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22268

CIA|SW |84-10011 X

Soviet High-Pressure Physics Research and Applications

Scientific and Technical
Intelligence Report

CIA HISTORICAL REVIEW PROGRAM
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23

SW 84-10011X
February 1984

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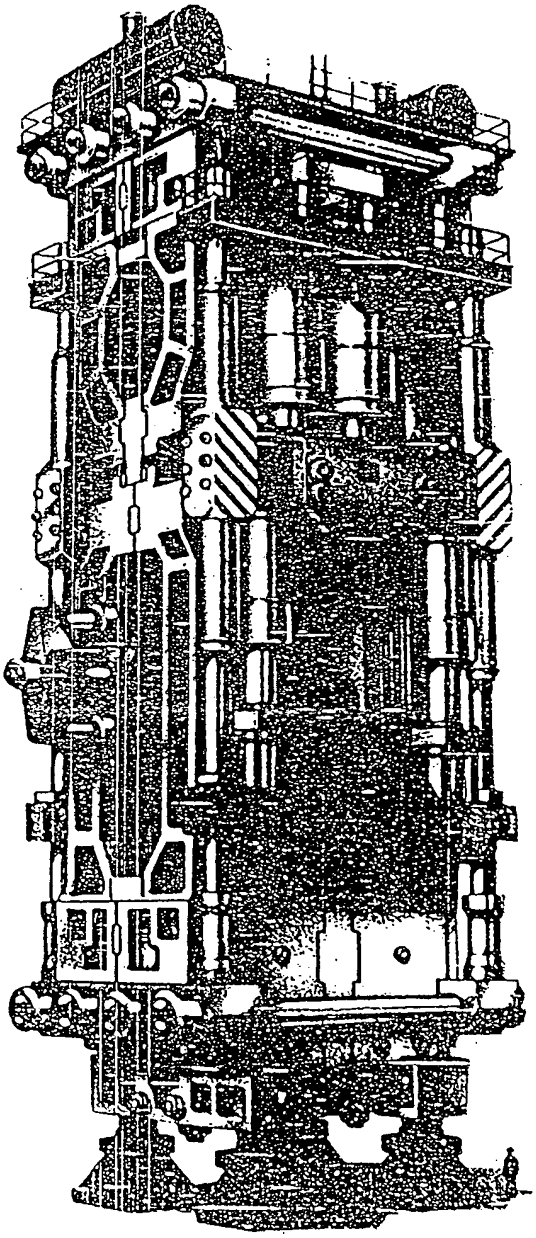
Figure 1. Soviet artist's drawing of a 65,000-ton press built for export to France. The 50,000-ton research press at the Institute of High-Pressure Physics (IFVD) apparently is almost identical to the press shown here (note figure for scale). The IFVD press took a decade to build. Its original purpose was to produce metallic hydrogen; that project has failed. The press has turned out to be a white elephant, and all plans to procure a still-larger successor press have been quietly dropped



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Soviet High-Pressure Physics Research and Applications

Key Judgments

Information available as of 1 December 1983 was used in this report.

High-pressure physics is the study of matter under pressures of thousands or millions of atmospheres. There are two classes of techniques for generating these high pressures. A sample of material can be placed in a press that uses hard anvils to concentrate force on a small area (see figure 1). Because the pressure can be maintained on the sample indefinitely, this technique is termed static. Typically, high static pressures range from thousands of atmospheres to just over 1 million atmospheres. Properties of matter such as density, crystal structure, and conductivity change significantly under pressure. High static pressures are used to create synthetic diamond, superhard boron nitride, and other important industrial materials

High pressures can also be achieved by subjecting a sample to shock waves created by chemical or nuclear explosions or by abrupt impacts of bodies. Shock waves can produce pressure of many millions of atmospheres for a few milliseconds, accompanied by temperatures of several thousand degrees Celsius. This class of high-pressure techniques is termed dynamic. Dynamic high-pressure physics research is important in the design of chemical and nuclear explosive devices and in the production of weapons to penetrate modern armor systems.

We believe Soviet research in dynamic high-pressure physics is strong, ahead of the West in many fields. Our judgment is formed primarily from analysis of open-literature publications by Soviet scientists [ ]Among the Soviet strong points are experimental shock-wave studies of material properties, research on materials synthesis using shock waves, and applications of explosive welding, forming, and hardening. Much of the Soviet research is oriented toward military applications, in particular armor/antiarmor

The USSR is strong in laboratory research on explosive materials processing but has had difficulty translating research results into industrial application. Quality control problems and a lack of incentives for industry to adopt new production technologies are the chief reasons for this difficulty. A shortage of large-scale scientific computers has slowed Soviet progress in theoretical dynamic high-pressure physics. Soviet scientific computing facilities, however, are improving gradually, and Soviet scientists are taking advantage of Western computer software

In contrast to their strength in dynamic high-pressure physics research, we believe the Soviets' research in static high-pressure physics lags Western research by several years. In particular, a large Soviet investment in massive experimental apparatus has not paid off in terms of basic or applied static high-pressure research progress. In recent years, Soviet scientists active in static high-pressure research have changed direction and have begun to use Western experimental technology in an attempt to catch up. We believe that the Soviets will succeed in narrowing the gap in static high-pressure research during the next few years, given the resources they are allocating to the field and their progress in using Western experimental technology.

In both static and dynamic high-pressure physics, Soviet scientists are increasingly directing their research toward applications. Besides the military systems applications to armor/antiarmor systems, Soviet researchers have produced large quantities of synthetic superhard materials for industrial abrasives and drill bits. The Soviets have also begun to use explosive-processing technologies to surface-harden metals and to fabricate metal and ceramic components for civilian industrial uses. At least five major Soviet centers exist for transferring the results of scientific research to industry and for training industrial scientists and engineers in applied high-pressure technology. Applications of high-pressure physics are becoming an overriding priority, superseding considerations of scientific prestige for most Soviet research institutions.

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Soviet High-Pressure Physics Research and Applications

Introduction

The USSR has a program in basic and applied high-pressure physics research that is significantly larger than that of the United States in many fields. The Soviets have devoted major resources to this research field since at least the late 1950s and have published extensively in the open literature. Soviet high-pressure physics research is a scientific priority in a country that places tremendous emphasis on the scientific progress required for industrial and military advancement

In this report, we assess Soviet basic research in high-pressure physics, emphasizing the implications of high-pressure research for materials-science applications. We discuss dynamic high-pressure physics first because it is a field in which the Soviets have a significant lead and because dynamic high-pressure research has numerous military applications. We define high-pressure physics as theoretical work, scientific experimentation, and production technology involving pressures of thousands or millions of atmospheres. Pressure as a physical quantity has dimensions of force per unit area. Throughout this discussion, pressures will be referred to in bars: 1 bar=0.986923 standard atmospheres. The standard international unit of pressure, the Pascal, is 10^{-5} bars

High-pressure physics is important in astrophysics and geophysics, nuclear weapons design, modern armor/antiarmor systems development, and materials synthesis. The most publicized application in the USSR has been in the production of superhard materials (diamond and boron nitride) for industrial grinding and machine tools. Another major subject long studied by Soviet high-pressure researchers is the forming and shaping of materials under high explosive pressures. In the military field, theoretical research has described the phenomena that take place when a penetrator or shaped-charge jet meets a defensive armor system. In nuclear devices, high pressures are produced both by conventional explosions (used to compress a subcritical fissionable mass) and by nuclear energy release:

