MHD pulsed power for geophysics and the SDI

Recent geophysical experiments using pulsed MHD generators indicate that the United States is finally attempting to catch up to the Soviets in this crucial SDI technology. Marsha Freeman reports.

This past September, a series of preliminary geophysical experiments took place near Los Angeles, California using a portable MHD (magnetohydrodynamic) generator. This system delivers a short pulse of electromagnetic energy which can potentially be used to map the geological structures of the Earth, find bodies of ore, and help in predicting earthquakes.

MHD technology applied to electromagnetic soundings of the Earth has just had its first trial run in the United States. The same MHD application, however, has been in use since 1973 in the Soviet Union. Academician E.P. Velikhov—the head of the Soviet magnetic fusion program, military and civilian laser development efforts, the MHD program, and work in computers—pioneered in the development of this advanced energy conversion technology, and has overseen geophysical experiments in the Soviet Union for more than a decade.

From the beginning of the Soviet program, however, it was clear to astute observers that this high-powered source of energy could be scaled up and used for more than scientific investigation. As the spokesman for the Soviets' supposedly nonexistent strategic defense effort—what is called the Strategic Defense Initiative (SDI) in the United States—one would assume that Velikhov has also been in charge of developing this technology for powering lasers, particle beams, and other SDI-related systems which will require very short bursts of very powerful energy.

According to the 1986 version of the annual book, *Soviet Military Power*, published by the U.S. Department of Defense, the Soviets "have developed a rocket-driven magnetohydrodynamic generator which produces over 15 megawatts of electric power—a device that has no counterpart in the West."

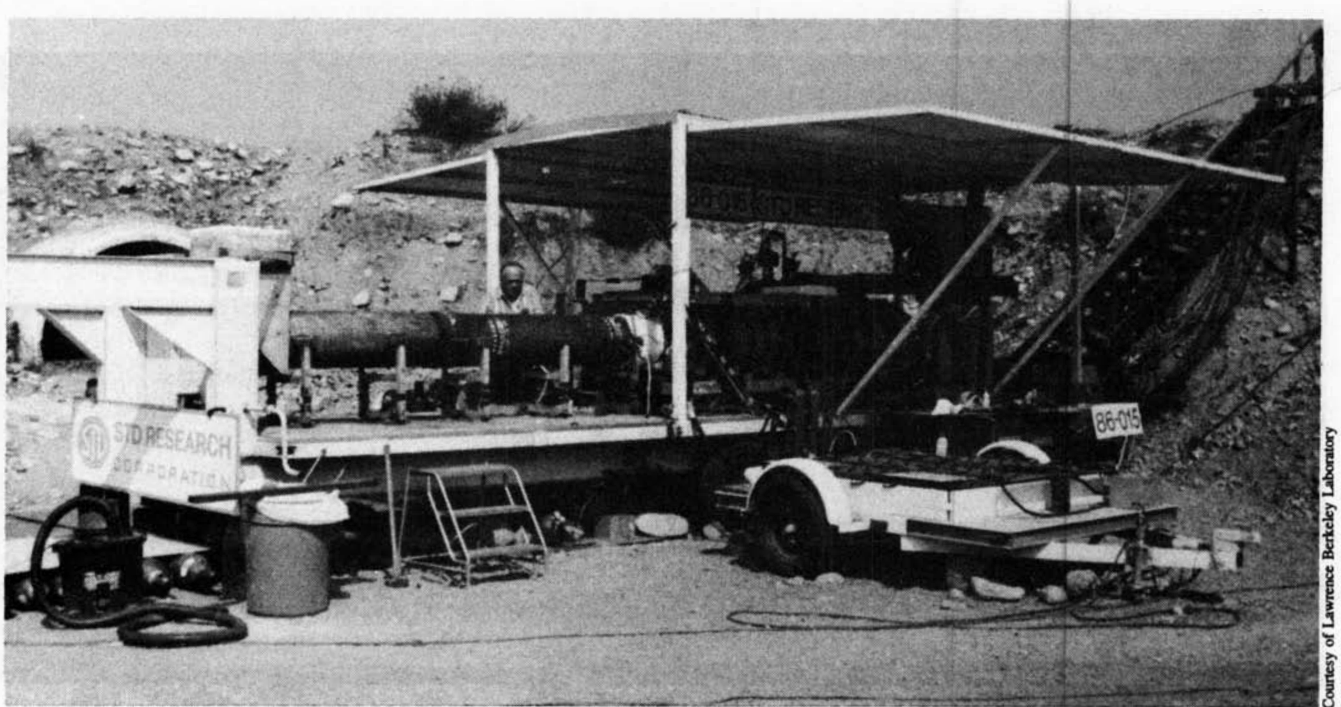
One can assume, however, that the United States is indeed finally developing this important pulsed-power energy technology, as indicated by the scientific tests done in California recently. This interest is also indicated by the fact that a representative of the SDI Organization office chaired one of the technical sessions at the 24th Symposium on Engineering Aspects of Magnetohydrodynamics, held in June 1986 in Butte, Montana.

