the Air Force, which paid for the system to be brought here, has no mission for using it.

MHD technology can be used for a wide range of applications, from baseload utility power generation to stand-alone pulsed power systems, materials processing, and space propulsion. The large-scale research efforts to develop MHD for electric utility use are at a standstill in both Russia and the United States. Smaller programs in other nations are likewise stymied.

MHD energy conversion is the basis for a family of technologies whose time has come. Direct conversion will be the technique of choice in the future for electricity production to replace century-old steam turbine technology. MHD opens the door to many special applications in energy production and use that are unique to this advanced plasma-based technology.

Velikhov's geophysics MHD generators

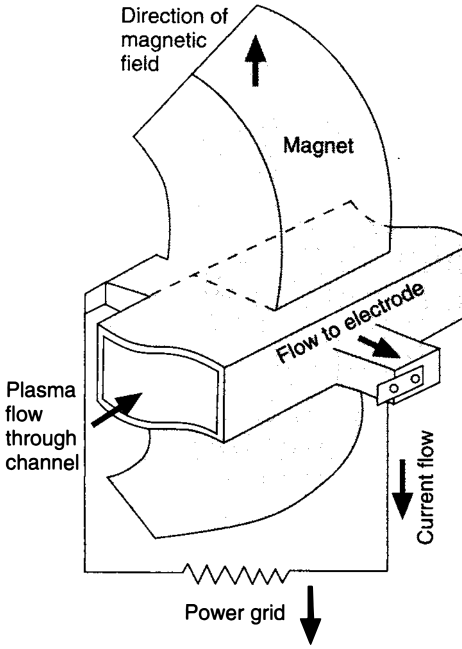
Over the past 20 years, Academician Velikhov has been in leading positions in the MHD, thermonuclear fusion, civilian and military laser, and advanced computer programs in the Soviet Union and Russia. He has played a leading role in science policy questions as an adviser to Presidents Mikhail Gorbachov and Boris Yeltsin, and has had the advantage of an overview of many of Russia's frontier technology projects.

Probing the crust of the Earth to determine its geological characteristics and structure in the past has depended, to a large extent, on studying the seismic waves produced during earthquakes. By measuring the rate of propagation and degree of deflection of seismic waves through layers of the crust produced by earthquakes or nuclear explosions, scientists can map the density and elasticity of the medium through which the waves travel.

But as Russian geophysicist B. Golitsyn remarked a number of years ago, earthquakes are like lanterns that illuminate the deep layers of the Earth just for an instant, and having to wait for earthquakes has obvious limitations. Furthermore, only the mechanical properties and elasticity of the material are illuminated through seismic waves, "appropriate for billiard balls, but not the Earth," another geophysicist has remarked.

In order to probe the remote areas of the Soviet Union, which are the normal foci for earthquakes, Velikhov developed his first-generation portable MHD generator, the Pamir, in the mid-1970s. The generator was developed jointly by the Institute for High Temperatures in Moscow and the Kurchatov Institue of Atomic Energy, which Velikhov heads today. In 1973, the generator was taken on its first trip to the

FIGURE 1
What is MHD?



Basic electrodynamics dictates that when a conductor is moved through a magnetic field in a perpendicular direction, an electrical current is created in the conductor. In MHD direct conversion, the moving conductor is the supersonic flow of an electrically conducting gas or liquid. The plasma gas flow can be made up of the combustion products of oil, coal, or gas. It can be a liquid metal that is heated by a nuclear fission reactor, or the plasma that is the fuel in a fusion reactor. As the diagram shows, electrodes placed along the side walls of the MHD channel, perpendicular to both the plasma flow and the direction of the magnetic field, are connected to the load that will utilize the power.

Pamir Mountains.

The Pamir-1 used solid rocket fuel to produce 15 MW of electrical power, in 1.5-second pulses. The 8.5-ton device was carried by truck into the Pamir Mountains and could register signals at a distance of about 20 km at a depth of about 20 km into the Earth's crust, through 3 km-long dipole cables (equally and oppositely charged) connected to the MHD channel's electrodes. The traditional approach to probing the depths of the crust has been to drill boreholes into it, a method which has a limit of about 8 km in depth. The early Pamir experiments transferred the pulses of power from the MHD generator to electrodes buried in the Earth.