Much of the Soviet high-pressure research occurring within the last eight years can be directly traced to a decision reached in 1975 at the 25th Congress of the Communist Party of the USSR on the development of science. In public pronouncements during the Congress, some of the short-term goals of research included the necessity of developing new structural, superconducting, and other materials and commercially valuable crystals. The development of new superconducting and superhard materials has important industrial implications

The large number of open-literature Soviet scientific papers on high-pressure-physics-related topics [ ] indicate that the Soviets have made large investments of capital and personnel in high-pressure research and are continuing to do so. Several hundred Soviet scientists devote a significant portion of their time to materials aspects of high-pressure physics, as shown by their technical publications. Approximately one-third of these people are full-time, active scientists involved in superhard materials research; another one-third are active in general shock-wave physics. The majority of these researchers are concentrated in institutes subordinate to the USSR Academy of Sciences. The Soviet levels of staffing are probably about several times higher than in comparable US institutes, but numerical comparisons are made less meaningful by the differences in the definition of a research scientist and by the presence of many researchers in military-related institutes in the two countries

Scientists working in high-pressure physics are well represented in the Academy of Sciences. Of a total of about 100 physicists who are academicians or corresponding members of the Academy of Sciences, we have identified seven—a relatively large number—who are active in high-pressure physics research. Three high-pressure investigators have been awarded the Lenin Prize for Science and Technology, the most prestigious S&T award in the USSR, and two have been awarded State Prizes in Science and Technology. The Soviets have 50 facilities active in research on the materials aspects of high-pressure physics—several times the number of US centers of research in this field. Six of the Soviet institutes are devoted primarily to high-pressure physics research and 12 have a large but secondary involvement in high-pressure research

Joint exploratory or applied-research projects in Soviet high-pressure physics commonly include Academy of Science research institutes, institutes subordinate to the Ministry of Higher and Specialized Secondary Education, and the State Committee for Atomic Energy. We have found very few examples of direct involvement by the Ministry of Defense or defense industrial ministries in Soviet high-pressure physics research. The defense industrial ministries, whose research efforts are applied and for the most part tied to actual design problem solving, apparently have been content to let the Academy of Sciences carry out the major portion of the fundamental and exploratory research effort. We identified no institutes subordinate to these ministries as performers of basic high-pressure research

In many subfields of high-pressure physics research, a handful of key scientists and their laboratories are responsible for almost all of the scientific progress. These key individuals operate almost autonomously; they determine the research directions to be explored and the resources devoted to those research avenues, within overall laboratory budget constraints. A complete assessment of basic scientific research in high-pressure physics must, therefore, include coverage of and comments on the leading researchers, their laboratory facilities, and their research directions. In this assessment we discuss these key individuals in the sections covering their major research activities

Dynamic High-Pressure Physics Research

Dynamic high-pressure physics research uses shock waves to create high pressures in materials. A shock wave is a disturbance that travels through a medium when energy is abruptly deposited in one part of that medium. Behind the shock front, the temperature and density of the material are elevated. A shock is thus like a very-high-intensity sound wave. Typically, shocks generated by chemical explosives can produce pressures of up to 10 megabars accompanied by temperatures of a few thousand degrees Celsius; nuclear-driven shock experiments can reach pressures of over 100 megabars. Figure 2 shows the range of pressures achieved by various dynamic and static high-pressure technologies.

Materials-Processing Research

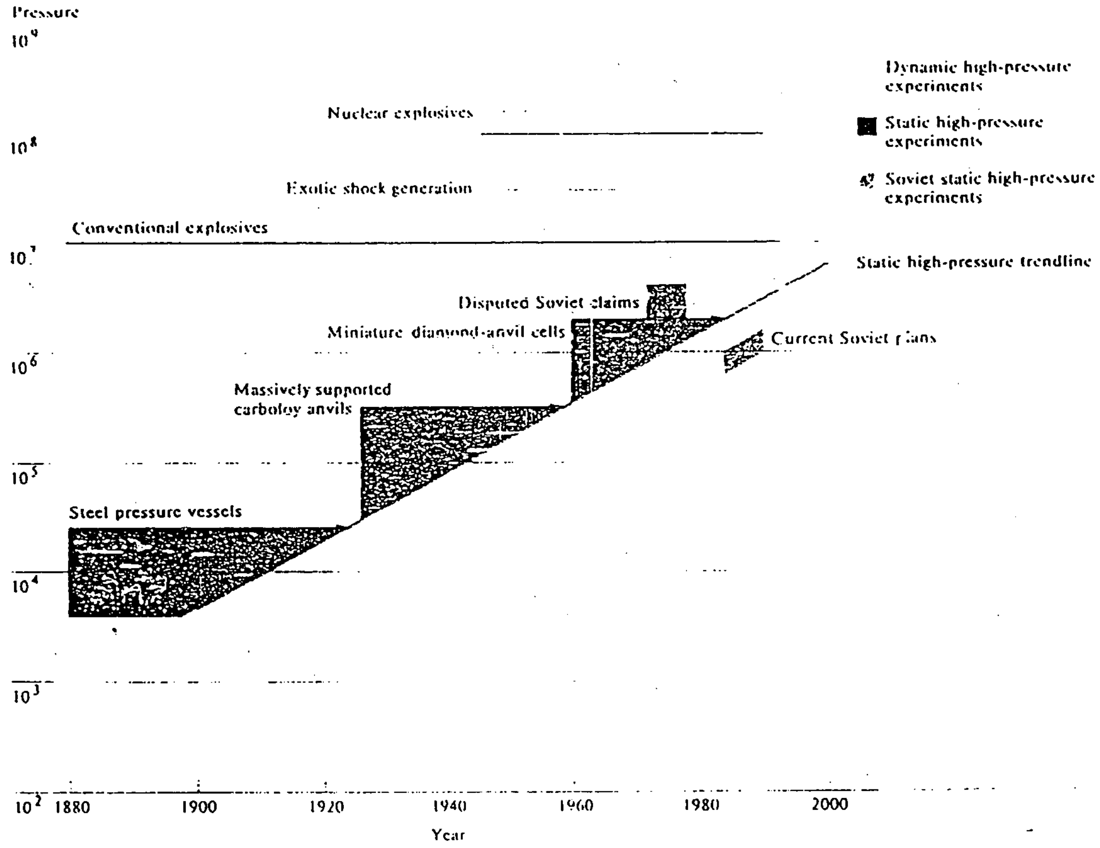
Explosive Welding, Forming, and Hardening. Explosive welding is the process of bonding two metal parts by detonating an explosive charge near or in contact with one of the parts. As shown in figure 3, two plates of metal are separated by a small angular gap; a high-explosive sheet in contact with one plate is detonated, and the moving plate impacts the stationary one producing near-instantaneous melting and bonding of the surfaces in contact. Explosive forming uses a mold into which the piece to be formed is driven by the explosive blast. Explosive hardening relies on a shock wave to disrupt the microcrystalline structure of a material and thereby change its properties.

