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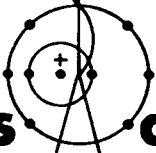
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METALLIC HYDROGEN:
A BRIEF TECHNICAL ASSESSMENT

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D. T. Vier and A. T. Peaslee, Jr.

ABSTRACT

A brief technical assessment of the status of international research on metallic hydrogen is presented. Research methods are outlined; published work in the USSR, the US, and several other countries is reviewed. A prognosis is given for metallic hydrogen. Potential military applications and future research requirements are discussed. A bibliography is included.

I. INTRODUCTION

Chemical classification of elements places those with a single outer (valence) electron, i.e., a single electron in the first unfilled shell, into a category called alkali metals. This category includes lithium, potassium, sodium, etc., in which the bonding of the valence electron to the atom is weakened by the presence of additional electrons in interior shells. Hydrogen (H) is placed in the alkali metals category by default, since the valence electron is the only electron present in the neutral atom. The first electronic shell of an atom is filled only when exactly two electrons are present. There is thus a strong tendency for hydrogen atoms to exist paired as diatomic molecules (H_2). Although the hydrogen atoms form diatomic molecules with strong internal bonding forces, the molecules experience only very weak forces in interactions with each other. Hydrogen is unique among the elements in its simplic-

ity; it could be expected to have some unusual properties.

Molecular hydrogen exists as a gas under normal conditions. It can be liquefied at about 20°K through cooling at atmospheric pressure. It will form a solid at 14°K with a complex crystal structure. Solid molecular hydrogen is a low-density (about 0.09 g/cm³) dielectric (electrical non-conductor) material.

Since about 1935, numerous theorists have postulated the existence of an additional solid state for hydrogen, the metallic state. In the metallic state, the atoms would no longer exist as diatomic molecules. Instead, they would be considered as a regular array of protons embedded in a sea of free-moving electrons. Many calculations have been made that indicate a degree of stability for this type of atomic hydrogen structure. However, the computed interatomic distances required for stability in the

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atomic form are considerably less than those observed for the molecular form. In order to achieve the compact atomic form, it is believed that a large external pressure is required to be exerted on the molecular form. The present literature indicates significant disagreement on the magnitude of the pressure required to obtain the molecular-atomic solid transition. The disagreement appears to arise from both the current lack of knowledge regarding the response of hydrogen molecules to such external forces, and the insufficiencies in the mathematical models used to describe systems of atoms and molecules.

Two important properties have been postulated for the metallic form. The first of these is metastability, i.e., retention of the metallic form (produced at low temperature and under high pressure) after the pressure is reduced and the temperature is raised. The second is superconductivity at temperatures far above that of ordinary superconductors (about 15°K). Most researchers today expect that a molecular-atomic transition will occur in hydrogen. Such transitions have been observed in the USSR for other crystalline materials (e.g., salt, sulfur, silica and alumina). Many researchers question the postulated metastability of the metallic form, especially at temperatures higher than the melting point of solid molecular hydrogen. Correspondingly, most researchers will admit the possibility of the metallic form being superconducting, but many question the postulated high critical temperature (the temperature at which it would cease being a superconductor).

The potential value of metallic hydrogen hinges on a favorable outcome for its postulated metastability and superconductivity. In the following sections, the known international research in this area will be reviewed, the prognosis for metallic hydrogen will be discussed, potential military applications for the material will be listed, and additional research

necessary to resolve existing questions will be discussed.

II. THE WORLD-WIDE METALLIC HYDROGEN EFFORT

Both theoretical and experimental research has been conducted on molecular and atomic hydrogen. In the following text, several research methods that have been used or proposed will be reviewed. The review is followed by a discussion of work that has been done in the USSR, in the US, and in other countries.

A. Research Methods

Nearly all experimental work has been oriented toward the production of very high pressures and the application of these pressures to molecular hydrogen and deuterium. The work generally falls into two major categories, dynamic and static.

The dynamic technique is exemplified by the work of Fowler at the Los Alamos Scientific Laboratory (LASL) and of Hawke at the Lawrence Livermore Laboratory (LLL). Hawke's description of the technique is:¹

Figure 1 shows a cross section of the experimental apparatus. An initial magnetic field is generated by use of a pair of coils and a capacitor bank. The magnetic field diffuses through a stainless-steel liner surrounded by high explosive. When the diffused magnetic field is close to its peak value, the high explosive is detonated and the liner is cylindrically imploded. The implosion compresses the magnetic flux and increases the magnetic field intensity. During the flux cumulation, eddy currents generated in the sample tube and liner interact with the magnetic field and exert an outward pressure on the liner and an inward pressure on the sample tube.