One of the most important observations made during the early Pamir experiments was that about two months before an earthquake, the electrical conductivity of the Earth's crust apparently changes. This would clearly be enough warning time to evacuate or prepare populated areas for earthquakes.

The basic Pamir design was upgraded to the Pamir-2 MHD generator, which was taken to the Caspian Basin to do oil prospecting. The pulse length was increased to seven seconds, and over three seasons, several thousand square kilometers were electromagnetically mapped. These measurements produced the first complete geological data through the total thickness of the crust in that region. Velikhov announced in the early 1980s that the Soviets were planning to do geological mapping and mineral prospecting with the MHD generator in eastern Siberia.

Two years after the Pamir-1 experiments began, the Urals-series of MHD generators started operation. This upgraded generator reached a power level of up to 50 MW and scientists were able to penetrate to 40 km depth, which is the entire thickness of the Earth's crust in the Urals, and register signals as far away as 70 km from the source of the signal. The generator used an automobile engine to start the generator.

Scientists discovered a 100-fold increase in electrical conductivity at a depth between 35-40 km. Further analysis showed this anomaly to be a deep fault, which they determined from the fact that the measurements had a significant anisotropy: There was a variation in physical properties in different directions (north-south versus east-west). The data also indicated the locations of bodies of magnetic ores.

Experiments on the sea

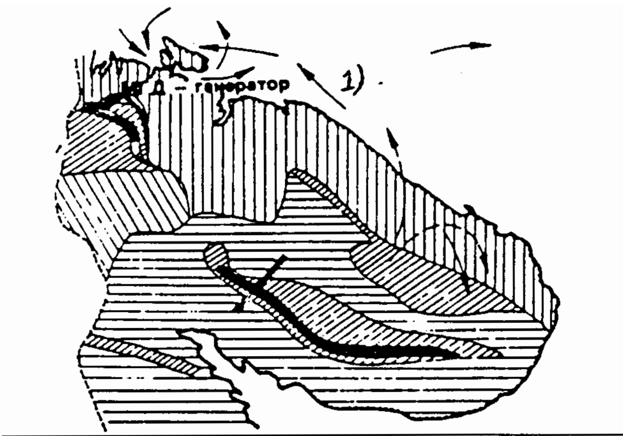
In 1980, the Soviets reported an interesting series of experiments, using their next-generation Khibiny MHD generator. This system was essentially two pairs of Ural-class portable generators. The power level reached 60 MW, the distance probed was extended an order of magnitude to 750 km, and the pulse length was seven seconds. One MHD channel producing electricity was used to keep the external magnets powered, and the second produced the power for each sounding pulse.

The Khibiny generator was taken to the Barents Sea, where its task was the mapping of the Kola Peninsula. Due to the proximity of the experiments to Finland, an agreement was reached with Finland's Academy of Sciences for joint mapping of the region.

Instead of laying down tons of aluminum cable to conduct the pulses of power, the scientists used the naturally conducting saline seawater as the "wave guide" for the pulses. The MHD generator was placed on an isthmus connecting the Sredny and Rybachy peninsulas with the main body of the Kola Peninsula, and the electrodes were placed in the sea. In order to carry the pulses from the generator to the sea, 160 tons of cable was laid, but the loop of water was able to cover an area of about 5,000 square kilometers. To cover such an area on dry land would have required 7,000 additional tons of aluminum loop.

FIGURE 2

Block structure of the upper 10 km layer of the Earth's crust of the Kola Peninsula, obtained by Soviet MHD probing



In a paper presented in 1986 at the Ninth International Conference on MHD in Tsukuba, Japan, Velikhov reported on the results of these experiments. Scientists measured discontinuities through the entire thickness of the Earth's crust. The upper layer, down to a depth of 10 km, had been believed to be composed of homogeneous rock with poor electrical conductivity. What they found was a dozen or so large blocks of rocks with electrical resistance varying by three orders of magnitude (see **Figure 2**).