In terms of technological level, we believe the USSR is about five to 10 years ahead of the United States in explosive welding, forming, and hardening. Our judgment is based on conversations with US scientists, on their written assessments, on a survey of open-literature Soviet publications [

] Explosive welding, forming, and hardening are of great interest to Soviet industry, where there is a high level of applications-oriented activity. Explosive techniques of materials processing can save significant amounts of time and physical resources. Explosive welding and forming can also be used to fabricate composite materials that cannot be practically manufactured by any other means

The basic research being conducted in the USSR has significant military and economic potential. Among specific capabilities demonstrated by Soviet laboratories in explosive forming are several with immediate applications. For example, [ ] visiting a Soviet laboratory were shown a titanium blade (a turbine component) that their hosts claimed had been formed hydrodynamically by a shock wave in water. The Soviet scientists said that this explosive-forming

Figure 2
High-Pressure Experimental Technologies

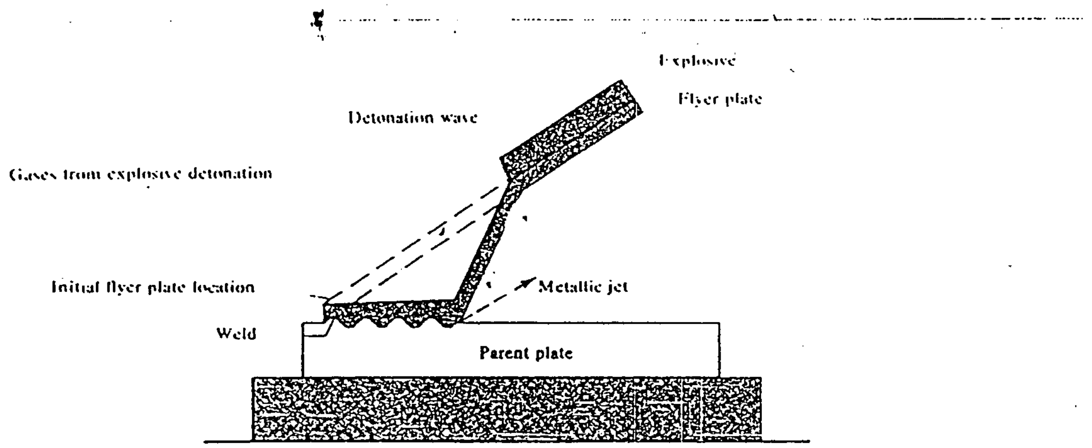


The zones shaded in yellow show the general ranges of dynamic pressures achieved by nuclear or conventional explosive compression and by "exotic" shock-generation means. The zones indicate rough upper limits to the pressures reached; a zone begins approximately when the technology began to be available. Actual laboratory achievement of the maximum pressure possible generally occurs some years later. In the lower part of the graph, the same information is shown for static pressures by the gray shaded zones.

From the beginning of the 20th century until the present, the maximum pressure achieved in reliable static high-pressure experiments has grown exponentially, as shown by the blue line on the figure. Further progress to higher static pressures is likely to be slower than in the past, unless new experimental technologies can be devised to overcome the limitations of diamond-anvil cells.

As shown in the first red zone, in the mid-1970s Soviet researchers claimed to have achieved pressures in the 2- to 4-megabar range as part of their metallic hydrogen project. Their claims were never substantiated and are generally disbelieved. In 1982 Soviet physicists published new research plans that indicate they only propose to be working at 0.8 Mbar by 1985 and possibly 1.5 Mbar several years later. In general, the Soviets appear to lag the state of the art in Western static high-pressure physics by five to 10 years.

Figure 3
Explosive Welding Technique



A flyer plate, backed by an explosive layer, is placed at an angle relative to the fixed parent plate that is to be welded. The explosive layer is detonated near the end of the flyer plate in contact with the parent. The flyer plate is driven down, impacts the parent plate, and produces a wavy, welded boundary and (in some cases) a liquid-metallic jet similar to the jet created in a shaped-charge detonation.

procedure eliminated four to five hours of machining and left only 30 minutes of finishing to do. Similarly, other Soviet laboratory chiefs have told [redacted] about Soviet explosive production of titanium-aluminum laminated plates, which we believe are intended for light armor use. Other explosively clad products shown by Soviet scientists include steel-aluminum conductors (for electrolysis applications), steel-brass bearings, and metal-coated spheres of steel and glass. Except for occasional uses in the shaping of very large metal parts, Western materials laboratories have done relatively little work in explosive forming since the 1960s

Soviet researchers also have demonstrated to foreign visitors their achievements in explosive hardening. Explosive surface-treatment processes developed by the Soviets can more than double a material's hardness and wear resistance. Some applications that have been discussed by Soviet laboratory chiefs include the manufacture of railway frogs (switch components) and the toughening of teeth on large shovels and other mining machinery. We believe that explosive hardening may also be applied by the Soviets to armor materials, where it could significantly improve a plate's resistance to penetration

The Soviet explosive materials processing technologies discussed above are still laboratory developments, but the Soviets are making vigorous efforts to get the technology refined and standardized so that it can be put to practical application. Those efforts are discussed in a later section of this report

Among the key Soviet centers of basic research into explosive welding, forming, and hardening are the

Lavrent'yev Institute of Hydrodynamics (IG) in Novosibirsk and the Institute of Chemical Physics (IKhF) in Chernogolovka, near Moscow. Both are Academy of Sciences institutes with extensive experimental facilities for explosive firing. At the IG, work on explosive materials processing is centered in the Special Design Office of High-Rate Hydrodynamics in Novosibirsk, directed by A. A. Deribas. Deribas is a leading researcher in the field of explosive welding and explosive materials processing. [redacted] Work at the IKhF is led by A. N. Dremin's Laboratory of the Detonation of High Dynamic Pressures. IKhF researchers, including colleagues and subordinates of Dremin, have been linked to the Soviet nuclear weapons program; IG researchers have ties to other institutes working on armor penetration mechanics. We believe that this close interaction between key Academy research institutes and military systems users is a sign that explosive materials processing is a state priority for application to practical ends.

Shock-Wave Synthesis and Dynamic Powder Metallurgy. Shock-wave synthesis is the formation of chemical compounds, metallic alloys, or other composite materials under the influence of high, short-duration pressures. Dynamic powder metallurgy is the compaction and/or sintering (partial melting) of powdered metals into coherent solids by use of explosive compression. The importance of shock-wave synthesis for the Soviets is that it allows inexpensive, large-scale production of some new and valuable metallic alloys, ceramics, and composites. Some materials that Soviet scientists have been working with have exceptionally high strengths, high toughnesses, or high melting points. These materials have possible applications as armors and armor penetrators. The Soviets are also actively researching shock-wave production technologies for industrial abrasives and grinding/cutting/machining materials.

We believe that the level of activity and the quality of the research in the USSR in shock-wave synthesis and dynamic powder metallurgy are high compared to that in the West. Some Western patents have been granted for Soviet explosive synthesis techniques; the Soviet researchers who got the patents are proud of the international recognition of their lead in this area of technology [redacted] who have visited Soviet laboratories, talked with Soviet scientists, and read Soviet publications also confirm the high activity and excellent quality of research in shock-wave synthesis in the USSR.