Pressures up to about 4 Mb have been obtained with this method; the duration of the high-pressure pulse is very short (submicro-second). Diagnostic equipment can include high-speed framing cameras with high-explosive-driven argon flash lamps, inductive pickup loops, and pulsed x-ray radiographic machines. The pressure obtained is not measured directly, but is deduced from radiographic measurements and indirect computations. Vereshchagin of the Soviet Union says of the dynamic technique:

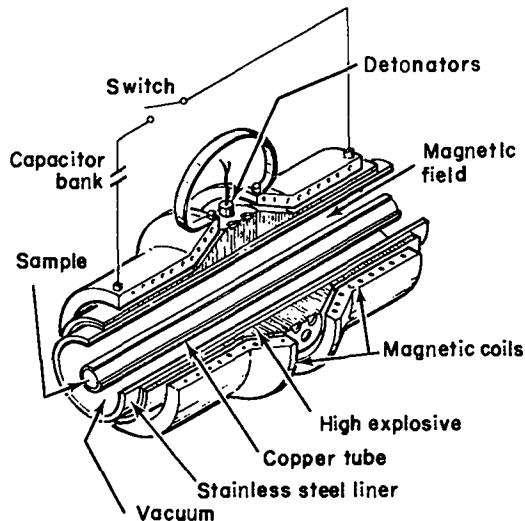


Fig. 1. Cutaway view of experimental apparatus.

The disadvantages of pulsed methods include the inability of saving the phases produced; moreover, the investigated phase transitions in many cases cannot take place within the time of existence of high pressures.

The static technique is exemplified by the work of Vereshchagin et al. His description of the technique is:

"Reaching such pressures by static methods requires not only the forces of colossal presses, but especially new construction materials with outstanding properties. Work is being conducted... on a press for investigating the problem of metallic hydrogen. The press is designed to produce a maximum force of 50 000 tons." (See Fig. 2.)

"One of the most effective methods... is development of multistaged chambers with the proper choice of material for each stage.

"Detection of a new phase is also an important problem. The fixation of transition to the metallic state is possible on the basis of measurements of electrical conductivity and temperature dependence; detection of transition from the molecular lattice to the atomic can be done by measuring the proton resonance.

The materials to which Vereshchagin refers include a form of man-made diamond (Carbonado), a form of boron nitride (Borazon), tungsten carbide, and high-strength steels. The experimental procedure involves placing a very thin layer of sample

material onto an anvil of Carbonado, and then loading the sample by means of a Carbonado plunger, as shown schematically in Fig. 3. Pressures of several megabars are attainable over very tiny nonuniform areas.

An alternate approach to the formation of metallic hydrogen has been proposed by Hess of Germany. This method involves the formation of atomic hydrogen by dissociation via an electric discharge in a cryostatted apparatus. The atomic form is maintained (without recombination to the molecular form) by means of high magnetic fields. The magnetic fields would be used to maintain spin alignment of the electron magnetic moments. Condensation of the atomic form at temperatures below 1.2°K might lead to metallic hydrogen. Further investigation of this method is being done at NASA's Lewis Research Center.

Reviews of the Soviet and US literature on metallic hydrogen, to be presented in the remainder of this section, show that most of the reported work is of a theoretical nature. Despite the thorough theoretical understanding of the detailed behavior of a single hydrogen atom, the *ab initio* determination of the characteristics of a many-bodied substance (such as solid hydrogen) from quantum theory is intractable. However, theoretical techniques have success-

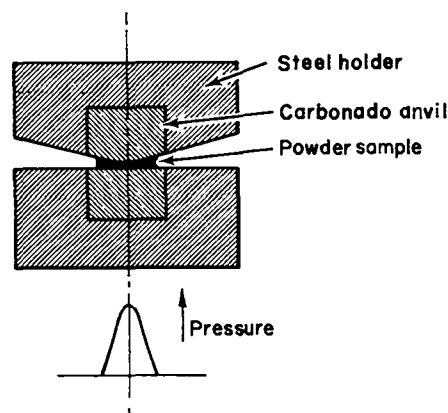


Fig. 3. Schematic of the anvils and qualitative pressure distribution.