MHD for geophysical research

MHD will be the energy conversion technology of choice in the future, because it converts the products of fossil fuel combustion, nuclear fission reactions, or thermonuclear fusion directly into electricity, without any intermediate steam turbine cycle. There are no moving parts in an MHD generator, except the flow of the plasma, or charged particles, as a working fluid.

The fundamental concept involved, is to move an electrically conducting gas or liquid through a stationary magnetic field. The positively and negatively charged ions in the plasma are separated by the magnetic field, and create an electrical potential across the channel containing the plasma flow. Electrodes on the channel walls are attached to a load, which can be a utility power grid, or any device requiring electricity (see box).

Experimental work on developing MHD technology began in the United States in the mid-1960s, concentrating mainly on the use of plentiful coal in this clean, economical, efficient conversion process. The potential of MHD in large-



The MHD pulsed power source used in the Berkeley tests: The combustor or rocket engine is at the left; at the right is the MHD channel, surrounded by circular magnets.

scale utility application is to double the efficiency of fuel-to-electricity conversion, from today's 35% maximum in commercial power plants. But there are also specialized uses of this compact, energy-dense, efficient conversion technology.

Because the MHD process does not require water to make steam, huge rotating turbines, or any moving parts, it is ideal as a portable power supply. For years, geologists have been probing the depths of the Earth by drilling boreholes into the crust, in order to measure movements and predict earthquakes. These holes are limited to a depth of about 8 kilometers (km).

Russian geophysicist B. Golitsyn stated years ago that though earthquakes are like lanterns that illuminate the deep layers of the Earth for an instant, during which it is possible to study the propagation of oscillations through the crust, waiting for earthquakes has obvious limitations.

Scientists have tried to study seismic waves for earthquake prediction, but these carry information only on the elasticity and mechanical properties of the material—"appropriate for billiard balls, but not the Earth," as one Soviet scientist remarked.

It has been generally known that electromagnetic sounding methods would yield additional information about the Earth's crust, by "poking" the depths with an electrical current or field. But since earthquake zones are usually located far from settled areas and power lines, stand-alone power supplies are required.

In May 1986, Prof. Frank Morrison, N.E. Goldstein, and Dr. George Kolstad from the Lawrence Berkeley Laboratory in California, proposed that a portable, 5-megawatt (MW) generator, built and tested by STD Research Corporation for the Naval Surface Weapons Laboratory, be "borrowed" to conduct the first U.S. electromagnetic soundings in geophysics research.

The scientists pointed to the considerable Soviet success in using this MHD technology and stated, "Electrical conductivity is a valuable physical property in the study of the Earth's crust." Existing field measurements "have shown that there are many zones within the crust where the conductivity is much higher than predicted" by contemporary geophysical theories, they pointed out.

Conductivity is strongly related to temperature, and can yield information on the porosity of the rocks, water content, and other parameters. The U.S. scientists pointed to the long history of the application of electromagnetic soundings in the Soviet Union, also for oil exploration.

The basic design of the experiment was to lay down electrically insulated loops of conducting cable, through which the MHD generator would send a pulse of power. The idea was not to transfer the electrical energy directly into the Earth's crust, but induce eddy currents in the ground, produced by the magnetic field created by the loop.

