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Some thoughts of an American scientist on the dynamic high-pressure work of Academician Ya B Zel'dovich

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There is no question that Academician Ya B Zel'dovich was the most talented individual to turn his efforts to the solution of problems in the field of dynamic high pressure; no one in the high pressure field was his equal except the Nobel Laureate P W Bridgman. Indeed, an exceptional legacy exists today in the work of his associates and students L V Al'tshuler, S B Kormer and Academician V E Fortov. And it must be said that the body of work by these investigators considerably exceeds that of workers in the same field in the United States in both quality and quantity of results achieved. In this introduction I will deal with the application of dynamic techniques to problems which were of interest to Academician Zel'dovich: problems of condensed matter physics, chemical physics, and geophysics. Although applied shock–wave physics was of considerable interest to Zel'dovich, it was not his principal research interest, and it will be mentioned here only in passing.

In the long period of the Cold War which now stands behind us, a major casualty was that free spirit of scientific collaboration we see exhibited today. Academician Zel'dovich was one of the casualties as were all of us who were denied the experience of reading and studying his work — and meeting him in person In this introductory summary, I would like to briefly describe my two meetings with Academician Zel'dovich. Then, I would like to close with a historical perspective on the American and Soviet dynamic high pressure programmes.

Those of us who worked on military programmes started with the mathematical text of Courant and Friedrichs [1], but our principal textbooks were the two-volume series by Zel'dovich and Raizer [2], the American text by Watson, Bond, and Welch [3], various review articles by Al'tshuler [4] and Kormer [5], and for those working in detonation physics, the text by Zel'dovich and Kompaneets [6].

At the AIRAPT† Conference in Moscow in 1975, organised by the late Academician L F Vereshchagin, L V Al'tshuler, S B Kormer, A I Pavlovskii, and other scientists from Arzamas 16 met colleagues from the USA for the first time. But it was not until the COSPAR‡ Conference in Budapest in 1980, that I had the privilege of first meeting Academician Zel'dovich. By this time Zel'dovich was fully involved in astrophysics. It was a period of great of excitement in the community, with new discoveries of pulsars, bursters, black holes, neutron stars, and other exotic objects taking place almost daily. As each paper on these topics was given, Zel'dovich would take his brush pens and prepare transparencies. At the end of these presentations, Zel'dovich would frequently come to the podium and clarify or summarise the work, often pointing out possible avenues of future investigations. He was particularly solicitous of the younger investigators just entering this exciting new field.

Zel'dovich did not attend the sessions on high pressure geophysics, but I did have a chance to chat with him at the Soviet Embassy one evening. In the afternoon, I had refereed a soccer game between a Russian and Hungarian team which included Academician Sagdeev on the Russian side. Sagdeev invited me to the reception honouring the Soviet Delegation that night at the Embassy. During the evening, I again encountered Academician Zel'dovich. "Ah, Professor Keeler" he said sweeping his arm in the direction of Budapest's main street. "There is a gymnasium (high school) down the street. At that gymnasium were Teller, Wigner, von Karman, Szilard, and von Neumann. What a gymnasium!" Zel'dovich knew that at that time that I was an associate of the noted atomic scientist, Edward Teller, and he was fully aware of the contributions of all these great men, although he was denied the opportunity to meet them.

The second and last time I met Academician Zel'dovich was in Moscow, at his office at the Landau Institute. It was in June, 1986, and I was passing through Moscow from Kiev where, as President of AIRAPT, I was participating in the planning of the 1987 conference. The meeting took the better part of a day, and at its conclusion Academician Zel'dovich posed for a photograph (Fig. 1). We discussed a number a topics in high pressure and detonation physics including ways of definitively testing the Chapman–Jouguet hypothesis, and whether a material could become colder upon the passage of an intense shock wave. These two topics will be discussed later in this introduction.

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‡COSPAR is the Committee on Space Research, a Division of ICSU, the International Council of Scientific Unions, and is based in Paris, France.