We believe, however, that some recent Soviet claims in shock-wave synthesis and dynamic powder metallurgy are exaggerated. At the Powder Metallurgy Conference in Italy in June 1982 and at international materials science conferences in late 1982 and early 1983, Soviet scientists boasted of their ability to form large (1-meter-square) crack-free samples of boron nitride, aluminum nitride, and aluminum oxide. The Soviets claimed to have achieved density near the theoretically maximum density in plates as large as 0.4 to 1.0 meter wide and a few centimeters deep. Such plates would have immediate use in armored vehicles, where they would give greatly enhanced protection against current penetrator systems. A West German scientist who visited Soviet laboratories in 1981, however, concluded at that time that the Soviets could not explosively compact boron nitride or aluminum oxide without severe cracking problems. Other visitors to the same laboratories in late 1982 also did not observe any physical evidence to support the Soviet claims. We conclude that most probably the Soviet claims were premature.

The key Soviet centers for research into dynamic powder metallurgy include Dremin's laboratory at the Chernogolovka branch of the IKhF, mentioned above as a focus for explosive welding, forming, and hardening. The Institute of Problems of Materials Science in Kiev, subordinate to the Ukrainian SSR Academy of Sciences, is a Soviet research leader in forming hard alloys for industrial and military uses. The Powder Metallurgy Institute (PMI) in Minsk, under the Belorussian Ministry of Higher and Secondary Specialized Education, is a key Soviet organization for development of explosive powder metallurgy technology, as is the Volgograd Polytechnic Institute

Industrial Applications of Shock-Wave Technology. We believe that the Soviet Academy of Sciences and other state organizations are beginning an active campaign to promote applications of dynamic high-pressure technology in Soviet industry. Signs of this campaign have appeared in Soviet newspapers and magazines, in open technical publications, [redacted] Special teaching-oriented centers have been established in some of the top Soviet materials laboratories to train managers and technicians from industry in explosive processing technologies. The Soviets have also begun international collaborative efforts [redacted] and have imported both raw materials and partially finished products for use in explosive processing. Statements by Soviet scientists [redacted] and the obviously good results of recent Soviet research indicate that Soviet activity in industrial applications of shock-wave technology will continue to increase.

Although the Soviet laboratory research into shock-wave materials processing is of high quality, applying that research to industrial production remains a problem. There are several reasons for this difficulty, reasons that are common to other areas of Soviet science and technology. Soviet factory managers have little personal incentive to risk trying new production technologies. If the new procedure succeeds, they get small rewards and higher quotas to meet; if it fails, the penalties are severe. The lack of economic competition removes most of the pressures on managers and planners to economize resources. If conventional industrial techniques can do a job at a cost of more wasted material, that is less of a problem than it would be in a profit-oriented enterprise.

Most critical among the factors hindering Soviet application of dynamic high-pressure technology, however, is poor quality control. Plants to produce raw materials such as powders for powder-metallurgical products frequently lack adequate metal-cutting machine tools, small presses, and essential instrumentation. The USSR thus has to import pure powders from the United States, West Germany, and Sweden. When pure powders are not available, the results of explosive compaction are poor. Some surprisingly frank complaints about low quality and productivity in dynamic high-pressure technology have appeared in the internal Soviet press.

Notwithstanding Soviet problems with bureaucratic inertia and poor quality control, we see many indications of a large and increasing effort by the Soviet scientific establishment to apply dynamic high-pressure physics in industry. We have not yet seen many specific examples of successful Soviet practical applications; and an assessment of those applications is outside the scope of this paper. We expect to see modest Soviet progress within the next five years on practical uses of shock-wave technology. Most of this progress appears likely to come from three key Soviet centers for technology transfer from laboratory to industry. These three centers are the PMI in Minsk, the Special Design Office of High-Rate Hydrodynamics in Novosibirsk, and the IKhF's Laboratory of the Detonation of High Dynamic Pressures in Chernogolovka.

[redacted] the PMI has long been actively collaborating with Soviet industry in an attempt to get the results of scientific research into practical applications. Director of the PMI, O. V. Roman, also directs the Belorussian Republic Research and Production Association for Powder Metallurgy, a recently founded center that serves enterprises in Belorussia regardless of their ministerial subordination. An emphasis on practical uses of research extends to internal projects at the PMI. The institute uses explosive compaction to produce titanium tubes and plates, probably for commercial uses as filters, to form boron nitride into simple shapes, and to weld aluminum explosively to steel and copper, probably for industrial use as electrodes or brake pads

The Special Design Office of High-Rate Hydrodynamics forms the vital interface for explosive-welding technology transfer to industry. It was started in 1976 and consists of several hundred people, about 40 of whom are staff scientists and technicians from Soviet industry. Several explosives firing chambers recently were acquired by the PMI from Novosibirsk, probably from the Special Design Office. [redacted] also suggests that in 1970 the Office's director, Deribas, supplied scientists from his research group (before his Special Design Office existed) to form new centers of explosive technology activity throughout the USSR. Most recently, [redacted] have reported that the Special Design Office has entered into an international partnership [redacted] In 1982 Deribas provided the [redacted] institute with designs for blast chambers and will train [redacted] scientists in metal cladding and bonding techniques using explosives

Probably the most significant work done by the Special Design Office is teaching explosive materials processing and explosive welding. The Special Design Office has trained a large number of individuals in applications of explosive welding. Deribas has described his work on explosive surface hardening of steels in open literature and at international conferences. [redacted] In spite of the high level of Soviet activity in explosive cladding the quality of the products is still low. Deribas has stated that large quantities of clad metal parts have to be imported from Japan and Sweden for applications requiring large crack-free plates.

The third significant research center that is attempting to move high-pressure results from the laboratory to industry is within the group headed by A. N. Dremin at the IKhF. In 1982 Dremin headed this group of about 80 scientists. He also actively works with visitors from more applied institutes. Scientists in Dremin's group have mentioned that he frequently has such outsiders work in his group for one to two years. The production technologies that Dremin's group is attempting to transfer to industry include explosive synthesis of industrial abrasives.

Armor-Related Research

Experimental Research. We believe that much experimental Soviet dynamic high-pressure research is guided by armor applications. In publications and conferences, Soviet scientists have not mentioned armor as a motivation for their work, but many of the shock-wave experimental setups they have described in scientific papers and discussed [redacted] bear a close resemblance to advanced western armor designs. Many of the topics Soviet researchers are studying have an immediate application to armor penetration. These topics include shock waves in ceramics and other hard materials (such as boron nitride), hypervelocity impact dynamics, and explosive surface hardening. At least one of the leading Soviet laboratories involved in armor-related research, the IKhF, has close ties to the Sarova nuclear weapons development center; because of similarities between armor-penetration mechanics and implosion physics, the work under way on nuclear research probably will enhance the quality of Soviet armor work.

We believe that within the Academy of Sciences fundamental research with experimental armor applications is concentrated in the IKhF and in the IG. At the IKhF, Dremin's subordinates are active in many areas of the experimental physics of high explosives, areas of relevance to armor penetration. At the IG, subordinates of Deribas, possibly led by A. M. Staver, are investigating the fabrication of ceramic plates and of multilayer metal plates, which may have applications to Soviet light armors. Hard ceramic materials such as alumina, some carbides, and boron nitride are the most attractive candidates for this purpose. The Soviet scientists are exceedingly hesitant to discuss experimental activities using boron nitride. [redacted] We believe this reticence is probably due to the application of this work to armor

We believe that other work at the IG also is contributing to the institute's armor effort. The late academician M. A. Lavrent'yev, for whom the IG is named, did some of the pioneering Soviet work on shaped-charge phenomena in 1944-47; IG scientists continue to be active in shaped-charge research, as shown by their articles in open-literature publications. Scientists at the IG also are investigating methods of producing hypervelocity impacts. Other IG research into explosive surface hardening of materials has significant potential application to the treatment of armor steels.