The magnetic field is produced when the current in the conducting loop is interrupted, which is why the electrical energy must be pulsed (turned on and off). The induced eddy currents, in turn, create their own magnetic fields in the Earth. By measuring the rate of decay of the secondary magnetic fields below the loops with very sensitive magnetometers, computer-generated "pictures" of rock structures, water, and fractures can be produced, to depths of 10 to 20 km.

The loop antenna used with the 5-MW MHD generator

E.P. Velikhov

The Soviet Pamir MHD generator. Included in this photograph are the generator, the condensers, and other pieces of equipment on site in the Pamir Mountains. The MHD generator was moved by truck to various places in the mountains to do electromagnetic soundings for earthquake prediction.

in this experiment was 200 meters by 250 meters, whereas with conventional sources of lower power, loops of one kilometer diameter are able to produce data. Morrison and his team took measurements at points 1.2 and 21 km from the center of the loop. With an operational system, scientists would take soundings every 2-3 km, moving the loop and generator, to produce a composite picture of an area.

The plasma working fluid for this MHD generator is a solid rocket fuel with cesium added, to increase the conductivity. Though up to 10 pulses could be derived with a single fuel load, in this experiment, only 2 pulses were fired. In order to produce the electrical power, the magnets surrounding the generator must be powered up first, which was accomplished with a bank of batteries.

The batteries create an initial magnetic field in the coils of .45 Tesla, and, at that point, the combustor rocket engine is ignited and the initial electricity from the MHD generator is fed back into the coils. The power to the magnets is shut off when they reach full strength, and the electricity produced is then fed into the loop. This kind of generator, pioneered by the Soviets, is described as "self-excited," as the strengthened magnetic field increases the electricity produced in the generator, and the power grows geometrically.

Professor Morrison described the recent tests in California as "engineering tests." The goal was to match the MHD power supply with the electromagnetic sounding equipment. The pulse length was about two seconds, and since it was the performance of the system that was being tested, there was no attempt to try "shots" repetitively.

One finding of this first series of soundings, was an indication of magnetic field changes suggesting a nearby "lateral inhomogeneity," which was possibly the San Andreas Fault, located only a few kilometers away from one of the receiver sites. The scientists hope to secure additional funding from the U.S. Department of Energy to conduct further soundings, using the portable MHD generators to "piggy-back" the development work that is being done for the Navy and the SDI.

The early Soviet program

In 1975, Academician E.P. Velikhov produced a scientific paper, presented at the International Conference on Magnetohydrodynamic Electric Power Generation in Washington, D.C. in 1979, which was the first detailed description of his portable MHD experiments.

The Soviets have developed three portable MHD generator designs, the Pamir, Urals, and Khibiny devices (**Table 1**). The basic design of the first generator, the Pamir, was the model for the STD machines in the United States. Using solid rocket fuel, the Pamir-1 generated up to 15 MW of power, and was carried on the back of a truck to various sounding sites in the Pamir Mountains. It was started by a bank of capacitors carried along. Because the pulse length of the Pamir-1 was only a couple of seconds, the device did not have to be artificially cooled, as it cooled off between pulses. The generator weighs about 8.5 tons, most of which is the copper magnet around the channel.

It could register signals about 20 km distant, at a depth of about 20 km into the Earth's crust. The pulse length was about 1.5 seconds and the dipole cables (equally and oppositely charged) connected to the MHD channel's electrodes,

TABLE 1
Major operational portable Soviet MHD machines

	Pamir	Urals	Khibiny
Power level (MW)	10-15	50	60
Distance probed (km)	20-40	70	750
Depth probed (km)	20	40	70
Mag. moment ($A-m^2$)*	4×10^6	4×10^{10}	10^{14}
Pulse length (sec)	1.5	3	7

The magnetic moment, which is one measure of magnetic field strength, is measured in Amp-meters squared.

were 3 km long. According to Velikhov, the data collected by the Pamir would be equivalent to taking readings for three hours with a continuous power source of 10 kilowatts.