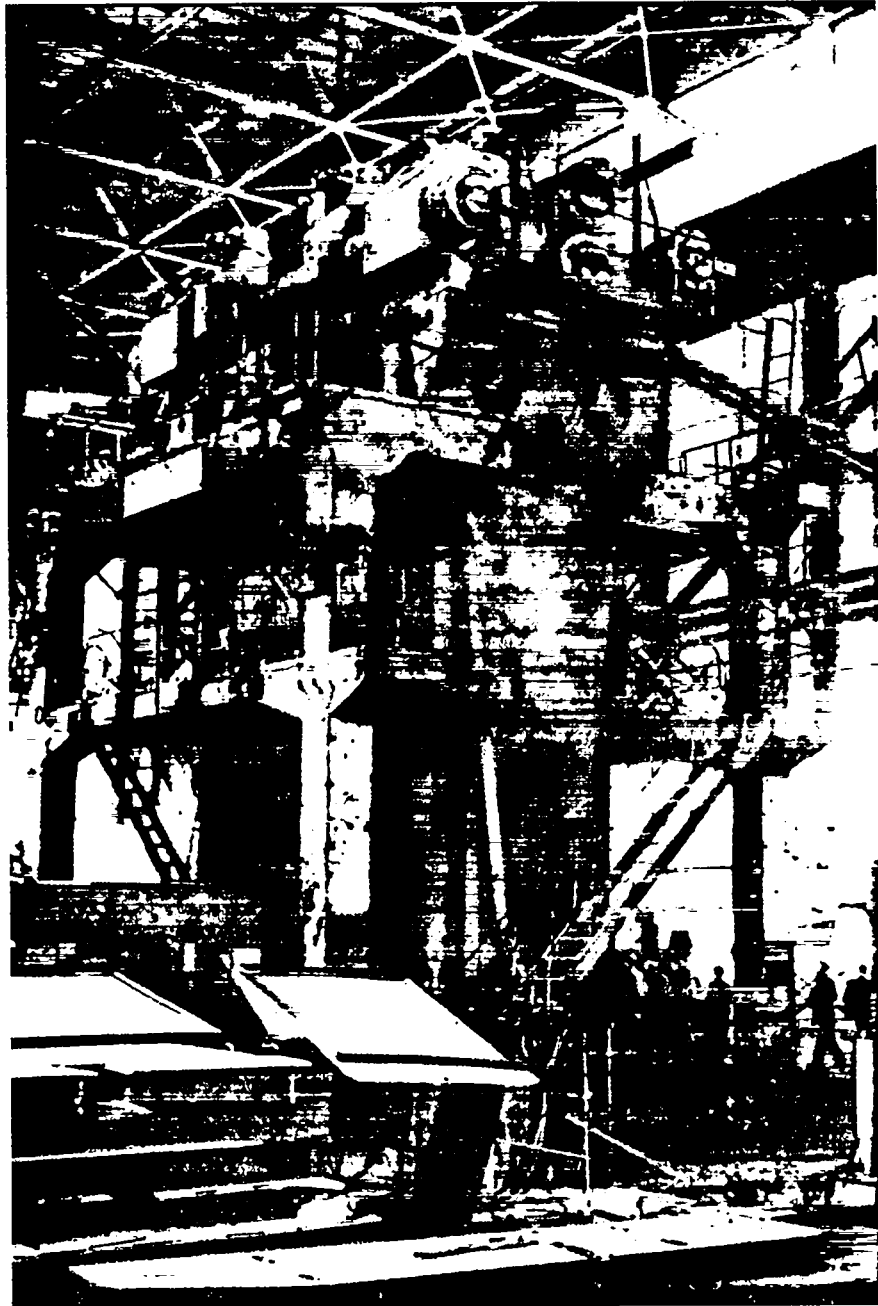


Fig. 2. The 50 DDD-ton press at Krasnaya Pakhra. Only the portion above ground level is shown; the press' foundation is located approximately five stories underground.

fully provided the framework to describe accurately the properties of some solids and metals. The same techniques should also be credible for the prediction of a metastable metallic solid hydrogen under extremely high pressures. The high pressures are needed to order the hydrogen nuclei in a regular lattice and to permit the emergence of a band structure and corresponding metallic behavior at room temperatures and even permit superconductivity at much lower temperatures. One such theoretical technique is the free-electron version of the one-electron Hartree-Fock method applied to the Born-Oppenheimer approximation in which the electrons are assumed to move freely within an array of fixed nuclei. The assignment of approximate values, inferred from the macroscopic properties of other substances, to the adjustable parameters in the approximate theoretical treatment is unsatisfactory. Such a procedure has been used by some to predict a room-temperature, atmospheric-pressure, stable, and superconducting metallic hydrogen. An alternate description is given by thermodynamic treatments which indicate that metallic hydrogen will return to ordinary molecular solid hydrogen at ambient pressure and will exhibit no superconductive behavior above the sublimation point of solid molecular hydrogen.

B. Review of USSR Work

The greatest concentration of effort in the field of high-pressure research in the USSR is at the Institute of High Pressure Physics (IFVD) of the Academy of Sciences of the USSR at Krasnaya Pakhra headed by Academician Leonid F. Vereshchagin. Other Soviet facilities are involved in investigations pertinent to metallic hydrogen (but not necessarily limited to such work) and are listed in Table I. Only a portion of the total staff at the IFVD are directly engaged in work on metallic hydrogen. Most of the 28 investigators at IFVD listed in Table A-1 in the Appendix have published in areas other than high-

pressure hydrogen. Metallic hydrogen, although considered to be important, is only a part of the large effort in a broad spectrum of high-pressure investigations. The IFVD staff with their special disciplines could readily be used to exploit any successes encountered by that portion of the staff directly engaged in metallic hydrogen investigations.

The 50,000-ton press is the focal point at IFVD, because it would be the apparatus ultimately used for the production of useful quantities of metallic hydrogen, and perhaps also because it is the biggest press under construction for high-pressure research. In May, 1975 Vereshchagin told US visitors to his installation that the completion date for the press would be June 1976. Indeed, the visitors found it difficult to believe that the 50,000-ton press will be usable even by that date. The press was first scheduled to be completed in 1972.