Theoretical Research. We believe that Soviet theoretical researchers in armor applications of dynamic high-pressure physics lag their Western counterparts in their capabilities to model complex modern armor systems and penetrators. This lag is not due to a lack of understanding of fundamental laws of penetration mechanics, in which the USSR is strong, as shown by their open scientific literature [redacted] Rather, the Soviet researchers are handicapped by poor scientific computing facilities. In spite of this handicap, Soviet armor researchers have the ability to model fairly advanced two-dimensional armor-penetration problems. The Soviet scientists have taken Western computer codes (large simulation programs) and adapted them to smaller, slower Soviet computer hardware. We also have evidence [redacted] that the computer facilities are being upgraded at the two leading Soviet theoretical armor analysis centers, the IKhF and the Institute of Theoretical and Applied Mechanics (ITiPM) at Novosibirsk. These enhanced computer facilities will enable the Soviets to develop lighter, more efficient armor systems in less time and at a lower cost in wasted experimental tests than they would otherwise have to spend. The new computers probably will enable the Soviets to begin to perform full three-dimensional armor-penetration calculations, a capability that US researchers have only had for the last few years.

Soviet theoretical armor researchers are studying plasma physics, high-explosive phenomena, and dynamic properties of materials (failure of abruptly stressed metals, spall, penetration mechanics, and such) [redacted] at least one Soviet group—at the IKhF under the direction of V. Ye. Fortov—has investigated the theory of penetration mechanics in boron nitride. According to its Soviet leader, that group also has studied the theoretical use of uranium rods as penetrators. We believe that the Soviets are investigating the use of uranium and other ultradense penetrator materials because the potential of these materials to defeat Western armors

One of the signs of increased Soviet theoretical armor research activity that we believe to be significant is the recent separation of an armor theory group from the major experimental armor research center at the IKhF. Three years ago [redacted] assessed the penetration mechanics work of this Soviet group as "dabbling" and unlikely to lead to any breakthroughs; he believed the Soviets were not applying enough resources to the research to produce significant results. We believe the situation has changed. The theory group leader, Fortov, has been working seriously on penetration problems for years, but the BESM-6 computers available to him have been a severe handicap. In 1980 Fortov said that his group's efforts were shifting from manual analytic solutions (of highly simplified situations) to digital computations, which can be much more detailed and realistic. In 1981 a researcher in Fortov's group asked [redacted] for help in obtaining copies of 24 US papers on penetration and fracture mechanics [redacted] most of the requested documents, however, could be obtained openly. The reports discuss computational tools for penetration mechanics, light armors, and ceramic armors

The cornerstone of Soviet armor research work has been the extensive adaptation and use of Western hydrodynamics computer codes. Two codes, named HEMP and Particle-in-Cell, frequently have been mentioned by Soviet scientists [redacted] Both codes were developed at the US Lawrence Livermore National Laboratory and have been widely distributed and discussed in the open scientific literature. Soviet workers claim to have successfully adapted and modified HEMP and Particle-in-Cell to run efficiently on their old, slow, relatively small computers. We believe that the modified programs are probably both accurate and reasonably fast; they thus are valuable research tools for Soviet armor investigators, because the programs save a lot of time in designing new armor systems, by reducing the number of experimental tests required to optimize system performance

Very advanced armor systems designs are being modeled by Soviet theoretical armor researchers. These armor designs contain arrays of materials in the form of solid plates arranged at an angle relative to the penetrator's anticipated direction. The plate materials studied by the Soviets and described by them in papers and technical conversations have included steel, aluminum, copper, fiberglass, and plastics, in various configurations, with air gaps in between. Such systems give greatly enhanced protection against both kinetic-energy and high-explosive antitank weapons, possibly more than twice as good as simple steel armor plate of the same weight. Modeling such complicated configurations, however, requires advanced computational equipment. Accurate modern armor calculations require hours of computer time on the fastest machines available in the West. Because of the lack of computer facilities, Soviet researchers have had to simplify and restrict their models

The Soviet armor modeling computer facilities were significantly improved in 1982 when the ITiPM acquired an El'brus-1 advanced scientific computer. The El'brus-1—a modern machine roughly equivalent to the CDC 7600—greatly enhances the ability of Soviet armor researchers to design and model complex armor systems accurately. Depending on the specific configuration, the El'brus-1 is at least an order of magnitude faster and has an order of magnitude more useful memory space than a BESM-6, the standard Soviet scientific computer of the 1970s. New computer systems frequently take many months to get working, however, and the El'brus series has been plagued with reliability problems. There are also time delays, several months at least, in adapting working software to run on a new machine. Therefore, we believe that the upgraded Soviet computer facilities are unlikely to be very useful for penetration mechanics calculations until well into 1984

Several leading Soviet researchers in advanced armor theory appear to be outside of the IKhF and the ITiPM groups. In particular, V. N. Kukudzhanov and V. I. Kondaurov have published exceedingly high-quality research. Their papers cite US armor researchers, and the Soviets' work has clear relevance to advanced modern armor design.

New Research Directions

New research directions include areas of high-pressure physics that are of fundamental importance but that are not closely tied to near-term applications. On the basis of open-literature scientific publications [redacted], we judge the Soviets to be very active in exploring exotic methods of generating ultrahigh dynamic pressures. Shock-wave chemistry is another subject that has been studied extensively in the USSR, far more than in the United States. While applications of advanced Soviet high-pressure research are not immediate, the basic research contributes to Soviet developments in their nuclear program, armor/antiarmor research, and studies of directed-energy weapons effects.

Exotic shock-generation systems produce shock waves by means other than the direct application of chemical or nuclear explosions. Figure 2 shows the general range of pressures reached by exotic systems, in comparison with other high-pressure technologies. There are several ways to deposit large amounts of energy in a system in a short time, including lasers, particle beams, and high-speed flyer plate impacts. An advantage of these systems is that they are precise and reproducible in the laboratory. They also can explore temperatures and densities that are difficult to reach using explosive shock-generation techniques. Disadvantages are the small size of the samples being shocked, the relatively high expense of the system, and the technological difficulty in getting an exotic system operational

We have considerable evidence [redacted] from Soviet scientific publications that Soviet laboratories are actively exploring the use of high-energy lasers and high-current electron beams for shock production. The key research centers for this work include the IKhF, the Lebedev Physics Institute, and the Kurchatov Institute of Atomic Energy. Both laser-induced and particle-beam-induced shock-wave experiments are on the frontiers of Soviet dynamic high-pressure physics research. Except for possible use in controlled thermonuclear fusion, however, these two directed-energy high-pressure techniques appear to be far removed from practical applications. We therefore believe that Soviet research and development work on laser and on particle beam methods of shock-wave physics will remain confined to the basic research centers for many years to come

Another method of laboratory shock-wave generation is the use of a gun to accelerate a small mass to high speeds (several kilometers per second). This mass can then produce a precisely defined shock when it impacts on a test sample. Guns to accelerate projectiles to very high velocities fall into two main categories: light gas guns (possibly multistaged) and electromagnetic guns (rail guns)

Light gases such as hydrogen or helium have high speeds of sound propagation and can therefore be used effectively to push a small mass (typically a few grams) to speeds of as much as 12 kilometers per second (km/s). Multistage systems use one fast-moving mass as a piston to compress rapidly the light gas in a reservoir and thus to bring a smaller mass to a still-higher velocity. The Soviets have recognized the advantages of precise, reproducible shock-wave generation, and they have made frequent efforts to learn more about Western light gas gun technology.