Velikhov proposed that either there is mineralized water that filled the pore of the rocks, or that they are measuring the valence electrons of metallic ores. His conjecture is that these results indicate the presence of oil reserves in the Barents Sea shelf.

One of the goals of the Barents Sea experiments was to measure the effect of these artificial electromagnetic pulses on the Earth's electrically conductive ionosphere. In addition to having important military implications, in terms of disrupting communications, knowledge about this layer of atmospheric plasma has important contributions to make to the understanding of weather, climate, and the relationship between atmospheric and geophysical phenomena.

In the mid-1980s, Velikhov had envisioned developing a family of second-generation portable pulsed MHD systems to be formed into geophysical complexes to collect, process, and interpret a steady stream of data. **Table 1** indicates the variety of applications the Russians visualized.

While Velikhov was doing his work on MHD in the Soviet Union, the U.S. military became more interested in pulsed power after the announcement by President Reagan of the Strategic Defense Initiative in March 1983. There were obvious applications for this technology to geophysics.

U.S. pulsed power MHD

In 1986, three scientists at the Lawrence Berkeley Laboratory in California proposed that a 5 MW portable MHD generator built for the Naval Surface Weapons Laboratory by the STD Research Corp. be "borrowed" to conduct electromagnetic sounding experiments.

Prof. Frank Morrison, N.E. Goldstein, and Dr. George Kolstad pointed out that electrical conductivity is a valuable physical property of the Earth's crust related to temperature. It could yield information on the porosity of rocks, water content, and other parameters.

Their proposal to do such experiments was approved, and for the test, a loop antenna made of electrically insulated loops of conducting cable was used. The MHD generator sent pulses of electric power through the antenna, but the idea was not to transfer the electricity directly into the crust of the Earth. The pulses of power create magnetic fields each time the electrical flow is interrupted, and these magnetic fields induce eddy currents in the ground. The induced eddy currents, in turn, create their own magnetic fields. By measuring the rate of decay of the secondary magnetic fields below the loops using very sensitive magnetometers, computer-generated images of rock, structures, water, and fractures were produced, to depths of 10-20 km.

The working fluid through the MHD channel of the generator was solid rocket fuel with cesium added to increase the conductivity of the fluid. A bank of batteries was used to power up the magnet, creating a field in the magnet coils of 0.45 Tesla. When that field strength is reached, the combustor rocket engine is ignited and the initial electricity produced in the channel is fed back in to continue to power the coils.

The power to the magnets is turned off when they reach full strength and the electricity is fed into the loop antenna. This generator design is described as "self-excited," as increases in the magnetic field increases the electricity produced in the generator, and the power grows geometrically.

Morrison and his team took measurements at points 1.2 and 21 km from the center of the loop. The tests were primarily to match the MHD power supply with the electromagnetic sounding equipment, but one finding of the soundings was an indication of magnetic field changes suggesting a "lateral inhomogeneity," which may have been the San Andreas Fault, located only a few kilometers from one of the receivers.

In 1986, the SDI Office became interested in MHD, and after a competitive bidding process, STD won the contract in 1990 to build a 25 MW generator. STD estimated that their superior design would allow a machine that would be one-fifth the size of the Soviet MHD generator of comparable power level. Work on the generator began, but when the device was 90% completed, the Bush administration decided that, perhaps because of its "success" in the Gulf war, such advanced technologies were no longer needed. The funds to

TABLE 1
Pulsed MHD design parameters for geophysical exploration

Type of structure (geophysical task)	Char. depth (km)	Current pulse length (sec)	Required magnetic dipole ($A-m^2$)
Crust, platforms, and shields Investigation of deep geoelectric section)	30-100	0.1-10	3×10^{10} to 3×10^{12}
Mountain systems (ranges) (earthquake prediction)	15-30	0.1-10	3×10^{9} to 3×10^{10}
Sedimentary cover (structural oil prospecting)	3-8	1-20	10^{8} to 5×10^{9}
Ore-bearing regions (ore prospecting)	1-3	0.1-1	10^{6} to 5×10^{7}
Contintental shelves (mineral prospecting)	1-10	$1\text{-}10^{2}$	5×10^{7} to 10^{9}

complete the MHD generator were never procured.