According to Vereshchagin, the theoretical basis for their experimental effort is in part the early theoretical work of I. M. Khalatnikov of the Landau Institute and Yu. M. Kagan of the Kurchatov Institute. It should be noted from Table II that Soviet theoretical efforts are not limited to these two institutes. Dynin at an unknown facility, Trubitsyn at the Schmidt

TABLE I
SITES OF SOVIET HIGH PRESSURE HYDROGEN WORK

Institute of High Pressure Physics	Krasnaya Pakhra
Lebedev Institute	Moscow
Kurchatov Institute (IAEh)	Moscow
O. Yu. Schmidt Geophysical Institute	Moscow
Institute of Metallurgy and Metal Physics	Moscow
Unknown Hydrodynamic Institute	USSR
Institute for Hydrodynamics	Akademgorodok Siberian SSR

TABLE II

RUSSIAN INVESTIGATIONS

WHEN	WHERE	PRINCIPAL INVESTIGATOR	SIZE OF EFFORT	PRESSURE RANGE	METHOD USED	SPECIES STUDIED
Present	IFVD Krasnaya Pakhra	L. F. Vereshchagin	Large	2-3 Mb up to 5 Mb	Static	Atomic & Molecular
1972	IAEH Moscow?	F. V. Grigorev S. B. Kormer	Small	8 Mb	Dynamic	Molecular & Atomic
1971-73	Lebedev Institute Moscow	A. M. Prokhorov	Small	-	Theoretical	Molecular
Present	IAEH Moscow	E. G. Brovman	Small	-	Theoretical	Atomic & Molecular
1966	O. Yu. Schmidt Geophysical Institute Moscow	V. P. Trubitsyn	Small	-	Theoretical	Atomic
1971	Institute of Met. and Metal Physics Moscow	E. I. Estrin	Small	-	Theoretical	Atomic
1972	Soviet Union (?)	E. A. Dynin	Small	-	Theoretical	Atomic
Present	Institute for Hydrodynamics (Akademgorodok)	V. M. Titov	?	up to a few Mb	Dynamic	Molecular

Geophysical Institute, and the Prokhorov group at the Lebedev have also contributed to the theoretical aspects.

More recently, the Institute for Hydrodynamics at Akademgorodok in the Siberian SSR is also reported to be working on hydrogen, employing a dynamic method. Thus far, no publications on metallic hydrogen can be attributed to this group, headed by V. M. Titov.

The first published claim for having made metallic hydrogen may be attributed to the Kormer group at an unknown USSR hydrodynamic facility. Their dynamic technique supports the postulated existence of metal-

lic hydrogen but does not and cannot directly verify any metallic property or the existence of a metastable structure. It is perhaps because of this original claim that Vereshchagin feels comfortable in claiming to have made metallic hydrogen by the static method at IFVD.

Notably absent from Table I and the more detailed listing in Table II are the Soviet universities. It is known that some high-pressure work is being done at Moscow State University, but it is apparently not related to metallic hydrogen.

In spite of the magnitude of effort and Vereshchagin's recent claims, there is a

lack of unanimity even in the Soviet Union on the success of the effort to produce metastable metallic hydrogen. Estrin has presented thermodynamic arguments which predict that metastable metallic hydrogen would melt at a lower temperature than solid molecular hydrogen. Iordanskii et al. argue that the predicted metallic hydrogen structure should be unstable due to unaccounted-for small changes in the electron-electron interaction. These points can only be resolved experimentally.

C. Review of US Work

In contrast to the Soviet centralization of effort at the IFVD described in the previous section, the US effort in static experimental high-pressure research is scattered throughout a large number of US universities and institutions. Although the US high-pressure work is of excellent qual-

ity, most of it is done at pressures under 200 kb. Table III lists the US facilities.

The US high-pressure workers who have contributed to the hydrogen effort are listed in Table A-2 in the Appendix. A brief review of US investigations more directly related to metallic hydrogen reduces the tabulation to the facilities and principal investigators shown in Table IV.

The efforts at LLL include the unpublished dynamic work of R. S. Hawke and coworkers as well as several theoretical papers by M. Ross and coworkers. This is a small effort. A few theoretical papers have been written at LASL dealing with the equation of state of both hydrogen and deuterium. Some experimental research using dynamic techniques has been done at LASL on deuterium.

TABLE III

US STATIC HIGH-PRESSURE WORK UNDER 200 KBARS

<u>Organizations</u>	<u>Universities</u>
Los Alamos Scientific Laboratory	University of California (Los Angeles)
Lawrence Livermore Laboratory	University of California (San Diego)
Sandia Corporation	University of Illinois
General Electric Corporation	Cornell University
E. I. DuPont Co.	Penn State University
Bell Telephone Labs	University of Chicago
National Bureau of Standards	Brigham Young University
Carnegie Institution of Washington (Geophysical Labs)	M. I. T. (Lincoln Laboratory)
United States Geological Survey	University of Rochester
Naval Ordnance Labs	Princeton University
Wright Patterson Air Force Base	Iowa State University
Lewis Research Center	University of California (Berkeley)
	Rice University
	University of Maryland

