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General survey of certain results in the field of high-pressure physics

Nobel Lecture, December 11, 1946

In this lecture I shall attempt to present a general survey of those parts of the field of high-pressure physics with which I have had direct contact, dealing first with technical matters of producing and measuring high pressure, and secondly with the physical phenomena which occur under high pressure.

With regard to technique, several different ranges of pressure are to be recognized. The first step was to devise a method of packing which should be without leak, since leak had limited the range of previous experiments. A packing was devised, shown in Fig. 1, which automatically becomes tighter the higher the pressure, so that any pressure is accessible up to the strength of the containing vessels. If the vessels are made of one-piece construction,

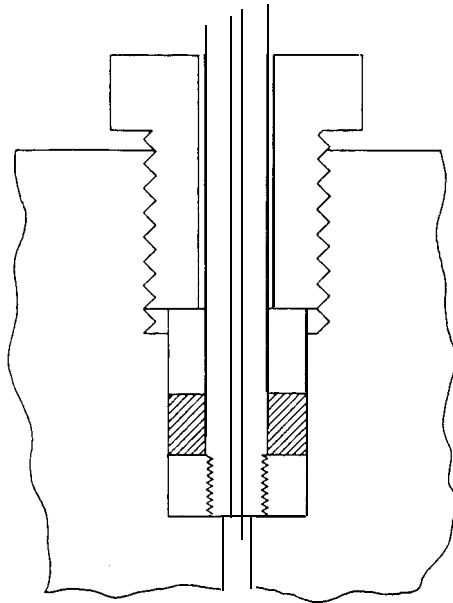


Fig. 1. The general scheme of the packing by which pressure in the soft packing materials is automatically maintained a fixed percentage higher than in the liquid.

from the best heat-treated alloy steels, it is possible to reach pressures of $12,000 \text{ kg/cm}^2$ as a routine matter and on occasion for short intervals of time as high as $20,000$. For many years my work was confined to this range, and in this range it proved feasible to measure nearly all the ordinary physical properties of substances. The next step was to give the pressure vessel external support which increases in magnitude at the same time the internal pressure increases. A simple method of doing is to make the external surface of the pressure vessel conical in shape, and to push it into a heavy collar with a force which increases as the internal pressure increases, as illustrated in Fig. 2. With apparatus of this kind it is possible to make routine experiments up to $30,000 \text{ kg/cm}^2$ with volumes of the order of 15 cm^3 , to get electrically insulated leads into the apparatus, and practically to repeat all the former work in the range to $12,000$. I am still engaged in carrying out this program. An extension of the same technique on a smaller scale with capacities of the order of 0.5 cm^3 can be made up to $50,000 \text{ kg/cm}^2$. In this range all ordinary liquids freeze solid, electrically insulated leads cannot be got into the apparatus, and the phenomena which can be studied are limited to various volume effects, such as compressibilities and phase changes, including fusions and polymorphic transitions.

The external support of the vessel is only one of the factors that makes possible the extension of range from $12,000$ to $50,000$. No steel piston will support as much as $50,000$; carbonyl, however, the recently developed substance for tools formed by cementing a fine powder of tungsten carbide with

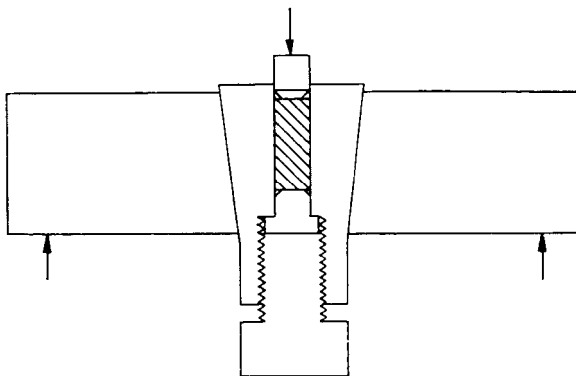


Fig. 2. Illustrating the general principle of the method for giving external support to the pressure vessel in such a way that support increases automatically with the increase of internal pressure.

cobalt, fortunately proves to have a compressive strength high enough for the purpose.

The next step in extension of range, from 50,000 to 100,000 kg/cm², demands still more effective support of the pressure vessel. This is done by immersing the entire pressure vessel in a fluid under pressures ranging up to

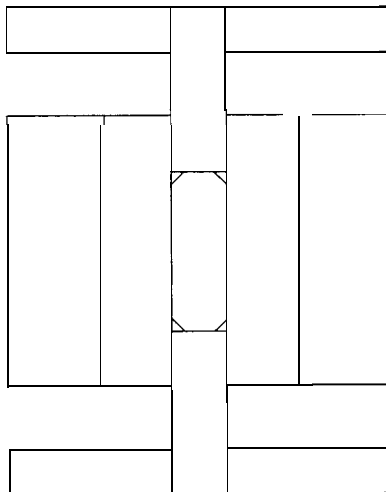


Fig. 3. The miniature apparatus for reaching 100,000 kg/cm².