One significant difference between the U.S. and earlier Soviet designs, was that the Velikhov generators pulsed their power directly to electrodes buried in the Earth. These aluminum plates transferred the pulse into the crust, but according to Morrison, chemical reactions from the surface of aluminum in the soil are also transferred into the ground. Different fields are measured in the two techniques, and in the Soviet design, the electrical fields are from the current "running away" from the electrode, not from secondary magnetic fields.

The development of the Pamir was a joint effort between the Institute for High Temperatures and the Kurchatov Institute of Atomic Energy in Moscow. In 1973, the MHD generator left Moscow, in the possession of the Institute of Physics of the Earth of the Soviet Academy of Sciences, and journeyed to the mountains to begin a series of experiments.

One of the most important observations made during the early Pamir experiments, is that about two months before an earthquake, the electrical conductivity of the Earth's crust changes. This would clearly be enough warning time to evacuate population and prevent major damage.

According to Soviet computations, 30 to 50 such portable MHD sounding units could adequately cover all of the seismically active regions of the Soviet Union. They would be linked together by a computer bank to process the recordings of a network of receivers, and monitor changes, as they occur.

The basic Pamir design was used later in the upgraded Pamir-2, 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.

Recently, Velikhov announced that during the early 1980s, the Pamir-2 was in Central Asia and detected anomalies at a depth of 60 km. He stated that the Soviets are planning to take it to eastern Siberia to do geologic mapping there.

Two years after the Pamir-1 experiments began, the Urals-series generators started operations. The Urals generator represented a significant increase in capability, reaching a power level of 50 MW. Scientists were able to penetrate 40 km, which is the entire thickness of the Earth's crust in the Urals, and register signals as far away from the source as 70 km. The generator was started with an automobile engine and made use of an aluminum dipole that weighed 40 tons.

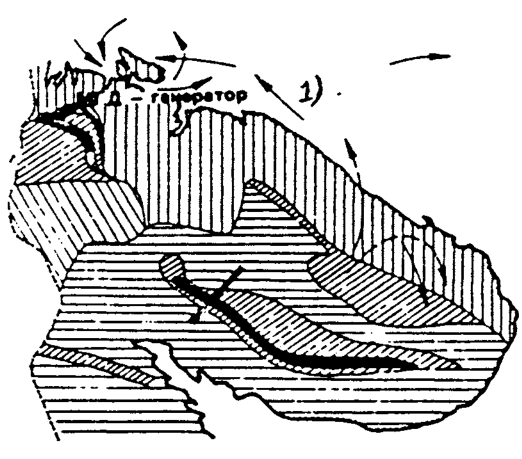
Scientists found a 100-fold decrease in electrical conductivity at a depth of between 35-40 km. Analysis showed this anomaly to be a deep fault, which was discerned by the fact that the different conductivity measurements had a significant anisotropy. This means that there was a variation in physical properties in different directions (north-south versus east-west). The data also indicated the locations of magnetic ore bodies, which could be further explored for exploitation.

Experiments on the sea

In 1980, the Soviets first reported a most interesting series of experiments, using their Khibiny generator. This system was a set of two pairs of Ural-class portable MHD generators. One MHD channel powers the two electromagnets (one for each channel), and the other channel produces the power for the pulses.

The power of the Khibiny device was 60 MW, and produced an unprecedentedly high magnetic field, which was able to extend its reach up to 750 km from the source. The Khibiny was taken to the Barents Sea, where mapping of the Kola Peninsula was the task. Due to the proximity to Finland,

FIGURE 1
Block structure of the upper 10 km layer of the earth's crust of the Kola Peninsula, obtained by Soviet MHD probing
1) MHD generator



an agreement was reached with the Finland Academy of Sciences, for joint mapping of the region.

Instead of laying down tons of aluminum cable to conduct the pulse of power, scientists used the saline, electrically conducting sea water as the "wave guide" for the experiments. 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 current from the generator to the sea, 160 tons of cable was laid, but the water loop was able to cover an area of about 5,000 square kilometers, which would have required 7,000 tons of additional aluminum loop, if the sea were not there.