We have seen few examples of successful light gas gun systems at key Soviet dynamic high-pressure research centers. At the IKhF, Fortov and F. I. Dubovitskiy have stated that they are developing a two-stage light gas gun to use for equation-of-state (EOS) studies. Also at the IKhF, Dremin has spoken of his use of gas guns and flyer plates for organic chemistry research, specifically for work on explosives and propellants. The other focal point for Soviet light gas gun research is at the IG. Vladimir Titov, deputy director of the IG, has repeatedly discussed his two-stage gun with visitors; apparently, he made little progress with that system between 1976 and 1981.

A rail gun system consists of an electrical energy supply, a channel made of two parallel conducting rails, and a projectile with a conductor to bridge the rails. The gun converts electrical energy to projectile momentum in the same way that an electrical motor works. It is possible to accelerate a small mass (several grams) to over 10 km/s using modern rail guns

Active Soviet research efforts are under way at the Institute of High Temperature (Moscow) and at the IG. The results of Soviet rail gun development to date have been poor, but the level of effort has increased continually in the past four years, and we expect it to continue to grow. Although Soviet interest in US rail gun technology is high, the recently reported Soviet rail gun projectile velocities fall short of the US state-of-the-art figure of more than 10 km/s

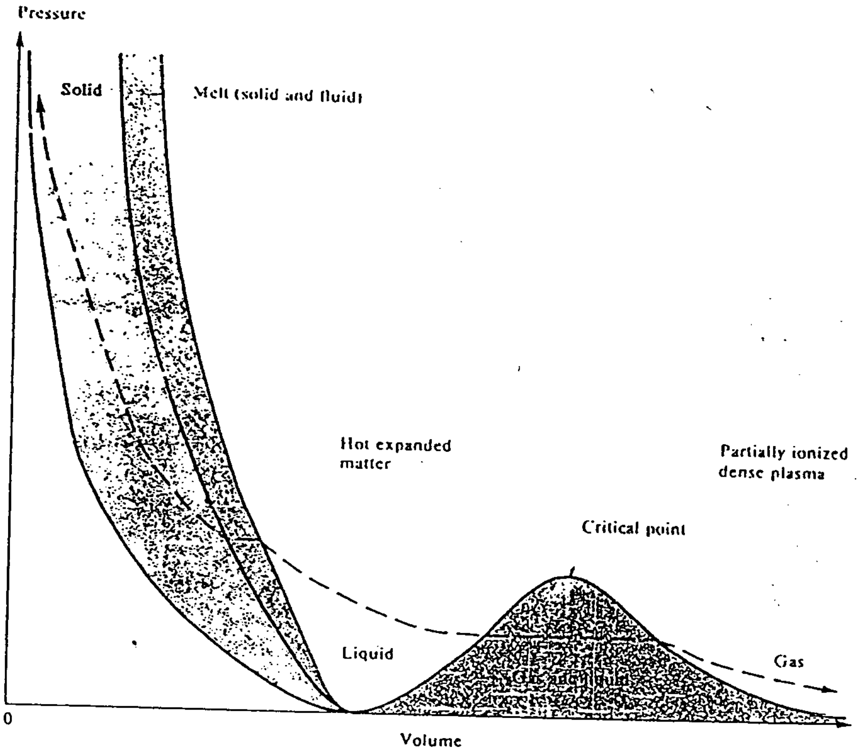
Rail guns and other electromagnetic launchers will be important research tools for Soviet high-pressure physicists when guns that operate regularly at high projectile velocities are developed. On the basis of current Soviet work in the field and the level of effort being applied, we believe that Soviet development of useful rail guns will occur by the late 1980s

In addition to use in high-pressure physics research, we believe the Soviets will use rail gun technology for military-related research in such areas as air defense, armor penetration, nuclear weapons design, and impact fusion studies. The connections of Fortov and other key rail gun researchers with the Soviet nuclear program and with armor penetration research have been repeatedly confirmed [redacted] We believe Fortov, who is a consultant to the Institute of High Temperature, will direct or will participate in rail gun experiments at the institute that have potential military applications. Fortov also has mentioned [redacted] that his colleague A. I. Pavlovskiy, a prominent Soviet scientist associated with nuclear and directed-energy weapons research, has worked on rail gun experiments. In addition, the IG, where rail gun research is under way, has close connections with the Soviet armor/antiarmor community.

Shock-induced chemistry—the study of chemical changes in substances under the influence of abrupt increases in temperature and pressure—is another advanced topic of high-pressure research in the USSR. There is relatively little activity in this field in the West. A key Soviet center is the IKhF, where the research under study includes shock-induced polymerization, the synthesis of compounds from elements of radically different melting points, and the use of shock waves to activate catalysts. The Soviet research effort in shock-wave chemistry, however, apparently has produced few useful results, and we believe it is slowing down or even stopping. We have evidence [redacted] from Soviet technical papers that key Soviet scientists are leaving the field or deemphasizing the shock-chemistry aspects of their work

On the basis of [redacted] open Soviet scientific publications, we believe the Soviets lead the rest of the world in many areas of equation-of-state (EOS) research. The EOS of a material describes how that substance changes its density and structure under

Figure 4
Typical Equation-of-State Diagram



The graph shows the states of matter (solid, liquid, gas, and such) and how the volume of a sample changes as the pressure applied is varied. Temperature (not shown) is a third parameter in the EOS. As the temperature increases, the point representing a substance tends to move upward and/or to the right on the pressure-volume graph. The dashed line shows the path a sample follows when the pressure on it is changed at constant temperature.

At pressures above the "critical pressure," the distinction between a gas and a liquid vanishes, leaving a fluid state. Two zones within the fluid state are of particular interest: hot expanded matter and partially ionized dense-plasma. Soviet researchers have been active in studying matter in these two areas. Their results have potential importance in understanding directed-energy weapons effects and other high-pressure/high-temperature/low-density phenomena.

varying conditions of temperature and pressure. Figure 4 shows a typical EOS; the figure caption explains the changes a substance goes through as the pressure on it rises. The EOS is a collection of critical information about a substance. Knowledge of a material's EOS under ultrahigh pressures is important in geophysics, astrophysics, and nuclear weapons design. At lower pressures, the EOS is an input to studies of armor penetration, conventional explosives, and a variety of materials science investigations. Soviet research is particularly strong in the experimental aspects of measuring EOSs at ultrahigh pressures. Some results reported by the Soviets more than a decade ago have only recently been confirmed by Western experimenters. Besides applications to directed-energy and nuclear weapons, EOS studies of explosive detonations have importance in understanding conventional explosives. The Soviet lead in experimental EOS studies has compensated, to a large extent, for their lag in computational facilities