TABLE IV

US INVESTIGATIONS

WHEN	WHERE	PRINCIPAL INVESTIGATOR	SIZE OF EFFORT	PRESSURE RANGE	METHOD USED	SPECIES STUDIED
1973	Lawrence Livermore Laboratory	R. S. Hawke	Small	~3 Mb	Dynamic	Atomic
Present	Lawrence Livermore Laboratory	M. Ross	Very Small	-	Theoretical	Atomic
Present	LASL	D. Liebenberg	Small	20 kb	Static	Molecular
Present	LASL	G. Kerley D. Liberman R. Mills	Small	-	Theoretical	Atomic
Present	LASL	R. Dick	Small	D.3 Mb	Dynamic	Molecular
Past	LASL	D. Janney	Small	9 Mb	Dynamic	Molecular
1968 to Present Future	Cornell (NSF)	A. Ruoff N. Ashcroft	- Small	~3 Mb -	Static Theoretical	Molecular, Atomic Atomic
Present	Watervliet Arsenal	L. V. Meisel	-	-	Theoretical	Molecular
Future		J. F. Cox D. M. Gray	Small	~1 Mb	Static	Atomic
Present	Lewis Research Center (NASA)	G. Brown	-	-	Theoretical	Molecular, Atomic
Future	University of Maryland (NASA)	I. Spain	Small	~2 Mb	Static	Atomic
Present	NBS	G. Piermarini	Small	>~.75 Mb	Static	No Hydrogen Work
Present	Colorado State University (NASA)	R. D. Ethers A. Anderson (LASL)	Few	-	Theoretical	Atomic
1962	Westinghouse Research Labs	W. J. Carr, Jr.	Few	-	Theoretical	-
1971	University of Utah	F. E. Harris	Few	-	Theoretical	Molecular, Atomic

Cornell University and Watervliet Arsenal have parallel programs for hydrogen work insofar as both facilities are constructing presses and are simultaneously publishing theoretical papers. The presses would be useful for research but would not be capable of producing large quantities of metallic hydrogen and would not achieve the megabar range of pressure in the near future.

Some of the impetus for the research on metallic hydrogen is due to the theoretical work of N. Ashcroft at Cornell in which the possibility of room-temperature superconductivity was reported based on the Bardeen, Cooper, and Schrieffer (BCS) theory of superconductivity. The early work of A. Ruoff at Cornell was funded by ARPA, but his funding is now from NASA and NSF as is the funding for the more recent theoretical papers from Cornell.

Carr published theoretical papers in 1962 from the Westinghouse Research Laboratory, but, apart from Cornell, the more recent publications have been from the ongoing work of R. Eppers at Colorado State University and Harris and his colleagues at the University of Utah as well as LASL and LLL.

Although no hydrogen work has as yet been done at the National Bureau of Standards (NBS), the highest pressure presently attainable in the US by static techniques (D.75Mb) would be available there.

The NASA-sponsored work at the Lewis Research Center in Cleveland and at the University of Maryland are of interest, the former because of the unique approach to the formation of atomic hydrogen with subsequent separation. The University of Maryland high-pressure research directed by I. I. Spain plans to use the split-sphere press concept for attaining pressures in the megabar range. This technique will be described in the review of Japanese work.

D. Review of Work in Other Countries

The work done on metallic hydrogen in both Europe and Canada involves but a hand-

ful of people as shown in Table A-3 in the Appendix. This work is of good quality and has been adopted as a basis for further research by both Russian and US investigators. The concept of forming and stabilizing atomic hydrogen by a dissociating electric discharge was initiated by R. Hess in Germany and has been adopted for further development in the US. Vereshchagin has been quoted as relying on the theoretical work of T. Schneider of Switzerland for furthering the Soviet investigations. The theoretical publications of Caron of Canada and Ostgaard of Norway are also well regarded. These investigators and their affiliations are listed in Table V. The Japanese high-pressure work is predominantly experimental and is the nearest potential competitor to the Soviet effort.

N. Kawai of Japan has built a split-sphere apparatus, in which the simplest single-stage version consists of segments of spheres with truncated inner faces assembled together with small spaces between them. The front faces that form the anvils enclose the sample to be compressed. Movement is accomplished by surrounding the outside of the sphere with a deformable membrane and immersing the sphere in a fluid for pressing in a hydrostatic chamber. By increasing the stages, and thus increasing the external surface area compared to the internal surface area of the sphere, pressure multiplication factors in excess of 10^3 may be readily achieved. A three-stage press is being developed at the Osaka University. Professor Kawai has 10 to 15 graduate students investigating various aspects of high-pressure physics. According to Kawai, the volume in the center of the split-sphere apparatus is much greater than that planned for the 5D DDD-ton press in the Soviet Union and is still capable of reaching pressures of 1 to 2 Mbars. The University of Maryland's apparatus is an outgrowth of the Kawai split-sphere press, an outcome of I. I. Spain's year in Japan with Kawai.