The latest comer in the military to be interested in MHD is the U.S. Air Force.

Pamir comes to America

The fall of the Soviet Union has led to a standstill in many promising areas of research and development, including MHD. But over the past year, one of Velikhov's aspirations for helping to bolster the Russian program through international collaboration in MHD, and to broaden the base of support for this promising technology in the world scientific community, came to fruition, with the delivery of a Pamir MHD generator to the United States.

In the summer of 1992, the U.S. Air Force put out a request for proposals to industry for a pulsed MHD generator that would produce 15 MW of electricity in 6-10-second pulses. Textron Defense Systems proposed that rather than build an MHD generator, it contract with the Institute for High Temperatures in Moscow to build one to U.S. Air Force specifications. Textron had purchased the Avco Everett Research Laboratory in Massachusetts, which did pioneering research in MHD under the direction of Dr. Arthur Kantrowitz, starting in the 1960s.

After the fall of the Soviet Union, the U.S. military was very interested in acquiring advanced technologies from Russia that the United States had not invested the resources to develop. The Phillips Laboratory in Albuquerque, New Mexico, which was managing the MHD contract, was to manage half a dozen Soviet Topaz space nuclear reactors. The Topaz purchases were the precedent for Textron's proposal to buy a version of the Russian Pamir MHD generator.

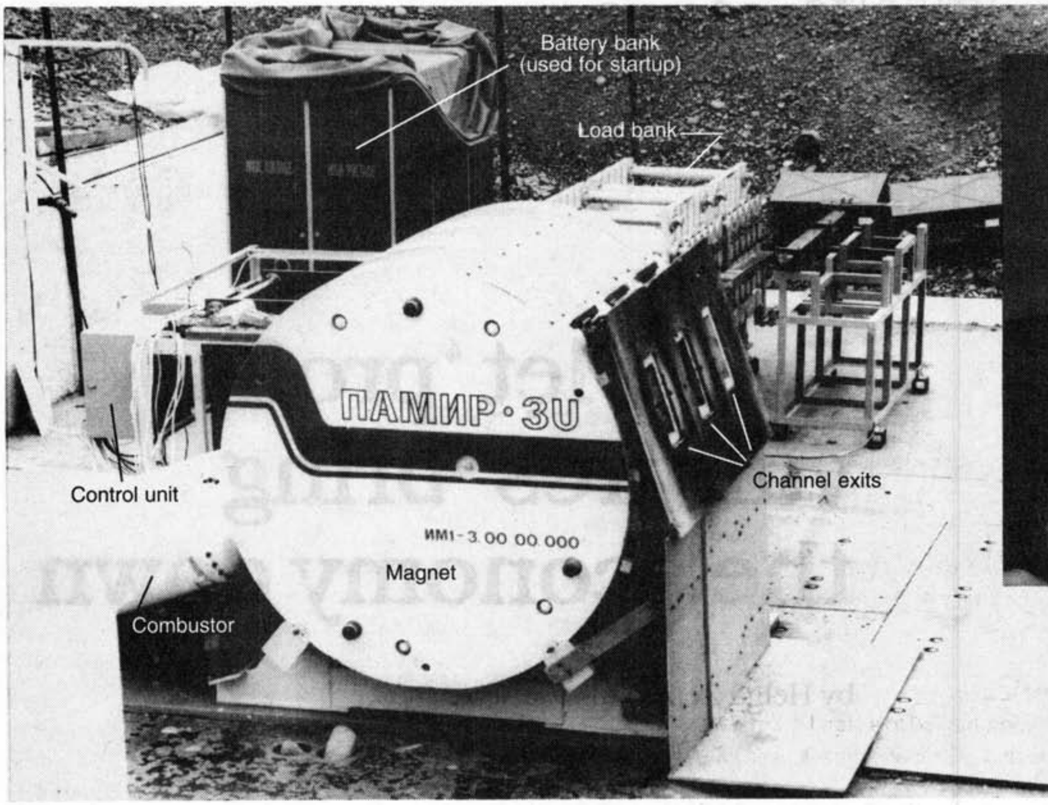
The work on the generator began in January 1993 in Moscow, with support work from the Nizhny Novgorod Machine Building Plant and the Lubertsy Scientific and Production Association Soyuz, both in Russia. The Pamir-3U went through initial testing in Russia in October 1994, and completed acceptance testing on March 1, 1995 at Aerojet Corp.'s facilities in California. It was transferred from the Air Force Matériel Command at Phillips to the rocket propulsion directorate at Edwards Air Force Base.