30,000 kg/cm². The pressure apparatus has to be made still smaller; the pistons are only 1.6 mm in diameter, and the capacity is only a few cubic millimeters. The pressure cylinder itself, as well as the pistons, is now made of carbonyl with an external jacket of shrunk-on steel to give it greater strength. The piezometer is illustrated in Fig. 3. Even with this type of construction so great an extension of range as from 50,000 to 100,000 would not have been possible if it were not for a fortunate change in the properties of metals under pressure. At pressures of 25,000 kg/cm² ordinary grades of steel become capable of almost indefinite deformation without fracture, so greatly has their ductility been increased, as shown in Fig. 4. Even carbonyl loses its normal brittleness and becomes capable of supporting without fracture higher tensile stresses than steel.

Up to the present, the compressibilities and polymorphic transitions of some 30 elements and simple compounds have been studied in the range to 100,000.

Much higher pressures than 100,000 can be reached in very small regions

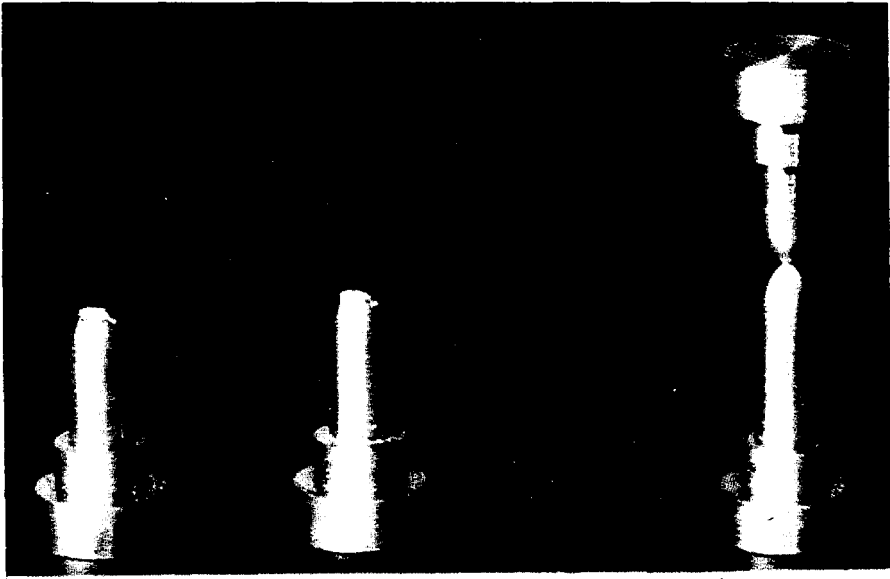


Fig. 4. Illustrating the effect of pressure in increasing the ductility of steel. *On the left*, a piece of mild steel broken in tension at atmospheric pressure. *On the right*, the same steel pulled to a much greater reduction of area without fracture in a liquid at 25,000 kg/cm².

by constructing the apparatus entirely of carbonyl, but up to the present no particularly important physical results have been attained in this range.

In addition to the problem of attaining the pressures, there is the problem of measuring them and measuring the effects which they produce. This demands in the first place the establishment of various fixed points. In the range up to 30,000 a sufficient number of such points has been established to permit measurements to an accuracy of about 0.1 per cent. A transition of bismuth in the neighborhood of 25,000 gives one such convenient point. An essential part of the measuring technique is the utilization of the change of resistance of manganin under pressure, first suggested by Lisell at Uppsala. Above 30,000 the territory is not so well marked out; it is probable that the measurements to 100,000 have an accuracy of about 2 per cent.

It is natural to think of volume compression as the simplest and most fundamental of all the effects of hydrostatic pressure, and for that reason it will be discussed first here. It is not, however, the simplest to measure experimentally, because the measurements immediately obtained are relative to

the containing vessel, which is itself distorted. Elaborate procedures may be necessary to eliminate the effect of such distortion.

The compression of gases is outside the range of this work; at pressures of 1,000 kg/cm² or more the densities of gases become of the same order of magnitude as those of their liquid phase, and there ceases to be any essential difference between gas and liquid. If the volume of any ordinary liquid is plotted as a function of pressure at constant temperature, a curve will be obtained which at low pressures has a high degree of curvature and a steep tangent, meaning a high compressibility, but as pressure increases the curvature rapidly becomes less and the curve flattens off. In Fig. 5 the volume of a typical liquid, ether, is shown as a function of pressure. For comparison, the curve of the most compressible solid, caesium, is also shown. Two different physical mechanisms are primarily responsible for the different behavior in the low and high pressure ranges. The low range of high compressibility is the range in which the chief effect of pressure is to push the mol-