With the 1987 AIRAPT Conference to be held in Kiev, the sentiment was strong among the Executive Committee to elect Academician Zel'dovich the 1987 Bridgman Award Medallist. In fact, 12 out of 18 voting members of the AIRAPT Executive Committee wanted to elect him. At that time, the outgoing president, Nestor Trappeniers, decided to modify the selection process, and appoint a committee of five scientists, serve as Chairman, and present the Executive Committee with two names to vote on. Imagine our surprise when neither of the names presented by the Committee was Zel'dovich and the Soviet Executive Committee members had presented another name in nomination. The members of the Executive Committee were upset, and we polled those members of the Award Committee we could contact. Harry Drickamer, the dean of US static high pressure work (who was supporting one of his former students for the award) referred to Zel'dovich as an ''obscure Russian chemical kineticist''; Trappeniers refused to support him as did Marvin Ross of Livermore, who apparently was ignorant of most of Zel'dovich's work. After several discussions, I decided to ask the Committee to wait for two years at which time we could renominate Zel'dovich under the new guidelines. With an overwhelming number of the Committee supporting him, his election was assured in 1989. This decision was a mistake that I will always regret. Academician Zel'dovich died on 2 December 1987. So you can see that it is something of a penance and a redemption as well as an honour for me to stand before you today in tribute to Academician Zel'dovich.

The journal *High Pressure Research* solicited an obituary for Zel'dovich. Some of us prepared an extensive summary of his work and career with emphasis on his achievements in the dynamic high pressure and detonation area. Unfortunately, the Editor of *High Pressure Research*, Marvin Ross, cut down this submission to few short paragraphs [7]. So there was no appropriate obituary for Academician Zel'dovich in the Western literature, at least in the area of dynamic high pressure.

Dynamic high pressure work had its origin in the development of high explosives and their uses. The relationships governing the behaviour of intense shock waves were first derived by H Hugoniot in 1871 [8] and a summary of typical work on conventional military applications is discussed in an excellent set of reviews edited by Burke and Weiss [9]. Although in the USA work in this area originated out at the Naval Ordnance Laboratory in White Oak and the Ballistics Research Laboratory in Aberdeen, and in the Soviet Union at the facilities at Chernogolovka near Noginsk, it is fair to say that before the Second World War, no significant physics experiments were carried out using dynamic or shock-wave techniques.