The Pamir-3U, now at Edwards Air Force Base, is an upgraded version of the early Pamir generator. The original Soviet design had three external magnets with two MHD channels in between. The Pamir-3U has four magnets and three channels, which increases the power generated. During the initial stage of powering up the generator, all three MHD channels supply power to the electromagnets. During operations, two of the MHD channels supply electrical power to the load put on the generator, and one to the magnet.

According to Dr. David Price, project officer for the MHD generator at the Phillips Laboratory, the Air Force wants to develop an in-house expertise in MHD technology. While he stated that the generator "would be a good power source for a ground-based laser," he reported that after two more tests are done at Edwards, "there is no planned follow-up experiment" for the Pamir-3U.

According to Dr. Price, the Russians are very eager to market this technology. At the acceptance test in California, the Russians commented that they are selling an MHD generator to the Japanese, who are interested in using it for geophysical research, particularly after the Kobe earthquake. His estimation is that the Russians may close the window of opportunity, in terms of exporting additional MHD technology, such as more advanced second- and third-generation devices, and he is concerned that expertise in this field in the United States could die because of political and budgetary considerations.

Now that the $4 million project of building and testing the generator is complete, Dr. Price said there is no funding in the budget for next year to use the MHD generator as a power source for any Defense Department experiments. According to scientists at Textron, the geophysics communi-



The Pamir-3U pulsed MHD generator built in Russia for the U.S. Air Force (inset: Academician E.P. Velikhov).

ty in the United States is just as conservative as that in Russia, and the company is still trying to find scientific applications for the technology, as is the Air Force. Geologists have told the MHD specialists that they can use less powerful pulses, for example, and employ sophisticated electronic techniques to increase the signal-to-noise ratio. But because there is a wealth of other geophysical applications for MHD, enthusiasts are still trying to interest the scientific community.

In the 1960s, American scientists pioneered this new application for plasma physics, MHD. In the 1970s, Soviet scientists were actively trying to develop and apply a similar line of emerging technologies to primarily defense missions. After signing the Anti-Ballistic Missile Treaty in 1969, the United States decided that it would not deploy or even develop a defense against nuclear weapons.

After the Soviet Union fell, Russia found that it could no longer support even its premier scientific institutions, while following the dictates of the International Monetary Fund's shock therapy. So the United States went on what has been described as a high-technology "shopping spree." This approach is a multi-edged sword. If it is done to buy advanced technologies from the Russians on the cheap, because we will not allocate the funds to make advances ourselves, we are not doing ourselves any real favor. We are also sending our scientists and engineers to the unemployment line.

Such purchases may temporarily financially stabilize the institutes of the Russian Academy of Sciences, but are no long-range solution to Russia's economic crisis.

In his speech to the American Physical Society, Velikhov outlined other areas of potential scientific cooperation. These included joint experiments in thermonuclear fusion energy, some of which are already under way, and an intriguing proposal to use formerly nuclear-armed submarines for undersea exploitation of oil and gas reserves.

Velikhov stated that the Kurchatov Institute, which he now directs, by tradition not only introduced new technologies, but "organized very efficient mass production of [weapons systems such as] nuclear submarines." With the Cold War over, the Russians plan to destroy 150 subs, he said. "Many of them were already sitting on the beach, and I hope we will never need to build them again. The problem is, what to do with this industry, which provides 150,000 jobs?"

Velikhov reported that three years ago, scientists at the Kurchatov Institute applied to the government to convert the submarine industry to production of offshore platforms. They have completed two structures, in cooperation with an Australian company, and have developed drilling techniques that can be used under ice.

As Velikhov outlined, there are many examples of Cold War technology that can be adapted for purposes of economic development. But for that to come to fruition, the guiding policy must be vectored toward economic development.