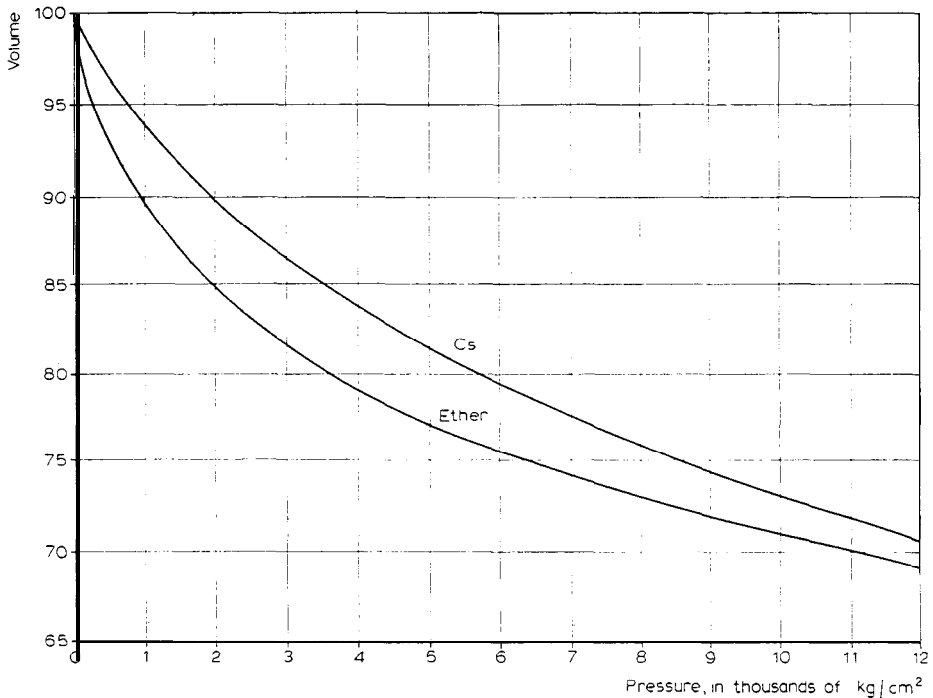


Fig. 5. Volume as a function of pressure for a typical liquid, ether. The corresponding curve is also shown for caesium, the most compressible solid. The liquid is initially much more compressible than the solid, but at higher pressures is less compressible.

ecules into closer contact, eliminating the free spaces between them. In this range individual substances may show large and characteristic individual differences. In the higher range the molecules have been pushed into effective contact, and the compressibility now arises from the decrease of volume of the molecules themselves. This effect persists with comparatively little decrease over a wide range of pressure. This effect is of course present also in the lower range of pressure, but there it is masked by the much larger effect arising from squeezing out the free spaces between the molecules. If one attempts to set up a formula for the effect of pressure on volume on the basis of measurements in the low range only, one will be likely to neglect too much the contribution from the compressibility of the molecules, with the result that the actual volumes at high pressures will be found to be materially smaller than the volumes which would be extrapolated from the low-pressure formulas. This, as a matter of fact, has been a property of practically all the formulas that have been derived from low-pressure data.

At high pressures, the volumes of ordinary organic liquids become surprisingly alike in spite of initial differences. To illustrate the rapid falling off of compressibility with pressure, the volume change in the first 5,000 kg/cm² is roughly the same on the average as the volume change between 5,000 and 50,000; the effect is accentuated by the fact that the volume decrement in the latter range often includes the volume discontinuity on freezing.

In the low-pressure range, in which the molecules are being pushed into effective contact, one might expect effects depending on the shapes of the molecules, and that these effects would be highly specific with the liquid. This is the case. In the low-pressure range a great variety of small-scale abnormalities are superposed on the larger-scale uniformities, and these small-scale effects vary greatly from liquid to liquid. Thus there may be sub-ranges of an extent of a few thousand kg/cm² in which the compressibility increases with increasing pressure instead of decreasing as is normal, or the thermal expansion may also increase with increasing pressure instead of decreasing. Any satisfactory theory of liquids must ultimately give an account of these small-scale effects but for the present the large-scale effects must have first attention. When the theory of liquids does come to be written, the first step may well be to set up an idealized « perfect liquid » in analogy to the perfect gas which has played so important a role in the theory of gases. The experimental results at high pressures show sufficient uniformity in the behavior of all ordinary organic liquids to indicate that such an idealized perfect liquid is not too far from the actuality.

The compressibility of solids varies over a much wider range than does that of the ordinary liquids; caesium, for example, is 350 times more compressible than diamond. The highest compressibilities among solids, judging from indirect evidence, are probably to be found in solid hydrogen and helium. As in the case of liquids, the compressibility of solids normally drops off with increasing pressure. This would be expected in general because of the operation of a law of « diminishing returns », and is obviously necessary when pressure is raised indefinitely, because if volume continued to decrease at its initial rate it would eventually become negative. For instance, the volume of caesium would become negative at a pressure of only 14,000 kg/cm² if it continued to decrease with pressure at the initial rate. In spite of the fact

