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HIGH PRESSURE PHENOMENA

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Perhaps the earliest high pressure work of note is the celebrated attempt of the Florentine Academy to find whether water is compressible. Using a lead container in which they probably had much less than a thousand pounds pressure, they concluded that water was an incompressible liquid. In 1762-64 Candon carried out some experiments in which he proved that water was compressible, and in spite of the fact that water is sometimes referred to today as an incompressible liquid, experiments have been carried out at the Armour Research Foundation in which water has been compressed to one-half its normal value. The fifty-year period ending 1869 was one in which a great deal was accomplished in the field of high pressure in spite of the fact that very few good numerical results were obtained. Since then a great deal of activity has been shown in the field of extreme pressure investigation, and the literature contains hundreds of articles published by a great many investigators so that at the present time there is a wealth of high pressure data available.

In 1938 I published a curve, (Fig. 1), in the Journal of Applied Physics showing the maximum extreme pressure employed in this work in the preceding two hundred years with the comment that it was rising at such an increasing rate that it makes even the high pressure investigator wonder what the future may lead to in this field.

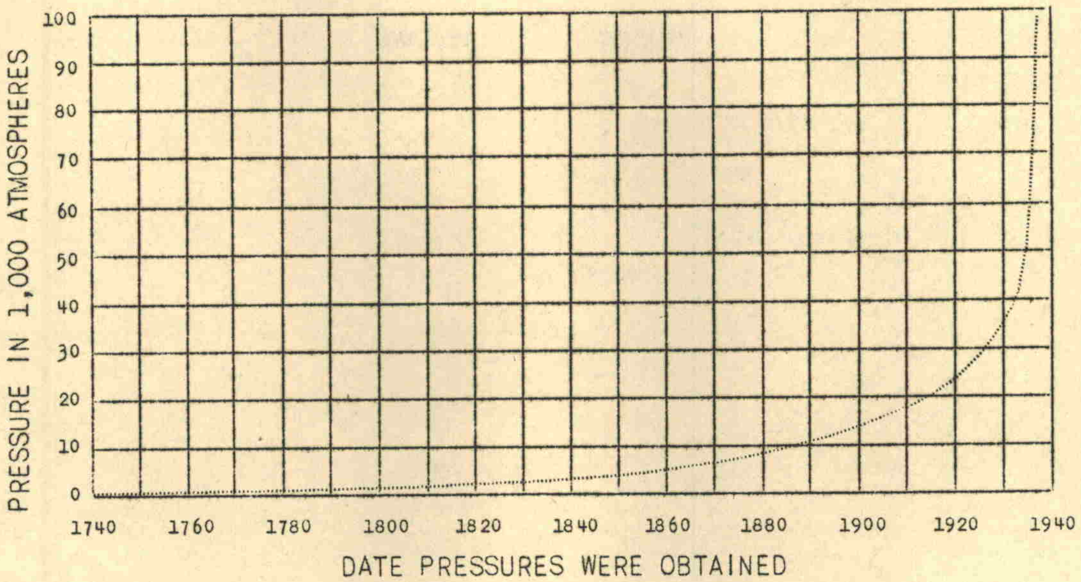

FIG. 1

Less than ten years have elapsed since those figures were conpiled and already pressures which if not controlled by man at least have been initiated by him that have surpassed the maximum values listed at that time by one hundred fold. It is obvious that such extreme pressures can only exist momentarily.

If we are to set up a table of orders of magnitude of pressures in fluids we are apt to consider a perfect vacuum as the minimum pressure that it is possible to obtain but if we wish to consider tensions in liquids as negative pressures, then we can greatly extend our pressure range. Temperley, H.N.V. and Chambers, L.G., (Ref: Proc. Phys. Soc., Lond., 58, 420-36 (July 1946) reported tensions of 600 psi in water not perfectly air-free and tensions of 90 in water saturated with air. Atmospheric pressure will force water to a height of about thirty-two feet; however, if a long clean glass tube one-fourth inch i.d. sealed at the upper end is completely filled with gas-free water and the tube is carefully lifted, the top end of the tube can be raised to a height of eighty feet without breaking the column of water. In other words, the tension in the water near the top of the column is about 22.5 psi.