Singularities were measured through the entire thickness of the crust. In a 1986 paper presented at the 9th International Conference on MHD in Tsukuba, Japan, Velikhov gave an overview of the experiments. They first studied the upper layer of the crust (10 km deep), which was believed to be made of homogeneous rock with poor electrical conductivity. They actually found a dozen or so large blocks of rocks with differing electrical resistance, varying by three orders of magnitude (1,000-fold) (**Figure 1**).

There are two theories, according to Velikhov, that could explain zones that recorded high levels of conductivity. One is that there is mineralized water that has filled the pores of the rocks, and the other is that the valence electrons of metallic ores is being measured.

His conjecture is that in the Barents Sea shelf, this sedimentary layer with high conductivity areas, could indicate the presence of oil reserves. The Khibiny apparatus has been designed for years of experiments, according to Velikhov, and the data will be compared to the Kola superdeep borehole.

One goal of the experiments was to measure the effect of these artificial electromagnetic pulses on the Earth's ionosphere. This could have important military implications. The electrically conducting ionosphere, is an integrally connected plasma. Perturbations emanating from one region, for example, in the Soviet Union, propagate around the entire globe extremely quickly.

If the Soviets have experimentally determined the effect on the ionosphere of an electromagnetic pulse from their device, they can create a planned disturbance, and be prepared with alternate ways of communicating across the country, and with their satellites in orbit. They might, for example, switch from regular microwave communications, to infrared, or another wavelength that could penetrate the disturbed ionosphere. Such disruptions could be used to cripple the capability of an adversary, and knock out his ability to have any use of intelligence or reconnaissance satellites in orbit.

Second-generation systems

Velikhov and his colleagues have big plans for their portable MHD technology, and research and development work is continuing to produce a series of second-generation systems. Each model type will be tailored for specific geological and other tasks, using various pulse lengths, power output, materials, fuel types, and magnet systems. Velikhov has stated that this tremendous geophysical capability will require "the early creation of a new generation of specialized

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 figure 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.

Basic MHD concept

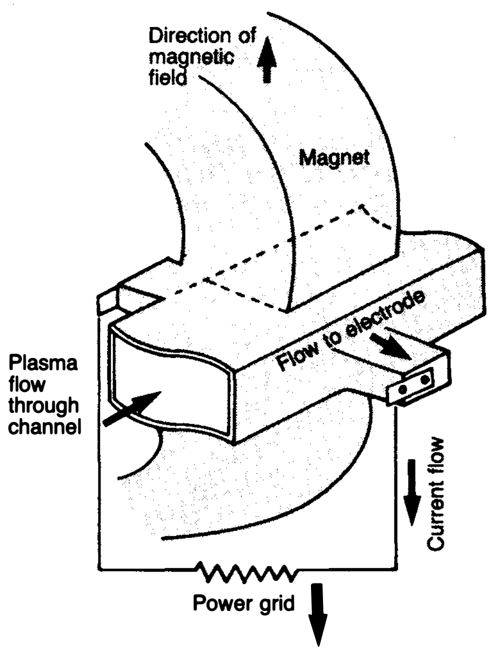


TABLE 2
Pulsed MHD design parameters for geophysical exploration

Type of structure (geophysical task)	Char. depth (km)	Current pulse length (sec)	Required magnetic dipole (A–m²)
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}
Continental shelves (mineral prospecting)	1-10	1-10^2	5×10^{7} to 10^{9}

geophysical complexes" to process and interpret the data.

Soviet scientists have determined the MHD generator characteristics required for various geophysical experiments (**Table 2**). A comprehensive theoretical and experimental research effort has been under way to solve the engineering problems associated with producing this full range of devices.

One of the changes made over the 15 years of development work, was to introduce diagonal channel electrode designs, in addition to the original segmented electrode generators (**Figure 2**). This has enabled a closer matching between the current produced in the channel and the electrical characteristics of the current-carrying cables.