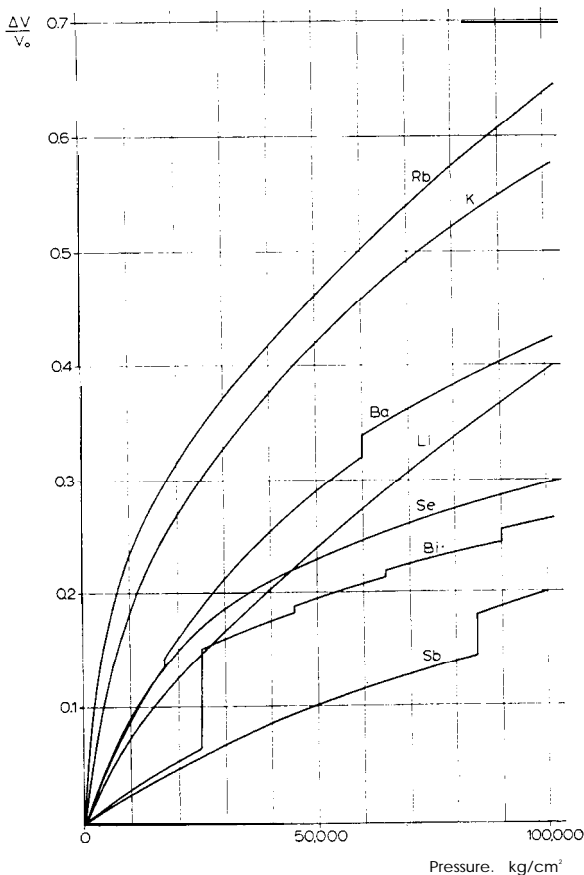


Fig. 6. The volume compression of several elements up to 100,000 kg/cm². The breaks in some of the curves indicate polymorphic transitions.

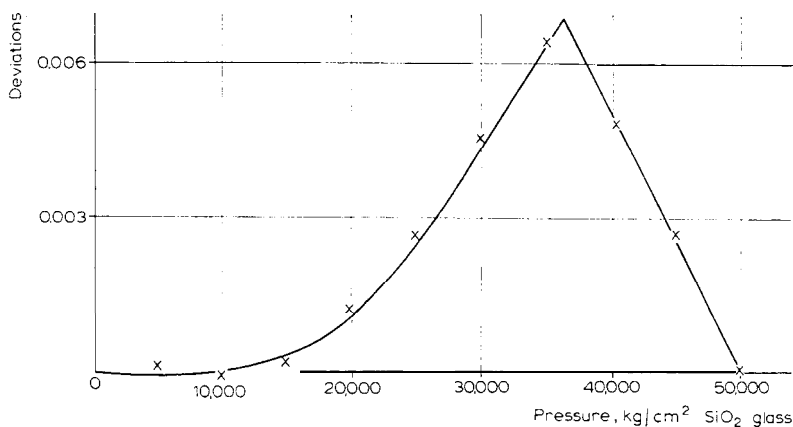


Fig. 7. The deviations from linearity of the volume decrements of quartz glass for pressure increments of 5,000 kg/cm² plotted against pressure. The cusp in the curve marks the change from abnormal to normal behavior.

that the compressibility of solids on the average must decrease with increasing pressure, there is a very marked qualitative difference as compared with liquids. The initial phase of very rapid decrease is absent, and the decrease is spread more uniformly over the entire pressure range. The difference is to be accounted for by the lattice structure of solids; with increasing pressure the atoms retain their position in the lattice with the result that a smaller part of the free space between the atoms is available for occupancy as the centers of the atoms are forced closer together.

The volume decrements of a number of the more compressible solids are shown as a function of pressure up to 100,000 kg/cm² in Fig. 6. The curvature is in general very marked.

There is no thermodynamic necessity that the compressibility should decrease with increasing pressure, although this opinion has sometimes been expressed. Solid substances are known in which the compressibility may increase with increasing pressure over a comparatively wide range of pressure. The most striking example is quartz glass. The compressibility not only increases with pressure, but increases at an accelerating rate. This continues up to 35,000 kg/cm² and then abruptly stops. At this pressure there is a discontinuity in the derivative, a transition of the « second kind » in the nomenclature of Ehrenfest, and from here on compressibility decreases with rising pressure as is normal. The mechanism which is responsible for the low-pressure effect abruptly ceases to act. Fig. 7 shows the relations.

So far we have been considering the effect of pressure on the volume of isotropic substances; this includes substances like glass and all cubic crystals. If the material crystallizes in some non-cubic system, the effects are more complicated. The compressibility is not the same in all directions, so that the shape of bodies composed of such crystals may change under pressure. The differences of compressibility in different directions may be large; thus zinc is eight times as compressible in the direction of the hexagonal axis as at right angles to it. Some difference in this direction might be expected, because the atomic spacing is greater along the axis than at right angles, but no simple consideration would lead to the expectation of differences as large as this. There is even one substance, tellurium, which has a negative compressibility along the axis. That is, when a single crystal of tellurium is subjected to hydrostatic pressure by a fluid in which it is completely immersed, it expands along the axis.

Considerable success has been achieved in calculating theoretically the effect of pressure on the volume of simple solids. The first success was with simple ionic lattices of the type of NaCl by Max Born, who was able to get acceptable values for the lattice spacing and for the initial compressibility. He was not at first successful, however, in reproducing the change of compressibility with pressure, and even today complete success has not been attained in this regard. More complete results have recently been obtained for the alkali metals by applying the methods of wave mechanics. Bardeen has had surprising success in reproducing the entire volume curve over the experimental pressure range for the alkali metals. The calculations are particularly simple here because there is only one free electron per atom, and it turns out that the major part of the effect arises from the increase of kinetic energy of the free electrons arising from their decrease in effective wavelength when the volume is decreased. Other metals, with more free electrons, are more difficult to compute, but it is anticipated that the difficulties are merely difficulties of the complexity of the calculation.