TABLE V

INVESTIGATIONS BY OTHER COUNTRIES

WHEN	WHERE	PRINCIPAL INVESTIGATOR	SIZE OF EFFORT	PRESSURE RANGE	METHOD USED	SPECIES STUDIED
1969 to Present	IBM Zurich Switzerland	T. Schneider	Small		Theoretical	Atomic
Present	Tokyo University Osaka University Okayama University Japan	S. Minomura N. Kawai T. Ito	Small 15 People Small	1-2 Mb	Static	No Hydrogen Work Yet
1971	Stuttgart Germany	R. Hess	Few	Low (~100 atm)	Static	Atomic
1973	University of Trondheim Norway	E. Dstgaard	Few	-	Theoretical	Metallic
Present	Canada	L. G. Caron	Few	-	Theoretical	Atomic

S. Minomura of Japan has studied in the US with Drickamer at the University of Illinois prior to establishing his own high-pressure facility.

T. Ito, a member of the Japanese Academy of Sciences, is assumed to have been in the high-pressure field for some time.

III. THE PROGNOSIS

The announced formation of metallic hydrogen by Vereshchagin and coworkers at the IFVD will increase interest in this material and accelerate studies of its preparation and properties. The independent verification of its preparation is of primary importance. Other evidence supports the existence of metallic hydrogen; on theoretical grounds, it has been predicted to exist under conditions of megabar pres-

ures. Experimental high-pressure shock-wave data for molecular hydrogen are interpreted as indicating the formation of the metallic form.

Its formation is suggested in a general way by the prediction and observation of metallic phases of other materials. One example is metallic carbon, also prepared by Vereshchagin's group using the static pressure technique. The metal was prepared at a pressure of about 1 Mbar. On lowering the pressure somewhat below the dielectric/metallic transition point, the metal was metastable and transformed back to diamond when heated at the reduced pressure. Upon raising the temperature further, it was possible to cross the retrograde diamond-to-metal pressure-temperature phase boundary to again form the

metal. This behavior is similar to that observed for silicon and germanium, which have also been prepared in metallic form at high pressure, and to that of the grey-to-white tin transformation (common white tin metal is metastable below 18°C). Other substances that have been prepared in metallic form at high pressures are compounds that are electronically and crystallographically similar to tin and germanium, and include ZnS, ZnSe, ZnTe, CdSe, CdTe, AlAs, InP, InAs, InSb (metastable at -25°C), GaAs, and GaSb, together with the dissimilar substances S, I, Se, SiO₂, NaCl, Al₂O₃, TaN, and La₂S₃. The latter two are both low-temperature superconductors and are metastable under ambient conditions.

The preparation of metallic hydrogen in metastable form is of vital interest, at least at low temperatures and ambient pressure. Unfortunately, no evidence exists that it is metastable at ambient pressure, nor have any stabilizers been reported. Hopefully, substances such as lithium might be added to stabilize the metallic form; LiF has been suggested as a stabilizer. Some metastability was reported by Vereshchagin et al, namely, that metallic hydrogen was metastable to a few tenths of a megabar and to a temperature of 20°K under pressure. Even a careful search for a stabilizer may not be successful, but at least a cursory search will be made by present investigators.

Another critical area is the determination of the physical and chemical properties of metallic hydrogen. In particular, there has been considerable interest recently in the application of metallic hydrogen as a "room-temperature" superconductor. The stabilization of the metal at room temperature is clearly less probable than that at low temperature. Suggestive of the problems are the melting and boiling points that might be expected for the metastable form. On the basis of phase studies and thermodynamic considerations, metastable phases have lower melting and boiling points than

the corresponding stable phase; the melting and boiling points of metallic hydrogen should thus be lower than 14 and 20°K respectively. The preparation and properties of metallic deuterium should be similar, but more favorable (molecular deuterium has melting and boiling points of 18.6 and 23.6°K respectively).

Metallic hydrogen may melt to form a liquid metal (now assumed to give Jupiter and outer planets a magnetic field) and vaporize to form atoms rather than molecules, particularly if the atomic vapor pressure (and hence the atomic-to-molecular recombination rate) is assumed to be extremely low. In this case, metallic and molecular hydrogen might be viewed as two different substances (e.g., oxygen, O₂, and ozone, O₃), and metallic hydrogen might exhibit considerable stability. Furthermore, several theoretical approaches consider the metal to be similar to lithium and other alkali metals, and the Debye temperature has been calculated to be well above 1000°K. Vereshchagin's reported observation of an instability at a few hundred kilobars at 4°K and at somewhat higher pressures at 20°K indicates that this type of stability is not obtained. A quench under pressure to about 1°K has not been reported and should be tried. Certainly, confirmation of the instability merits consideration.

IV. POTENTIAL MILITARY UTILITY

For the purpose of discussing the potential military utility of metallic hydrogen, and depending upon the particular applications, at least some of the following assumptions will be made regarding the material:

1. It will be metastable under all natural environmental conditions.
2. It will be superconducting at temperatures at least as high as the boiling point of nitrogen (77°K).

3. It will be chemically compatible with at least some containment materials.
4. The release of atomic-molecular transition energy (about 400 kJ per gram-mole) can be obtained on demand.
5. It can be produced economically in quantity.