Similarly, if a compression wave is transmitted through water the average pressure throughout the wave will be the fluid pressure of the water at that point. Now from the energy that can be transmitted through gas-free water in the form of a compression wave of sufficiently high frequency and amplified it can be shown that tensions of as much as 12,000 psi can be developed. Measuring both ways from a perfect vacuum and considering one atmosphere as unity we can arrange the following table of orders of magnitude of pressure in fluids with examples of physical phenomena that would produce such pressures.

TABLE I
ORDER OF MAGNITUDE OF PRESSURE IN FLUIDS

-15,000 to -1500	Tension in compression wave train in certain gas-free liquids.
-1,500 to -150	Tension in compression wave or violent turbulence in gas-free liquids.
-150 to -15	Column of water, compression wave on.
-15 to 0	Column of water. Compression waves.
0 to 15	Vacuum to atmospheric range in laboratory techniques, also the atmosphere.
15 to 150	Air pressure, water system, fire hose, low pressure steam systems etc.
150 to 1,500	Hydraulic and high pressure steam systems.
1,500 to 15,000	Low order explosions. Hydraulic systems.
15,000 to 150,000	Cavitation erosion, high order explosions and hydraulic systems.
150,000 to 1,500,000	Extreme pressure work.
1,500,000 to 15,000,000	Shaped charge.
15,000,000 to 150,000,000	(20 mi. per sec. - 2 meteors head on) Atomic Bomb explosions.

TABLE II

	Decrease in Temp.	Increase in Press.
DENSITY	Increase	Increase
INDEX OF REFRACTION	Increase	Increase
ELECTRICAL CONDUCTIVITY	Increase	Increase
THERMAL CONDUCTIVITY	Increase	Increase
MAGNETIC PERMEABILITY	Increase	Increase
DIELECTRIC CONSTANT	Increase	Increase
OPTICAL REACTIVITY	Increase	Increase
PHYSICAL STRENGTH	Increase	Increase
ELONGATION	Increase	Increase
HARDNESS	Increase	Increase
VISCOSITY	Increase	Increase
SPECIFIC HEAT	Increase & Decrease	Increase & Decrease
VOLUME	Decrease	Decrease

EFFECT OF TEMPERATURE AND PRESSURE UPON PHYSICAL PROPERTIES OF MATTER.

Correlation of Physical Properties at the Same Density as Obtained by Pressure vs Temperature and What Lies Beyond Absolute Zero Temperature

As the temperature of any material is changed, most of its physical properties are also changed. This is equally true if the temperature is maintained constant and the pressure is changed.

An examination of Table II will show that there is a striking correlation between the changes in physical properties as produced by a decrease in temperature and an increase in pressure. Not only are these effected qualitatively in the same direction but in many cases there is a quantitative relation in the magnitude of these effects.

It is the opinion of the author that many such quantitative relations do exist which have not yet been recognized. Quantitative studies have been made of the correlation between the effect of pressure vs temperature for many of these physical properties. Le Chatelier first formulated the relation between the effects of pressure and temperature upon chemical reactions, in what is known as the Le Chatelier Principle.

The Lorenz-Lorentz relation $\frac{N^2-1}{N^2+1} X \frac{1}{d} = K$ was developed theoretically and studied over rather wide temperature ranges and a very limited pressure range. In 1931 C. Ritchey, Carl Beny and the author, (Thos. C. Poulter, C. Ritchey and Carl Beny, "Effect of Pressure on the Index of Refraction of Paraffin Oil and Glycerine "Phy. Rev. 41, 366-367, 1932) rarefied this relation as a function of pressure to more than 200,000 psi paraffin oil and glycerine, both in the liquid and solid phase.