Theory is apparently not yet in a position to attack with much success the problem of non-cubic crystals.

We now consider the discontinuous volume effects arising from phase changes of various sorts. The simplest of these is the effect of pressure on melting. Historically the study of the effect of pressure on melting was approached with the anticipation that the effects would be found to be similar to the effect of pressure on vaporization, and in particular that there would be critical phenomena, so that above a certain pressure and temperature con-

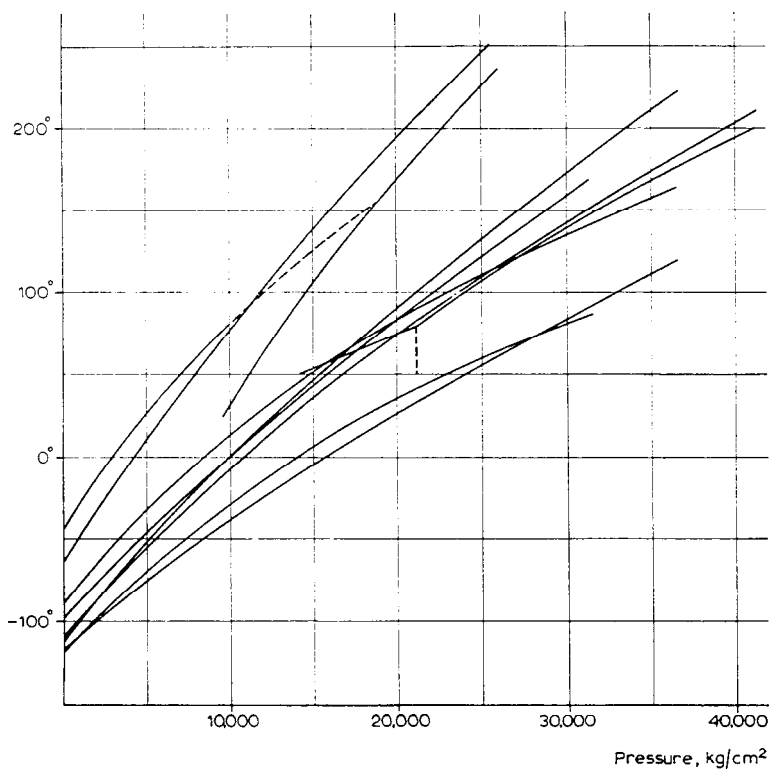


Fig. 8. Melting temperature against pressure for a number of substances. At 15,000 kg/cm^2 the order of substances, reading from top down, is chloroform, chlorobenzene, chlorobenzene (second modification), water (ice VI), 4-butyl alcohol, carbon bisulfide, methylene chloride, *n*-propyl bromide, ethyl bromide, and ethyl alcohol.

tinuous passage would be possible between liquid and solid. It soon appeared, however, that the pressure scale of any such effects must be much more extensive than the scale of the critical effects between liquid and vapor, and that whereas pressures of a few hundred kg/cm^2 were adequate in the latter case, pressures of thousands of kg/cm^2 would be required to produce analogous effects for solid and liquid, if indeed they could be produced at all. With every extension of pressure range the probability of the existence of any such critical phenomena has become increasingly remote. Melting curves have now been followed up to 40,000 kg/cm^2 ; a number of these are shown in Fig. 8. The melting curves of all substances have certain qualitative features in common, so that it is appropriate to speak, of *the* melting curve just as one may speak of *the* vaporization curve. In other respects, however, the situa-

tion with regard to melting is qualitatively different from that with regard to vaporization. In particular, all melting curves, that is, the curve of melting temperature against pressure, are concave toward the pressure axis with a curvature becoming less at higher pressures, and the curve of difference of volume between liquid and solid as a function of pressure is convex toward the pressure axis with a curvature decreasing with increasing pressure. No critical point has ever been observed in the experimental range. If there were such a point outside the range, the latent heats and the volume difference between liquid and solid would have to vanish at a common pressure and temperature. Extrapolation of the curves for latent heat and volume difference indicates that neither of them will vanish at any finite pressure or temperature, to say nothing of both vanishing at the same pressure and temperature. The probability at present seems overwhelming that there can be no critical point between liquid and solid, at least for the type of substance investigated up to now, which includes organic substances of various types and a few metals. The same line of argument rules out the existence of other such features on the melting curve as a maximum temperature or an asymptotic temperature. In general, the melting curve rises to indefinitely high temperatures with indefinitely increasing pressure but at a diminishing rate, the curve becoming more nearly linear.

It is possible to show thermodynamically that if a substance expands when it melts, its melting temperature must rise with increasing pressure, and, conversely, it falls. There are only three substances which belong to the latter category in the ordinary range, water, bismuth, and gallium. Consistent with thermodynamics the melting curves of these three substances are found to fall. Furthermore, the curvature increases and the curves drop more and more rapidly as pressure increases. Such a state of affairs apparently cannot continue indefinitely. Nature extricates itself from the dilemma by the « liquidating » of such abnormal substances. Above a certain pressure the lattices in which these substances initially crystallize become unstable, and the lattice collapses into another lattice. The new lattice has a volume so much less than the former lattice that the solid phase is now more dense than the liquid, and from here on the melting curve rises as for other substances. The collapse of the lattice occurs at a pressure of about 2,000 kg/cm² for water, at 12,000 for gallium, and at 25,000 for bismuth.