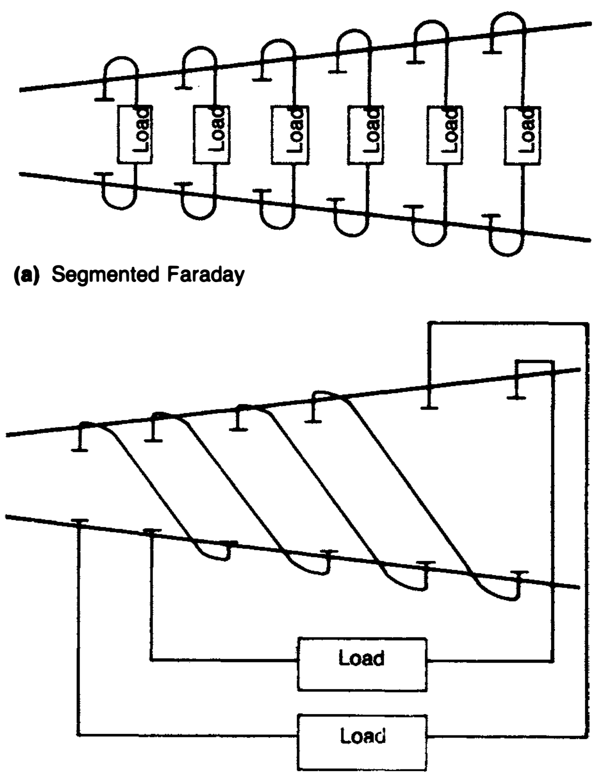
One U.S. scientist reported after a 1983 trip to Moscow for the 8th International MHD Conference: "My work is much more appreciated in the Soviet Union than in the United States. They were the first to recognize our work and the advantage of the diagonal conducting wall generators."

There has also been vigorous research under way to produce more efficient fuels. The first portable MHD generators made use of the solid fuel used in the space program, for solid booster engines with the same disadvantages. The amount of fuel is set per shot, and cannot be varied or shut off once it is ignited. The power cannot be controlled in these fuels, the cost is high, and they are dangerous.

Experiments at the Kurchatov Institute have used coal or other carbon-based fuel powders with aluminum added for increased energy density. Tests have shown that if the aluminum content is 50% of the fuel, less oxidant is needed for combustion, and the burn produces more total energy. Powdered salts of potassium or cesium, up to 10% of the total weight, are also added, to increase the conductivity of the combustion products or plasma.

The powdered carbon fuels are less expensive, are easily manufactured, explosive-proof, harmless to personnel, and work over a wide range of operating temperatures. In addition, oxygen can be directed into the fuel flow more easily—much superior to burning in air—and the oxidant-to-fuel ratio can be varied. The electrical conductivity with this fuel mixture is four orders of magnitude (10,000 times) greater than conventional solid fuels.

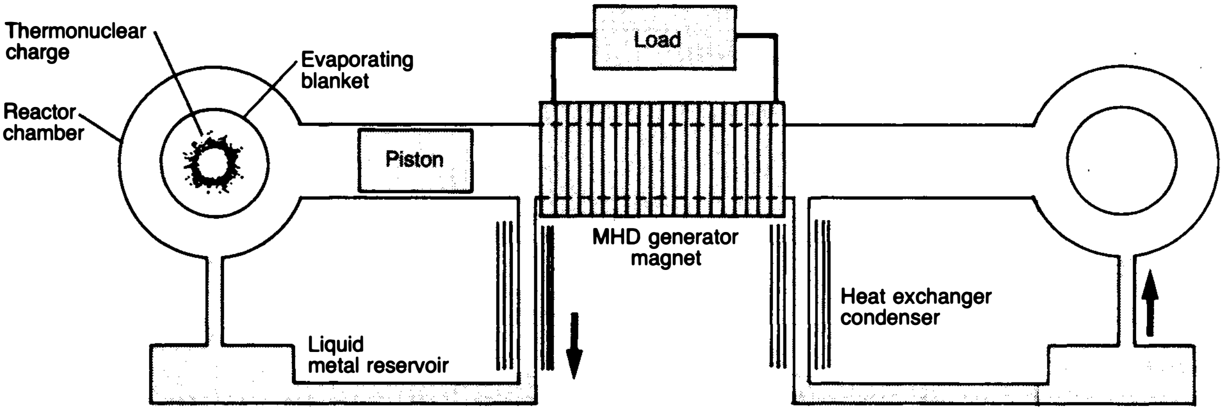
FIGURE 2
Various MHD generator electrode configurations



(a) Segmented Faraday

(b) Diagonal Faraday

FIGURE 3
MHD generator for pulsed thermonuclear reactions



In order to meet the needs of certain geophysical objectives, there are pulsed MHD devices being tested with longer pulse lengths and pulse shaping. One way to reduce the weight and cost of longer-pulsed, higher-powered systems, is to go from copper to iron core magnets, which require longer excitation time. It has been estimated that this can reduce costs fourfold.