Tables III and IV from article. Phy.Rev.Vol. 41, page 367, 1932.

TABLE III

Refractive Index and Density of Paraffin Oil.

Pressure (atm.)	Density (gm/cc)	n	K
1.	0.8706	1.4749	0.324
2697.	0.954	1.5340	0.325
5394.	1.006	1.5659	0.324
8091.	1.031	1.5895	0.326
10789.	1.052	1.6008	0.324
13585.	1.069	1.6039	0.324

TABLE IV

Refractive Index and Density of Glycerine

Pressure (atm.)	Density (gm/cc)	n	K
1.	0.987	1.4722	0.282
1803.	1.025	1.4858	0.279
3703.	1.054	1.4962	0.278
4510.	1.078	1.5103	0.279
7212.	1.100	1.5210	0.279

It has subsequently been shown that the paraffin oil listed in Table I, solidified at a pressure of less than 8000 atmospheres so that the last three values are for oil in the solid state thus showing that the equation holds even though a transition from one physical state to another occurs.

In 1927 to 1930 the author studied the effect of pressure on the optical rotation in solutions of a number of sugars and found that the magnitude of the rotation regardless of its direction, increased with increase in pressure or decreased in temperature and was therefore a function of density.

In studies on the effect of pressure on the viscosity of oils, it has been found that as in the case of Index of Refraction, the values obtained are roughly a function of density independently of whether that density was obtained by adjusting the temperature or the pressure. This is also true in general of electrical and thermal conductivity, magnetic permeability, electric constant, and even hardness.

This opens up some very interesting fields of study. For years, man has attempted to reach a temperature of absolute zero, and in doing so has discovered many interesting phenomena such as superconductivity and numerous photosensitive processes.

It appears theoretically that it is impossible to reach or that there is no meaning to temperatures below absolute zero but haven't you ever wondered what lie beyond that theoretical lower limit in the temperature scale?

In pressure lies our chance to take a peek behind that limit for since so many of these physical properties of matter are a function of density and by means of pressure the densities of many materials can be carried beyond that which would be obtained by lowering the temperature to absolute zero.

This has been done in the case of a number of organic liquids particularly petroleum oil products. Many of these acquire hardnesses ranging from that of metallic lead to metallic copper and some organic compounds acquired hardnesses equal to that of steel.

It would be extremely interesting to make a study to see if superconductivity conditions can be reached by means of extreme pressure instead of low temperatures or perhaps some materials having a high electrical resistivity could be made to acquire a good electrical conductivity.

This would throw some additional light upon the mechanism of the conduction of an electric current in solids. In connection with the studies of the "Effect of Pressure upon the e.m.f. of the Western Standard Cell" (Thos. C. Poulter and C. Ritchey, Physical Review pp. 816-820 Vol. 39 No. 5 Nov. 1, 1932). Conductivity measurements were made on the oil used to surround the cell and although the effects were negligible for the measurements being made, a slight increase in conductivity was observed at twelve thousand atmospheres.

Another very important way in which temperature and pressure effects have been found to be equivalent is in the matter of relieving residual stresses in metal. The process of relieving stresses in metals used to be accomplished only by maintaining an elevated temperature for a period of time. It was then found that if the temperature was cycled a few times that the stress relieving process could be made more complete than it could be by prolonged heating.

Some good experimenter then concluded that if the process of changing the temperature was helpful why not cover a wider temperature range by using a lower minimum value. Cycles between 100° C and dry ice temperature have been standard for several years for stress relieving and accelerated aging of metal parts where maintenance of precise dimensions over a period of years was important. This process is used in the manufacture of lapped fits, precision gage blocks, etc.

Such temperature cycles were found to be even more effective on many of the aluminum copper alloys so commonly used for making precision machined parts for all types of military computing mechanisms, particularly if these parts were machined from rolled plate.