The phase changes of these three substances afford a particular example of polymorphism. The phase diagram of bismuth is shown in Fig. 9. Under pressure, polymorphism is a very common phenomenon; the number of in-

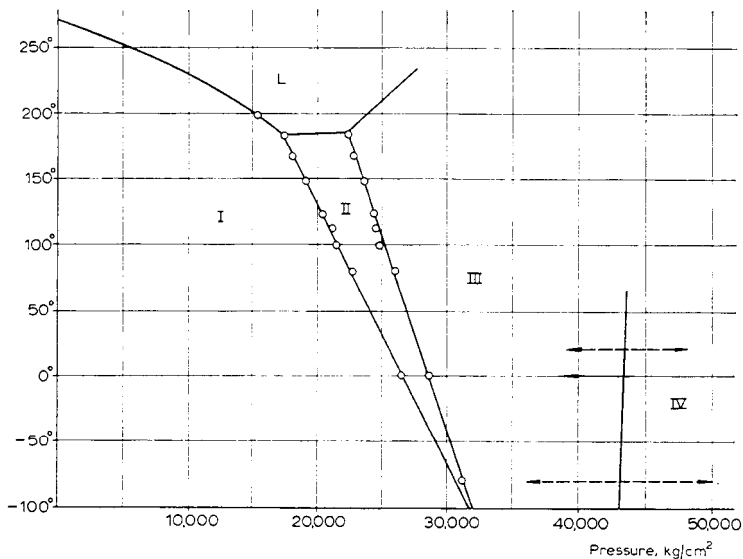


Fig. 9. The phase diagram of bismuth. The arrows on the transition line III-IV indicate the pressure limits within which the transition runs with increasing or decreasing pressure.

stances increases with increase in the experimental pressure range and with increasing sensitiveness in the methods for detecting small discontinuities of volume. In the range from room temperature to 200°C and up to pressures of 50,000 kg/cm², roughly one-third of the substances examined have proved to be polymorphic. In the much greater range of conditions encountered in the crust of the earth, the presumption seems to be that no substance exists in the lattice with which we are familiar under laboratory conditions, unless perhaps the lattice is of a particularly simple type. The importance of such a conclusion for geophysics is obvious.

The thermodynamics of a polymorphic phase change is the same as the thermodynamics of melting, but beyond that there is little resemblance between the two phenomena; there is no such thing as a polymorphic transition curve as there is a melting curve. There are only three falling melting curves, and these disappear at higher pressures; there are many falling transition curves, and they become increasingly numerous at higher pressures. Between 12,000 and 50,000, 41 per cent of the new transition curves are of the falling type. Transition curves may have horizontal or vertical tangents; melting curves have neither. Transition curves may have upward or downward curvature; melting curves are always concave downward. The dif-

ference of volume of two polymorphic phases may increase or decrease in the direction of increasing temperature along the transition line; the difference of volume between liquid and solid always decreases. The compressibility of the high-pressure phase may be greater or less than that of the low-pressure phase; the compressibility of the liquid is always greater than that of the solid. Substances are capable of existing in a number of polymorphic forms, and the complete mapping of the transition temperatures and pressures for all the forms may result in phase diagrams of great complication. Thus bismuth has six different phases; water, which has some striking analogies to bismuth, has seven phases. The most complicated phase diagram investigated to date is that of camphor, which has eleven phases.

There are only two generalizations with regard to polymorphic transitions that stand to date. The first is that critical points and continuous transitions between different polymorphic forms do not occur. If there were such points this would demand a continuous transition from one type of lattice to another, and this seems highly improbable, although perhaps not logically inconceivable. The second generalization is that transitions in the simple CsCl type of lattice in the direction of smaller volumes are not produced by pressure; this lattice seems to be of such a simplicity that it is not likely to be disturbed. This second generalization naturally rests on a much smaller number of examples than the first, and is correspondingly less secure.

We have so far been discussing transitions which are thermodynamically reversible; when pressure is released the original form is resumed. In addition to these reversible transitions, the existence of irreversible transitions is to be recognized, that is, of changes effected by pressure which remain permanent when they have once taken place. Two well-marked examples of this have been found. The first was phosphorus. If ordinary yellow phosphorus is exposed to pressure above $12,000 \text{ kg/cm}^2$ at temperatures above 200°C , it is permanently changed into a black solid much like graphite in appearance, and like it a conductor of electricity, although yellow phosphorus is a good insulator. This remained the only example for many years. Recently I have found that ordinary liquid CS_2 , may similarly be changed permanently into a black solid at temperatures in the neighborhood of 200°C and by pressures of the order of $40,000 \text{ kg/cm}^2$. This black substance is definitely not a mixture of sulfur and carbon, which one might at first expect, but is apparently a unitary substance, truly a black solid form of carbon bisulfide. It has been suggested that the structure may be that of a single giant molecule like the known structure of SiO_2 , which from the atomic point of view is very sim-