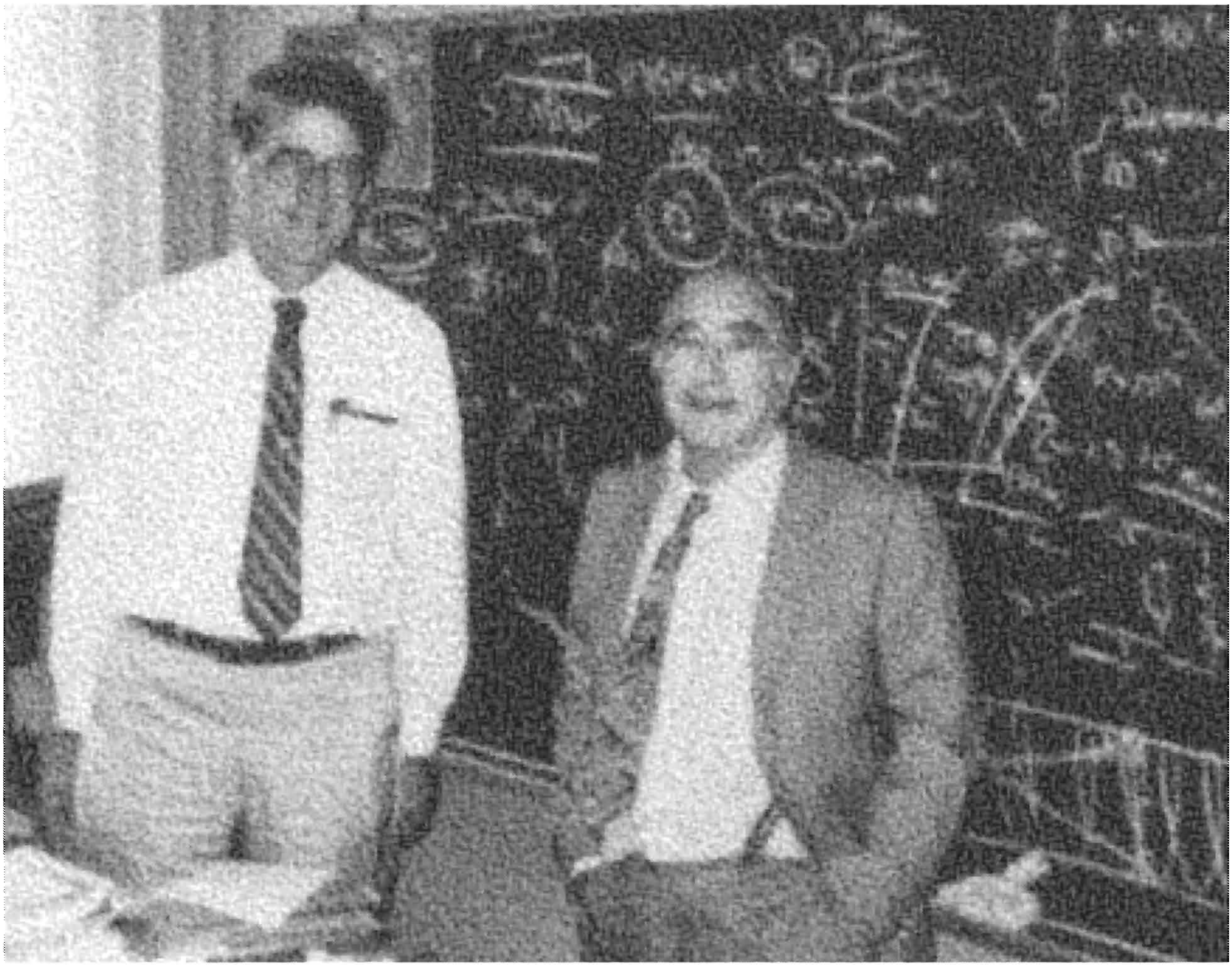
The first and most significant theoretical papers in the US on shock and detonation waves were written at Los Alamos by Hans Bethe [10]. He paved the way for the beginning of our understanding of how to use shocks and detonations to do physics experiments. Somewhat later, Zel'dovich and L V Al'tshuler began to apply shock-wave techniques for equation-of-state determination. Much of this activity began in Arzamas 16 in 1948.

The US effort became concentrated at Los Alamos under the direction of Roy Goranson, and after 1952 was directed by J M Walsh and subsequently R W McQueen. The Los Alamos group at first concentrated on high pressure effects, and the manifestations of phase transitions and elastic–plastic phenomena on equation of state [11, 12]. They were the first to clearly understand the nature of the release adiabat as being isentropic. The Livermore group began much of its work in 1956 under the direction of Dr B J Alder, who was the first in the US to clearly understand the breadth of scientific possibilities of dynamic high pressure work [13]. This group was led by Russell E Duff from 1961 to 1968, and under his direction began to produce innovative scientific results of the highest originality. They were the first to carry out laser spectroscopy, flash x-ray diffraction, shock demagnetisation, various equation-of-state and conductivity measurements on materials of geophysical interest [14], and, finally, the determination of the metallisation pressure of condensed hydrogen to be 2 megabars† [15], which has been verified by fly-bys of the planets Jupiter and Saturn. However, in 1975, this group shifted its emphasis to rather routine applied hydrodynamics and, with the departure of John Shaner for Los Alamos in 1979, the group limited most of their studies to liquefied gases. They also initiated some controversial programmes such as attempting to prove that materials can experience a decrease in temperature after the passage of extremely strong shock waves, and a collaboration with the California Institute of Technology to try (unsuccessfully) to determine the melting temperature of iron and its alloys by shock-wave temperature measurements‡ [17–19]. The question of shock-induced cooling, which runs counter to intuition (see, for example, the previously cited work of Bethe) and created all sorts of anomalies in $P-V$ space (isotherms crossing, isentropes lying below the associated Hugoniots) could be due to experimental error [20]; in any case, no independent experiments were carried out to verify the dissociation to which the phenomena were attributed. Also, no analysis was done to determine how the energy taken up by this new degree of freedom was apportioned. As Academician Zel'dovich pointed out on reviewing this work, ''It is not reasonable to propose a new phenomenon not independently verified, then attribute all of an experimental anomaly observed to this new hypothetical mechanism''. In the case of the melting of iron, the anomalously high temperatures reported by Ahrens have now been explained in a recent work of Brown [21] who points out the errors associated with his experiments. Thoughout the earlier more creative period, however, these exciting projects owed much of the success they achieved to the experimental genius of Arthur Mitchell§ [22]. At the same time, a considerable amount of original theoretical work on equation of state was carried out at Livermore by H C Graboske [23], A K McMahon, Forrest J Rogers, and F H Ree [24]. Some of this work still continues. Much of this earlier work was ahead of its time, since experimental realisation of the states studied was some 20 years in the