A significant activity among Soviet researchers in high-pressure physics is the study of the EOS of materials at temperatures and pressures far from the usual shock-produced regions. Ordinary shock-wave techniques for studying the EOS of materials are capable only of investigating hot, dense, high-pressure regions of the possible states of matter. Other important regions include zones where the pressure and temperature are high but where the density is low. Such a state is called hot expanded matter or, at higher temperatures, a partially ionized dense plasma (see regions indicated on figure 4). These states of matter have great importance in understanding directed-energy weapons effects on targets and in studying reentry vehicle vulnerability. Hot expanded matter and partially ionized dense plasmas are difficult to model theoretically, as they fall in the complicated region between ordinary, well-understood matter and ultrahot, totally ionized, simple plasmas

To study the behavior of matter when it is partially ionized, hot, and yet not too dense, Soviet scientists have taken porous or foamy metal samples and subjected them to intense shock loading. Much of the Soviet work is nuclear related; Fortov mentioned (in late 1981) plans for at least three nuclear-driven EOS experiments. Other Soviet scientists have done work on generating hypervelocity jets of hydrogen, which can be useful in EOS studies of cold compressed metals and powders

Static High-Pressure Physics Research

Static high-pressure physics involves the application of pressure for times long compared to the time necessary for sound to travel through a material. In contrast, dynamic high-pressure physics involves shock waves and rapid pressure changes. Typically, high static pressures range from kilobars to more than 1 megabar, as shown in figure 2. Under these pressures, material properties change significantly. For practical purposes, the most important changes are those that persist (at least to some degree) when the high pressures are no longer being applied. Unlike dynamic high pressures, static pressures can be applied to a sample slowly, at low temperatures, and thus can more easily produce important new industrial materials

Experimental Technology

Before 1980, Soviet experiments in generating very high static pressures followed the "bigger is better" philosophy and used large, massive presses. In the most outstanding example of the Soviet approach, the Institute of High-Pressure Physics (IFVD) acquired a gigantic press, 30 meters high, capable of applying a total force of 50,000 metric tons to a test sample. This huge press was under construction from 1965 through 1976. No good photographs of the 50,000-ton press are available; figure 1, however, shows a 65,000-ton press that was built by the same Novokramatorsk Machine Works that made the IFVD press. The two presses appear to follow the same design and look almost identical

We believe that throughout the 1970s Soviet scientists at the IFVD made a deliberate effort to mislead outsiders as to the actual state of their big press and to the research that was being conducted with it. Experimental results from other devices were credited to the 50,000-ton press, and foreign scientific visitors to the IFVD were kept away from the press except for brief tourist-like showings. We believe that some of this deceptive activity was aimed at Soviet bureaucrats; that is, because the press was such a big investment, the Soviets would not admit to any difficulties using it

In 1982 open Soviet literature indicated that the press was not actually operational at ultrahigh pressures. IFVD scientists are still working on the design and construction of the inner anvils to concentrate the press's force onto a small area. The quoted target for a three-stage anvil arrangement is to achieve 800 kilobars by 1985 and eventually to reach 1.5 megabars. These pressures are to exist in a volume of 1 cubic centimeter, very large by Western standards. In the mid-1970s, IFVD scientists claimed to have achieved pressures in the range of 2 to 4 megabars. Their claims of ultrahigh pressures were never substantiated and are generally not believed by scientists outside the USSR. Figure 2 shows Soviet claims and current plans

We have observed that the best Soviet scientists in the static high-pressure field have begun to push for development in new experimental directions. Two highly critical review articles in Soviet scientific journals conclude that relatively little has been accomplished by past Soviet experimental approaches and suggest that a much more productive experimental technique exists; that is, the use of gem-quality diamond anvils to compress tiny (0.01 cubic millimeter or less) samples in an observable, highly controlled environment. Western scientists are using this approach in their laboratories for current state-of-the-art research

We believe that the adaptation of diamond-anvil technology by Soviet static high-pressure experimenters will take place soon and that the new technology will enable the Soviets to catch up with Western research in this field. Diamond-anvil cells are small, but they permit precise control and observation of the sample under pressure. Diamond anvils have almost no relevance to production of materials because of their tiny working volumes; we judge this lack of production capability probably has made the diamond-anvil technology harder for Soviet scientists to justify to their funding agencies. But for fundamental research into achieving the highest possible pressures in small samples, no other static technique approaches the diamond anvil method

Superhard Materials Research and Industrial Applications

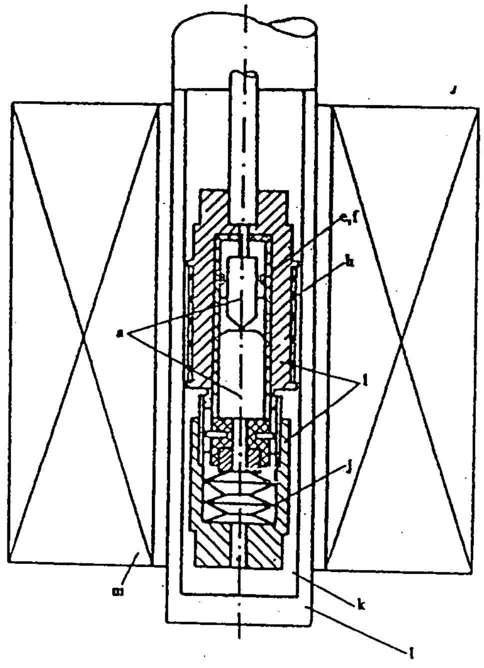
As early as 1960, the first Soviet synthetic diamonds were produced by Vereshchagin and others at the IFVD [redacted] The Soviet process was probably copied directly from the General Electric diamond synthesis method developed and patented in 1954-55. Artificial diamonds filled a Soviet need, and the technology rapidly went from the IFVD laboratories to the Kiev Institute of Superhard Materials (ISM), which further developed it and passed it along to several newly founded production associations

Following the development of diamond production technology, the Soviets quickly developed methods of synthesizing superhard forms of boron nitride. Superhard boron nitride is a compound closely analogous to diamond in crystal structure, physical properties, and method of synthesis. It has a hardness slightly less than that of diamond, but has the advantage that it can be used at higher temperatures or in corrosive environments that would degrade diamond tools. With industrial applications in mind, Soviet researchers went on to develop a large variety of composite superhard materials, made up of many tiny crystals of a superhard substance held together by a tough, strong matrix

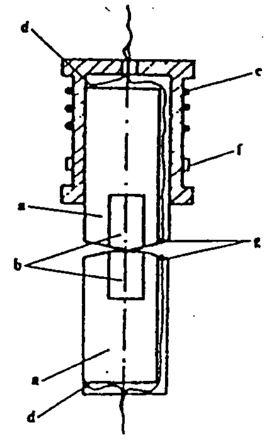
The Soviets have developed at least half a dozen composites for industry and export. The superhard materials developed by Soviet researchers have been vigorously promoted as abrasives or grinding/cutting materials in the Soviet export journals. The Soviets also have made great claims in their open press of the economic value of superhard composites in their machining and mining industries. [redacted] suggest, however, that there remain many problems of quality control in the production of superhard materials in the USSR. We believe that Soviet synthetic superhard materials have probably been most valuable in low-priority applications, where high toughness and long lifetime are not critical. In the highest priority or most demanding applications, such as deep oil well drilling, we believe that natural diamonds remain the Soviet superhard material of choice because of their superior quality.