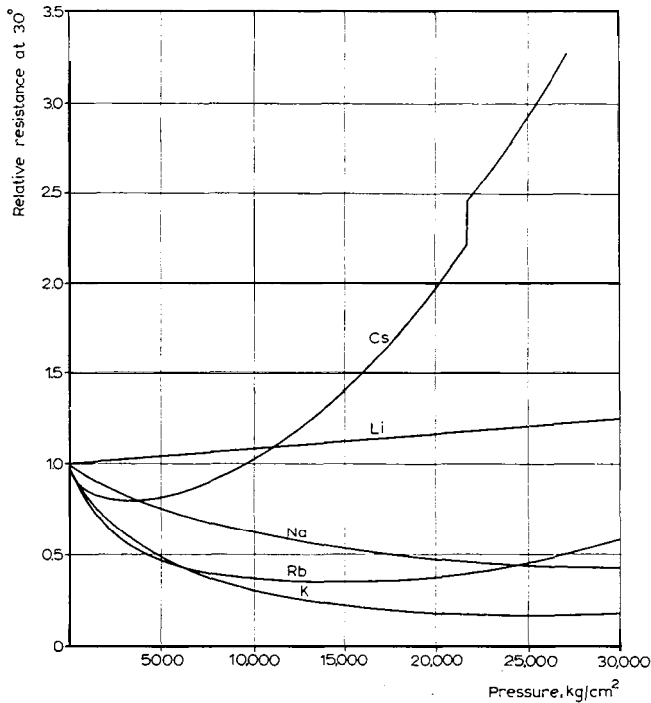


Fig. 10. The relative resistances of the alkali metals up to 30,000 kg/cm². The break in the curve for caesium is due to a polymorphic transition. Potassium has a very flat minimum near 23,000.

ilar. It is fascinating to speculate that there may be many other common substances which may be pushed by sufficiently high pressures over a potential hill of some kind permanently into some hitherto unknown form. Until we have theoretical understanding of these two known permanent transitions, we can not help attaching a certain reasonableness to the assumption of the possible existence of other such substances. In fact, there is experimental evidence that many other such transformations may be effected. In experiments in which I combined high shearing stresses with high hydrostatic pressure I have observed some cases of irreversible transitions to forms already known, and have also observed a large number of color changes, which are the indication of some sort of permanent change. It was not possible to establish whether new substances were formed under these conditions because the quantities of material involved were too small to permit satisfactory analysis.

We pass now to other sorts of pressure effects. Perhaps the simplest of these to measure are the effects of pressure on electrical resistance. Measurements

have been made at room temperature or higher up to 30,000 kg/cm² and at the temperature of liquid air to 7,000. At low temperatures there is a natural limit to the pressure range imposed by the freezing of the medium transmitting pressure, which in this case was gaseous nitrogen. Fig. 10 shows the effect of pressure on the alkali metals at room temperature up to 30,000 kg/cm².

In the first place, there is a specific effect of pressure on resistance; the pressure coefficient of resistance is in general of the order of magnitude of ten times greater than the volume compressibility. This would involve as a corollary that the effect of pressure on the resistance of a highly compressible metal is greater than on a metal of low compressibility. This is indeed true in general, but exceptions are common. The resistance of perhaps three-quarters of the metals decreases with increasing pressure; as is to be expected, the rate of decrease itself decreases with increasing pressure, that is, the curve of resistance against pressure is convex toward the pressure axis. On the other hand, there are several metals, of which lithium, strontium, and bismuth are examples, whose resistance increases under pressure. For these metals, surprisingly, there is a law of increasing returns, that is, the rate of increase of resistance itself increases with increasing pressure. This means that for these metals also the curve of resistance against pressure is concave upward. Finally, there are a few metals which combine both types of behavior, that is, the resistance initially decreases, then passes through a minimum, and then turns upward. Examples are caesium, rubidium, potassium, and barium. It would appear, therefore, that the upward curvature is common to all metals, and that all resistance curves may be regarded as pieces of one single curve, the only difference for different metals being that what might be called the intrinsic zero of pressure is differently situated with respect to atmospheric pressure for different metals.

Considerable success has been achieved by theoretical physicists in explaining theoretically the effect of pressure on resistance. As might be expected when effects departing so largely from linearity are concerned, we can recognize the presence of at least two different mechanisms working in opposite directions. There is in the first place an effect of pressure on what is the analogue of the electron free path in the old gas electron theory of metallic conduction. This is connected with the change of dimensions, and in general works in the direction of an increase of free path, that is, a decrease of resistance, with increasing pressure. In the second place, there is a rearrangement of the energy levels, and this may, when the energy bands are nearly

completely occupied, work in the direction of a change in the effective number of free electrons. Depending on the details of the atomic relations, this effect may be either an increase or a decrease. The calculations have been carried through approximately in a few simple cases. It turns out that the increase of resistance of lithium with pressure is due to the preponderating effect of a decrease in the effective number of free electrons.