† See, for example, a paper by M Ross [16] attempting to explain these experimental results. A credible case is made for incrementally small shock waves in superfluid helium in a controlled laboratory environment, but not for strong shock waves in highly compressed liquid nitrogen for the reasons cited herein.

‡ These results were shown to be inconsistent with well established data by L V Al'tshuler at the AIRAPT Conference at Paderborn, Germany, in 1989, and subsequently by other investigators.

§ Arthur Mitchell perfected the use of the two-stage light-gas gun.



Yakov Borisovich Zel'dovich and R Norris Keeler in L D Landau Institute of Theoretical Physics, RAS, June 1986

future. Since it is not the primary topic of my part of the introduction, this area is only mentioned in passing and will be discussed by others. Also, since the work in the US on the attainment of high pressure by staged systems and with nuclear explosives was extremely limited, and for the most part unpublished, I will leave this area to my colleagues Professor Avrorin and Academician Fortov [25].

In considering the confusion which ensued from the attempt to make these optical measurements in the US, one recalls that Zel'dovich returned to the field of dynamic high pressure twice in his career: once to clarify the issue of electromagnetic effects in shock waves [26] and another time to provide a solution for his colleagues on the problem of some anomalous shock temperature measurements [27]. One might wish that Zel'dovich could have provided colleagues at Livermore with some guidance as they attempted to use these difficult optical techniques in their own experiments [28]†.

With the arrival of John Shaner at Los Alamos a new era of creative work with extremely strong shock waves began there, and in collaborative work with the static high pressure community Shaner established the ruby standard now commonly used throughout the world [29]. S Schmidt and D Moore continued the laser spectroscopy work initiated at Livermore [30]. Work on equation of state and sound velocity of shocked solids established the melting pressure of iron [31], and expanded the diamond region of the carbon phase diagram [32]. Shaner's 'expanding wire' experiments extended our knowledge of the melting of refractory metals, as well as of the behaviour of liquid metals at supercritical volumes [33]. Other interesting shock-wave work was done in Taylor instability, electronic transitions, instrumentation, and photonic compression. In 1987, Shaner joined the DOE Strategic Disarmament Negotiating Team, and left shock-wave work behind. The programmes he started were eventually discontinued and that group has become inactive.

Sandia Laboratory carried out a certain amount of work on the electromagnetic effects encountered in shock-wave passage [34], and this will be discussed in our paper in the general session. They also developed the widely used 'Visar' gauge [35], as well as other types of gauges, which I will also discuss later. More recently, some effort was expended in using shock waves to synthesise various materials, but nothing of consquence emerged from this work [36]. This group as well has become mostly inactive, although static measurements of high quality still continue.

A limited amount of work was carried out at universities and the Stanford Research Institute, but this work was not

†In some of the last work to be carried out at the Los Alamos shock-wave facility, US investigators appeared to have finally gained a sound understanding of these difficult experiments. See the excellent recent work [28].