However, one major problem in going to longer pulse lengths is the overheating of the channel and the magnets. The Prognoz MHD model generator, at the Institute for High Temperatures, has extended pulse lengths to 100 seconds, by using a water-cooled channel. It is designed for repeated pulsing and builds on research conducted on water-cooled channels since the 1970s, on the large U-25 generator at the Institute.

MHD systems of the multi-hundred megawatt power level will require superconducting magnet systems, where the material does not waste energy by dissipating heat, and is kept at a temperature near absolute zero using liquid helium. Such superconducting magnets are also needed in large base-load MHD power plants and for thermonuclear fusion plants.

From now through 1988, tests are being done on the Probe-1 generator, which uses superconducting magnets. Though Velikhov has admitted that it is a difficult challenge to make a portable superconducting system, the Soviets are committed to developing one. Since 1973, the Kurchatov Institute has built three superconducting magnets for pulsed MHD generators, each with different magnet geometries.

At the Tsukuba conference, Velikhov announced that a new and larger, mobile 25-MW pulsed MHD unit is being designed. Two explosive MHD pulsed generators are also being developed, with rapid repetition rates. (More will be said about explosive MHD below.)

The Zond-1 laboratory MHD generator is doing tests on the problem of the breakdown of electrodes in the MHD channel, and theoretical experiments are being conducted to measure the effects of shock waves and instabilities in the plasma, and to develop new materials.

A new-generation Pamir-4 generator is being developed to incorporate the developments in fuel mixture, iron-core magnets, and other advances, and it is being optimized to do oil and gas prospecting. Costs have been reduced 15-20% in this second-generation machine.

Pulsed MHD generators in the Soviet Union have become an accepted tool in the exploration for natural resources, and for geological surveys and earthquake prediction. The same basic technology that can be used in portable form for exploring, can also be used in both mobile and stationary form, for the SDI.

Military MHD applications

In the 1974 issue of *Atomnaya Energiya,* Velikhov authored an article titled "MHD Conversion of Energy From Pulsed Thermonuclear Reactors." The paper outlines a number of possible configurations for producing gigawatt-scale microsecond pulses of power from a fusion reaction, using MHD direct conversion. There is no question that the most important application for this capability is related to strategic defense.

In Velikhov's design, the amount of energy released in the thermonuclear explosion is approximately 10 billion to 1 trillion joules, or the equivalent of 2.5 to 250 tons of TNT. The pulse produced in this system would be about 10 gigawatts. No one can argue that this is intended for a city power grid.

In the "dumbbell" system (**Figure 3**) two explosion chambers are separated by a solenoid. The nuclear charge (fuel) is surrounded by an evaporating blanket made of an easily ionized material, such as lithium, potassium, or sodium. This blanket is vaporized by the fusion reaction, and pushes a metal piston past the solenoid to the other reaction chamber.

The kinetic energy of the moving piston is transferred into electrical energy, which is drawn off through a load attached to the solenoid. A second fusion reaction in the opposite chamber sends the piston back to the first chamber. This is a closed-cycle system, where the cooled liquid metal vapor is collected, condensed, and recycled through the liquid metal reservoir back into the reactor blanket to be revaporized.

This type of pulsed fusion MHD system is clearly not portable, and would most likely be an underground facility. Such 10-15 GW pulsed devices, with rapid repetition rates, would be the ground-based cornerstone of an anti-missile defense system. They could be deployed in the regions of the Soviet Union which are targeted by U.S. intercontinental ballistic missiles, and used as a terminal defense.