A. Compact Energy Storage

It has been estimated that the energy required to achieve the molecular-atomic transition in hydrogen is about 400 kJ/gram-mole. This energy, provided from an external source during formation of the metallic form, would be stored in the atomic lattice and be available through initiation of the reaction $2H \rightarrow H_2$. A weight-basis comparison of this energy release with that of more familiar reactions is given in Table VI; the transition energy is about 40 times that of TNT.

If the transition energy release rate is not controllable once the reaction is initiated, applications may be limited to explosive devices such as conventional bombs and shells. If the reaction can be

controlled only in those cases where the material is finely divided (as is the case in most conventional high explosives such as RDX), then applications could include rocket motor fuel for propulsion or pulsed power (e.g., MHD) sources. If the reaction is totally controllable, additional applications may include heat sources for compact power supplies (fuel cells, etc.), and propellant for nuclear-powered propulsion units.

The application of metallic hydrogen to conventional bombs and shells is attractive in terms of available firepower. Since the density of metallic hydrogen is postulated to be about 1 g/cm^3 , a shell designed to contain 10 kg of TNT would contain 6.3 kg of metallic hydrogen whose energy yield would be 27 times that of the TNT.

B. High-Temperature Superconductors

Estimates of the critical temperature (T_c) of the postulated superconducting metallic hydrogen range from $<14^\circ\text{K}$ to room temperature (about 300°K). At the present time, superconductors have little or no direct military applications because of the elaborate cryogenic equipment required to maintain the very low temperatures necessary for superconductivity. If the optimistic

TABLE VI

ENERGY RELEASE

<u>Reaction</u>	<u>Approx. Energy (J/g)</u>
Thermonuclear Fusion (D-T)	2.8×10^{11}
Fission of Uranium	8×10^{10}
$2H \rightarrow H_2$	2×10^5
Hydrogen Combustion $2H_2 + O_2 \rightarrow 2H_2O$	1.2×10^5
TNT Detonation	4.6×10^3

estimates for T_c are more nearly correct, several immediate applications may be found.

Nearly every current-carrying element in aircraft and missiles could be improved through substitution of metallic hydrogen for the presently-used copper, silver, or aluminum, on the basis of weight savings alone. However, the future for military use of superconductors probably lies in advanced weapons of the beam type (lasers, neutral- or charged-particle). These weapons will use huge pulses of electrical power; the energy generation, storage, and conditioning equipment will have to be light, rugged, and efficient. Magnetic energy storage and field devices, e.g., inductive stores and magnets, are logical applications of superconductors, but their practicability is presently limited by the necessary cryogenic equipment.

Although it is not of immediate military significance, one of the major present applications for superconductors is in electrical power transmission lines. The goal of this work is the development of nearly lossless transmission lines for high-current, high-voltage, DC power transfer.

C. Laser Fusion

Present laser fusion research is directed toward laser-induced implosion of small pellets of a liquid deuterium/tritium mixture. Substitution of the metallic form would allow higher densities, and hence higher energy yields, to be obtained.

V. NECESSARY ADDITIONAL RESEARCH

Independent confirmation of Vereshchagin's announced experimental result should be undertaken using his type of apparatus. His data indicate a total load on the Carbonado anvils of only 5D kg -- a load that is easily obtainable with routine laboratory equipment. High pressures were achieved by virtue of the extremely small contact area of the anvils (approximately 0.1 mm diameter). Carbonado-type material is available

in the US from Megadiamond Corp. of Provo, Utah. This material might be used to duplicate Vereshchagin's anvils.

It is clear now that the construction of the huge 50 000-ton press at Krasnaya Pakhra was not undertaken just to verify the existence of metallic hydrogen. However, the press will be a research tool with unique capability to produce super-hard materials in quantity. In addition, it will have the capability to provide relatively large samples of materials in metastable or metallic states -- samples large enough to allow good determination of their physical properties. There are larger presses already in existence in the Soviet Union and in the US (about 70 000 tons capacity). The distinguishing feature of Vereshchagin's press is that the design of the press is uniquely suited to research purposes, rather than to the production of large metal stampings, forgings, or extrusions.

There are several major questions that must be addressed before the value of metallic hydrogen can be assessed. These questions are posed and discussed in the following:

Q: Is the postulated metastability real?

Is the postulated superconductivity real?

Vereshchagin's results only indicated a transition to the conductive (and inferred metallic) state, and an unknown degree of metastability with respect to pressure release at very low temperatures. All other regimes in which metastability is important, i.e., low temperature and low pressure, room temperature and high pressure, room temperature and low pressure, remain to be investigated.

A complete and detailed pressure-volume-temperature map is required for hydrogen. Estimates have been made of the effort required to obtain such a map. With the static technique, and pressures up to about 100 kbars, three to five people would require about 5 yr. With the dynamic technique,

a similar effort would be necessary to extend the pressure range up to about 1 Mbar.

Q: What is the feasibility and necessity of producing atomic hydrogen?