'on the frontiers' of the field [37] as one prominent scientist observed.

The Soviet program has always been extremely vigorous, and exceptionally well led right up to the present. Immediately after World War Two, L V Al'tshuler assumed leadership of the Arzamas 16 programme, and shortly thereafter, S B Kormer, a student of Academician Zel'dovich became active. Their interests were complementary, with Al'tshuler exploring the world of shocks, reflected shocks, Mach stems, obtaining extremely high pressure by staging techniques, and some limited work on conductivity [38], and Kormer exploring optical effects [39]. Al'tshuler carried out the first high pressure work using spherically imploding high explosive systems, and the use of nuclear explosives to obtain pressures in the tens of megabars region [40]. Kormer was first to use porous materials to achieve high temperatures at extended volumes, a technique originally proposed by Zel'dovich [41]. Work on porous substances is being carried out at this very moment by my co-chairman, at the dynamic high pressure research facilities at Chernogolovka. In 1966, Al'tshuler left Arzamas 16, but remained active in shock-wave work through the present [42]. Kormer's experiments, carried out until his death in 1980, involved a number of optical experiments, many of them in collaboration with Academician Zel'dovich. He mastered these techniques thoroughly, and was able to measure the melting temperatures of the alkali halides [43]. In these experiments he was able to show optically that the band gap decrease reported by US workers on the basis of conductivity measurements [44] was spurious, and due to the excitation of electrons from shock-induced donor states attached to dislocations created by the shock-wave passage [45].

The majority of shock-wave work in Russia today is being carried out at Chernogolovka by one of Zel'dovich's students, Academician V E Fortov and his talented colleagues. Fortov is unique, in the sense of P W Bridgman, in having created an entirely new field of physics — the field of dense plasmas. For many years there was a general belief that certain plasma states could not be achieved experimentally; these were extremely dense states of density up to critical density and temperatures up to several electron-volts. Using techniques from adiabatic compression by ballistic projectiles to detailed studies of release isentropes, measuring the release pressures in combination with electrical conductivity and spectroscopic techniques, as well as experiments into the hundreds of megabars region involving nuclear explosives, Fortov has opened up a grand view of $P-V$ space never before explored, and has provided a new generation of theoreticians with experimental results they never dreamed of obtaining [46].

One of the better known shock-wave scientists in the US is said to have remarked that he had "kept shock-wave research alive for another ten years". Is shock-wave work really near death? From the work continuing to emerge from Russia, it certainly is not. But consider other possible work, work on the frontiers of science which cannot yet be carried out by the now widely used diamond anvil cell technique. One of the yet unsolved problems is the proof of the Chapman – Jouguet hypothesis. This involves in situ measurement of the sound velocity in detonation products. And what about the phase diagram of carbon? Work on that problem, which started so strongly at Los Alamos in the 1980s and showed that the melting line of diamond has a positive slope in the $P-T$ plane (a discovery which completely changed our view of this question) was discontinued years ago. Is the liquid phase in equilibrium with diamond conducting or insulating? And if it can be both, is there a first order liquid – liquid transition between these two liquid states? The melting line of iron has been determined — but only on the principal Hugoniot. Determination of the slope of this line could help establish the presence (or absence) of an ε-iron – γ-iron – liquid triple point. This issue is now being explored by 'dynamic' experiments carried out in diamond anvil cells. Ammonia and water have been converted to completely ionised dense fluids. When do they become metallic? The ingenious expanding-wire experiments of Shaner can determine surface tension and viscosity in supercritical metals. Viscosity of highly compressed fluids and plasmas can also be obtained. More geophysical measurements are there to be made. These are only a few of the areas which could be explored.

The shock-wave community in the United States is no longer able to carry out these types of experiments. The key personnel have gone, there is no scientific leadership, the laboratories are eliminating this type of work, and the emphasis is shifting to defense conversion. So, in closing, I might observe that one of the many lasting legacies of Academician Zel'dovich is a strong and productive research programme in dynamic high pressure physics in Russia. And I am looking for new leadership and the future return of the US to an active programme in this field.

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