The effect of pressure on the electrical resistance of single crystals is sometimes very complicated. If the crystal system is cubic, the material behaves electrically like an isotropic body, but if the system has lower symmetry, there may be differences in different directions. In antimony, for example, the sign of the pressure effect is different in different directions. There are directions in the crystal for which the resistance passes through a maximum with increasing pressure, whereas for other directions the resistance decreases with normal curvature.

The resistance of some semi-conductors may be decreased by such large amounts that they approach the absolute resistance characteristic of the metals. An early investigation in this field was made on selenium and silver sulfide by Montén in Uppsala. At higher pressures, tellurium approaches the properties of a metallic conductor under 30,000 kg/cm². Not only does the absolute value of the resistance drop to a characteristically low figure, but the temperature coefficient, which initially is negative, reverses sign under high pressure and becomes positive like that of the metals proper. Theory is as yet hardly in a position to explain these complicated effects, either in single crystals or in semi-conductors.

Closely related to the electrical conductivity of metals is their thermal conductivity; the relationship is expressed by the approximate equality of the Wiedemann-Franz ratio of electrical to thermal conductivity for all metals. Under pressure, thermal conductivity changes as well as electrical conductivity. It is much more difficult to measure than electrical conductivity, and satisfactory measurements have been made only for a few metals and those up to only 12,000 kg/cm². It appears that for these metals the Wiedemann-Franz ratio is approximately independent of pressure.

The effect of pressure on the thermal conductivity of liquids is much larger than on that of metals, and is much easier to measure. In general, the thermal conductivity increases for ordinary liquids under a pressure of 12,000 kg/cm² by a factor varying between 2 and 3. The effect on water is smaller; at 12,000 the increase for it is only 50 per cent. There is a close connection between the effect of pressure on thermal conductivity of normal liquids and

the effect of pressure on the velocity of sound in the liquid. That is, thermal conductivity in a liquid is primarily a mechanical affair; heat is transferred by microscopic mechanical waves travelling with the velocity determined in the conventional way by the compressibility. The small effect in water is associated with the small change in the compressibility of water brought about by pressure.

Another property of metals obviously related to electrical and thermal conductivity is the thermo-electric characteristics. These properties are also affected by pressure. In general, a metal under pressure behaves thermo-electrically differently from the same metal not under pressure, so that a thermo-couple may be made with one branch of any ordinary metal and the other branch of the same metal exposed to hydrostatic pressure. Under a pressure of 12,000 kg/cm² the thermo-electric power of such couples may be as large

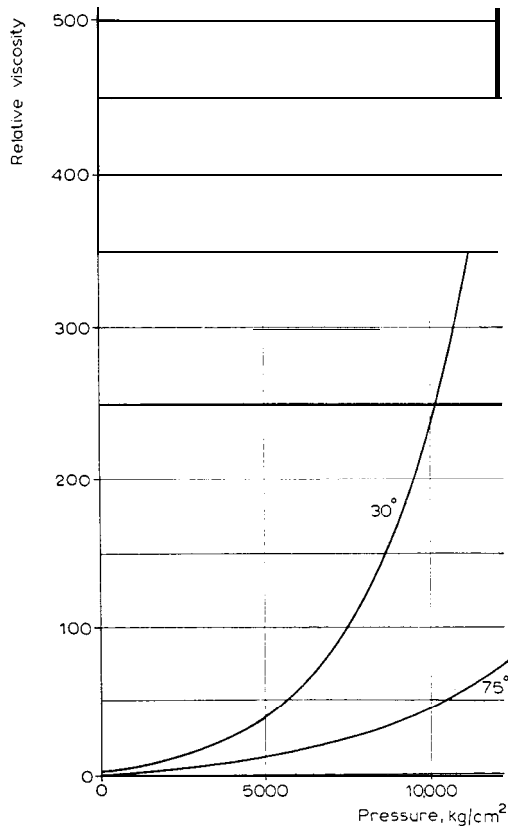


Fig. 11. The effect of pressure on the viscosity of isobutyl alcohol.

as that of ordinary couples composed of two entirely different metals. A number of such « pressure couples » have been investigated. The effects are complicated; there is not any universal rule with regard to the sign of the effect. There may be reversals of sign and large departures from linearity. No satisfactory theory of these effects has been formulated. At present one can only draw the conclusion that the interplay of several different mechanisms must be involved.

The largest of all the pressure effects studied to date is on the viscosity of liquids. In general, viscosity increases under pressure at a rate increasing rapidly with increasing pressure. The curve of viscosity against pressure usually rises exponentially with pressure, and sometimes more rapidly than exponentially. In Fig. 11 is shown the viscosity of isobutyl alcohol at 30° and 75° at pressures up to 12,000 kg/cm². The total rise may be by as much as a factor of 10⁷ for a pressure increase of 10,000 kg/cm² (for eugenol). The rate of rise is definitely linked with the complication of the molecule, and is greater the more complicated the molecule. For the comparatively simple liquid water the rise of viscosity under 10,000 kg/cm² is by a factor of only 2 or 3 and for monatomic mercury by only 30 per cent. For methyl alcohol the increase is by a factor of 10, for propyl alcohol by a factor of 100, and for amyl alcohol by a factor of 1000. In the last few years the theoretical physicists have had considerable success in accounting for the effect of pressure on the viscosity of liquids.