Current experimental approaches start with the molecular form of hydrogen and attempt to achieve the metallic form through direct application of pressure. The metallic form is an atomic, not molecular, form. It has been suggested that one should start with the atomic (i.e., dissociated) form in order to get the metal. However, the strong tendency for atomic hydrogen to recombine into the molecular form may preclude this approach. Hess' suggestion involving strong external magnetic fields may offer a way out of this difficulty; it may even make the application of high pressures unnecessary. The behavior of free atomic hydrogen in the presence of the molecular form at low temperatures and pressures is not well known and should be vigorously investigated.

ACKNOWLEDGMENTS

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APPENDIX

HIGH-PRESSURE RESEARCHERS

Table A-1 contains a list of known high pressure research personnel in the Soviet Union. Most of these people are directly concerned with metallic hydrogen.

Table A-2 is a list of personnel engaged in similar work within the US. Not all of the US personnel listed have worked specifically on metallic hydrogen -- the

work of some has been confined to molecular hydrogen.

Table A-3 is a list of persons engaged in high-pressure work in other countries. The Japanese have not been concerned with hydrogen, but they have the capability of doing high-pressure hydrogen work.

TABLE A-1

KNOWN SOVIET HIGH PRESSURE RESEARCHERS

Institute of High Pressure Physics

L. F. Vereshchagin	N. Kuzin
E. N. Yakovlev	V. A. Stepanov
Y. A. Timofeev	T. D. Vartolomeeva
G. N. Stepanov	V. N. Slesarey
V. P. Sakun	L. E. Shterenberg
B. V. Vinogradov	S. M. Stishov
A. A. Semerchan	J. S. Konyayev
V. P. Modenov	N. S. Fateeva
T. T. Bocharova	F. F. Voronov
S. V. Popova	V. V. Eydekimova
N. I. Pal'nikov	S. S. Kabalkina
L. N. Fomicheva	G. E. Itskevich
V. Badanov	V. V. Kechin
Yu. Sadkov	D. A. Alichunov

Institute of Atomic Energy imeni Kurchatov

E. G. Brovman	A. Kholas
Yu. M. Kagan	V. V. Pushkarev

Institute of Physics imeni Lebedev

G. A. Askaryan	V. A. Namiot
M. S. Rabinovich	M. A. Markov
A. M. Prokhorov	O. N. Krokhin
O. V. Bogdankevich	A. A. Rukhadze

Institute for Theoretical Physics imeni Landau

I. M. Khalatnikov	S. I. Anisimov
S. V. Iordanski	O. V. Lokutsievskii
E. B. Vul	L. A. Sidorovich
A. M. Finkel'shtein	

Geophysical Institute imeni Schmidt

V. P. Trubitsyn	V. Zharkov
A. Makalkin	

Institute of Metallurgy and Metal Physics

E. I. Estrin

Institute of Hydrodynamics (Akademgorodok)

V. M. Titov

Location Unknown

F. V. Grigorev	S. B. Kormer
O. L. Mikhailova	A. P. Tolochko
V. D. Urlyn	E. A. Dynin

TABLE A-2

US HIGH-PRESSURE RESEARCHERS

Cornell University

J. A. Krumhansl	N. W. Ashcroft
E. L. Pollock	A. L. Ruoff
T. A. Bruce	E. E. Salpeter
G. V. Chester	D. Straus

Lawrence Livermore Laboratory

W. G. Hoover	C. F. Bender
R. N. Keeler	D. Boutwell
M. Van Thiel	M. Ross
B. L. Hord	F. H. Ree
R. S. Hawke	G. F. Chapline, Jr.
R. J. Olness	J. G. Huebel
F. J. Rogers	

University of Utah

David E. Ramaker	Lalit Kumar
Frank E. Harris	J. J. Monkhorst

Los Alamos Scientific Laboratory

D. Liebenberg	E. Kmetko
D. Liberman	A. Anderson
G. I. Kerley	M. Krupka
D. Janney	R. Mills
T. Neal	C. M. Fowler
R. Dick	

NASA Lewis Research Center

G. V. Brown

University of Michigan

R. S. Kass	W. L. Williams
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University of Maryland

I. I. Spain	J. M. Marchello
J. Paaue	

Purdue University

J. D. Raich (Presently at Colorado State University)

Iowa State University

C. A. Swenson

US Military Academy, West Point

W. Streett

TABLE A-3

KNDWN HIGH-PRESSURE RESEARCHERS OF OTHER COUNTRIES

JAPAN:

Osaka University

N. Kawai
S. Mochizuki
H. Fujita
S. Endo

A. Nishiyama
A. Onodera
M. Togaya

Tokyo University

S. Minomura (FNU) Akimoto

Okayama University

T. Ito

GERMANY:

Stuttgart

R. Hess

CANADA:

University of Sherbrooke

L. G. Caron

NORWAY:

University of Trondheim

E. Ostgaard

SWITZERLAND:

IBM Zurich

T. Schneider
P. F. Meier

E. Stoll

University of Zurich

H. Beck