Soviet synthesis of superhard materials takes place in dozens of production plants. The production plants receive technical guidance and troubleshooting help from research institutes, chiefly the ISM. The ISM (and its predecessor organization) has been an interface between the research centers of static high-pressure physics and the manufacturing plants since the early 1960s. Since about 1980, the ISM has received considerable praise in the open Soviet press for its successful joint projects with the production plants; the Soviet press treatment of the ISM indicates it is being heavily supported by the state

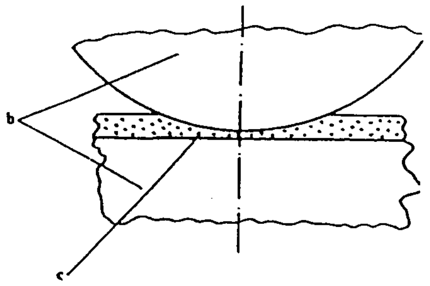
Figure 5
Soviet High-Pressure Apparatus



Overall View



Detail of Pressure Cell



Detail of Inner Anvils

- a. Beryllium bronze mounts
- b. Carbonado anvils
- c. Sample
- d. Current leads
- e. Manganin thermometer
- f. The sample of Pb for thermometer calibration
- g. Potential leads
- h. Heater
- i. Beryllium bronze screw clamp
- j. Disk springs
- k. Thermal exchange gas (He)
- l. Vacuum jacket
- m. Superconducting magnet

The figure is taken from a recent open-literature scientific publication. It shows the synthetic diamond (carbonado) anvils used at the Institute of High Pressure Physics in experiments to create metallic hydrogen and other new high-pressure states of matter.

scientific bureaucracy and is being used as an example for other scientific research organizations to follow

Metallic Hydrogen

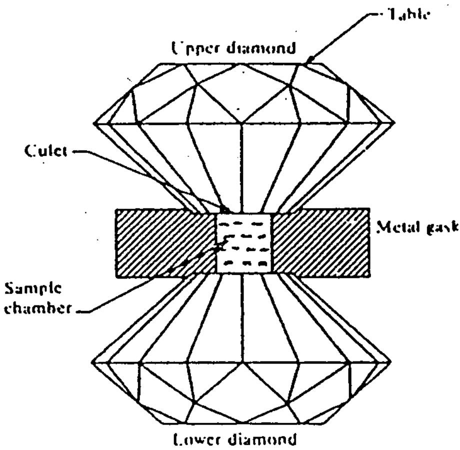
According to theoretical calculations, hydrogen will transition into a highly conductive, metallic state under pressures estimated to be in the range of 2 to 5 megabars. Metallic hydrogen has a high energy content, about 35 times the energy per gram stored in TNT. It thus would be a powerful explosive or a high-energy fuel, depending on the controllability of its transition back to ordinary hydrogen. Metallic hydrogen isotopes (deuterium and tritium) would be valuable for nuclear fusion applications. Metallic hydrogen might also be a superconductor at room temperatures, which would give it extraordinary electrical uses. Recent theoretical work by both US and Soviet researchers, however, casts doubt on the possibility of metallic hydrogen's high-temperature superconductivity

During most of the 1970s, Soviet static high-pressure physicists concentrated on the attempt to produce metallic hydrogen. That attempt is generally recognized, by both Western and Soviet scientists, to have ended in failure. Three factors contributed to this failure: early theoretical estimates of the pressures needed to produce the metallic phase were too low; Soviet experimenters overestimated the pressures they were capable of achieving in their presses; and preliminary suggestions that metallic hydrogen would be metastable and persist at low pressures were probably wrong

Figure 5 shows a Soviet design for a high-pressure apparatus used in the attempt to create metallic hydrogen. At moderately high pressures the thin sample probably will be squeezed out from between the anvil surfaces, allowing the anvils to short-circuit the resistivity measurements of the sample. Critics of the Soviet experiment suggest that such a squeezing out explains the results that the Soviets interpreted as the production of metallic hydrogen

The Western diamond-anvil cell is a significantly different design, shown in figure 6. The carbonado diamonds used in the Soviet apparatus are composed of many small diamond crystals in a metallic matrix. The carbonados are thus electrical conductors, quite opaque to light. They do not allow for the precise observation and control of the test sample that the gem-quality diamonds of the Western diamond-anvil cell allow

Figure 6
Typical Diamond-Anvil, High-Pressure Cell Design



The sample chamber is usually 0.2 millimeter to 0.3 mm in diameter and 0.1 mm to 0.2 mm deep upon compression. Pressures of more than 1 Mbar can be achieved with the diamond-anvil cell. The transparent diamonds allow easy experimental observation of the sample, using X-rays or visible-light instrumentation. Ruby fluorescence measurements can determine the pressure in the sample volume, and electrical leads can be embedded for resistivity measurements. Unlike the Soviet high-pressure apparatus shown in figure 5, the diamond-anvil cell has a gasket around the sample, which prevents it from being squeezed out under pressure.

We believe that the failure of the Soviets to produce metallic hydrogen resulted in at least two significant lasting effects on Soviet static high-pressure physics. First, the failure has led a new generation of Soviet physicists into a critical reexamination of their research program. The result we have observed, in

Soviet scientific writing [redacted] is that experimental high-pressure work in the USSR is belatedly turning to the Western approach. Second, at the IFVD, we see research into high-pressure phenomena moving in new, much more applied directions.

New Research Directions

We believe that Soviet high-pressure physics research has been redirected toward applied aspects. In recent years, [redacted] have reported that the IFVD, the key Soviet static high-pressure institute, has responded to Communist Party pressures and noticeably increased its ties with industry. Geophysical research at the IFVD in collaboration with the Institute of Earth Physics in Moscow was reported two years ago and confirmed again in 1983 in open Soviet literature. Earthquake prediction was mentioned as a motivation. Possible army involvement in this geophysical research has been mentioned. [redacted] although we do not place high credence in that [redacted] Although static high-pressure experiments have applications to geophysical studies of conditions deep in the Earth, most geological phenomena of direct military interest (such as signatures of underground nuclear tests or silo vulnerability studies) are dynamic and would be better studied with shock-wave experiments than with large presses.

Other research work reported under way at the IFVD in 1982 and 1983 includes: storage of hydrogen under pressure in metals; development of new magnetic and thermionic materials; studies of artificial polycrystalline diamonds for industrial use; and syntheses of new materials using powder-metallurgical techniques. We believe that hydrogen storage could be for Soviet industrial or other energy consumer use, or it could be related to nuclear weapons design work. We believe the other IFVD projects all have a reasonable chance of yielding practical, near-term applications

We believe the IFVD has deemphasized many areas of basic research, but we have evidence [redacted] that it has grown stronger in other, more practical subfields of high-pressure physics. From the viewpoint of [redacted] this redirection may give the appearance of "drift." Putting the pieces together, though, indicates that the institute's chief (Yakovlev) is a very successful leader, doing precisely what is necessary for the IFVD to recover from its metallic hydrogen failure. His move toward applications-oriented research fits in with the general, politically driven trends in Soviet high-pressure physics today.