They could power various wavelength laser systems, to blind or knock out satellites in orbit as they cross over the path of the laser. They also could power next-generation ABM defense and perhaps disrupt the ionosphere, as Velikhov mentioned recently.

In 1977, retiring U.S. Air Force Intelligence chief Gen. George Keegan stated that there was evidence that the Soviets were developing beam-defense capabilities, and that they could "Sputnik" the United States in this field. The question then was, and still is, "Is the United States catching up?"

U.S. military MHD applications

Since the dawn of MHD research in the 1960s, the Soviets have not been the only ones who recognized the potential of MHD technology for weapons and defense systems. In 1968, a team of scientists at the University of Tennessee Space Institute in Tullahoma, worked on experimental diagonal wall MHD generator designs, under the auspices of the Aero Propulsion Laboratory at Wright-Patterson Air Force Base in Ohio.

Experiments were conducted using solid rocket motors as combustors, to study the conductivity and other characteristics of the working fluid in the generator. By the early 1970s, due to the ABM Treaty and other détente-era machinations, the military "lost interest" in persuing this research. Of course, this standdown in research occurred only on the U.S. side of the treaties.

More recently, even as interest in this area was resurrected by the current SDI program, the effort has still not been supported on the serious, crash basis that is required.

In the April 1984 issue of *Defense Electronics,* Dr. Steven Gill reported that his company, Artec Associates, had developed and tested a new pulsed plasma magnetohydrodynamic (PPMHD) technology that converted the chemical energy of an explosive cartridge directly into pulsed electrical energy.

Unlike the multi-ton rocket-powered devices developed by Velikhov and the STD Research Corporation, the Artec equipment used ordnance-related components, operated much like a gun. It is fired, reloaded, and fired again. Gill stated that rates of up to 100 pulses per second appeared feasible.

Tests done produced over 10 GW of electrical power and 500 kilojoules of energy from an experimental cartridge only 7 inches wide and 17 inches long. The fuel used was Octol, which is a typical military explosive. The entire power production process required only 200 microseconds.

In 1984, the PPMHD system successfully completed the advanced research stage, under Defense Department funding, and was ready for testing and development. However, according to Gill, "progress is slow" in terms of getting support from the government.

Artec could not wait for the Defense Department to decide to continue funding, and has since become Magnetic Pulse, Inc., developing a scaled-down version of the PPMHD for commercial applications.

Magnetic Pulse, Inc. developed a system to pump 100-microsecond pulses, at a power level of 100 MW, into wells that have been drilled for oil. Conventional drilling techniques will not give the explorer a horizontal picture of possible oil reserves far from the drilled hole—only a vertical picture of the Earth's layers is possible.

With the PPMHD system, a 100-meter cross section picture can be produced, which provides a three-dimensional map of the area around the drilled hole. The very short pulse restricts the use of the explosive cartridge technology to small areas, unlike the longer-pulse portable Soviet MHD generators, which are used mainly to locate large structures and ore bodies. One shot from the PPMHD system is needed every 30-40 meters to map a large area, to determine whether there is oil and gas, and how much.

Gill believes the Soviets are working on a gigawatt-scale pulsed MHD device, and feels that though there are still engineering and development problems to solve for military application of his PPMHD system, a 50-GW military unit is possible. At lower power levels, the cartridge design makes it a good tactical weapon that would produce an electromagnetic pulse that could disrupt aircraft, communications, and electronics.

No one has doubted that the Soviets, who have had an uninterrupted 20-year MHD program, are serious about developing this technology—for both commercial and military applications. They may be behind schedule in their planned power plant facility, but at least they are building one.

Like the civilian space program, and every other frontier technology area, the United States, which has been asleep, could certainly outrun the lumbering Soviet bear, if it decides to get up. As Defense Secretary Weinberger and CIA deputy director Gates have amply pointed out over the past six months, as things stand now, the Soviets have a much more advanced, and more serious, SDI effort than the United States does.

The U.S. scientific community pioneered MHD research, going back decades. Now we must start using this accumulated expertise and experimental facilities for commercial power systems, SDI, and scientific investigation.