It is not uncommon for a one inch wide strip one foot long, cut from a rolled plate Dural one-fourth to one-half inch thick (17ST 24ST etc.) to warp as much as a quarter of an inch out of straight upon having a very thin layer of metal macking from one surface. This tendency is almost completely eliminated by two temperature cycles between 100° C and the temperature of dry ice.

It was also found that the transmission of a compression wave of large amplitude through such objects as steel castings would in many cases accomplish considerable stress relieving and some foundries adopted a procedure of vibrating castings or subjecting them to severe shocks to accomplish at least a partial stress relieving.

Being more than usually pressure conscious, it occured to us that as in the cases already discussed that perhaps the change in temperature was not the important thing in a temperature stress relieving cycle but that the change in volume which accompanied it is the important thing.

Some experiments were therefore undertaken which were designed to determine the effectiveness of a pressure cycle in relieving stresses. In order to use large pressures it was necessary that we select small specimens which could be introduced into our pressure cylinders. We also wanted specimens that exhibited rather large residual stresses the presence of which could be conveniently detected.

Two different types of specimens were selected, the Prince Rupert drop and a strip of 24ST. The Prince Rupert drop was selected as exhibiting the maximum in stress that we could think of and also being glass would be one of the most difficult materials in which to produce plastic flow at room temperature.

The 24ST was selected because of the known effective of the temperature cycle. Either of these specimens could easily be tested for the effectiveness of the process, the Prince Rupert drop by observing any decrease in its tendency to shatter when the tip was broken off and the (24ST) by machining a thin layer off one surface and comparing its curvature with a control specimen cut from the same sheet.

A considerable number of Prince Repert drops were made up and several of them cycled between atmospheric and 70,000 psi twenty times.

While it was still possible to obtain shattering in some of the pressure cycled specimens their tendency to shatter was very appreciately decreased.

The strips of (24ST) were marked as they were cut from the sheet so that the same side would be machined from the test specimen and the control. These specimens were one-half inch wide and six inches long and cut from a one-eighth inch thick sheet. The test specimens were cycled twenty times at 140,000 psi. When 0.02" was machined from one surface of both the control specimen and the test specimen, the test specimen showed less warping than the control specimen.

Two similar specimens were then shock-blasted on both sides so that they were straight. The test specimen was then cycled to 140,000 psi ten times, and 0.02" machined from one surface of both the control and the test specimens. The curvature of the specimen that had been pressure cycled was thirty percent less than the control specimen.

This method of stress relieving glass proved very useful in relieving residual stresses in small glass capsules used in certain military application.

The procedure that was adopted in this case was developed in the high pressure laboratory at the Foundation. It employed a pressure in the glass in excess of 100,000 psi. In this particular case it served a dual purpose of eliminating those specimens with thin sections as well as relieving the stress in the remainder. The entire production of as many as eighty-thousand specimens a day was treated by this method with the complete eliminations of failures resulting from residual stresses in the glass.

This method of stress relieving has an important advantage in that a complete pressure cycle in many cases can be completed in less than a second and in certain applications a few hundred or thousand cycles is not necessarily every time consuming.

In hydraulic systems cavitation aside from any of the accompanying destructive erosion effects is perhaps one of the most troublesome phenomena encountered by the hydraulics ~~system~~ engineer and plays an equally important part in decreasing volumetric efficiency at a higher rate of flow.

In an investigation of this phenomena at the Armour Research Foundation and reported in 1941 at the annual meeting of the American Society of Mechanical Engineers ("The

Mechanism of Cavitation Erosion" T.C. Poulter, Journal of Applied Mechanics, Vol. 9, A-31-7, (1942), it was shown that it is not unreasonable to expect pressures in excess of 100,000 psi to be developed as a cavity in water collapses and such a pressure located as it is at the point in the liquid is immediately dissipated in the form of a compression wave. When we consider that the pressure in a sound wave necessary to be painful to the ear is only about 0.2 psi it is not surprising that the noise from cavitation in a hydraulic system can be very disturbing.

The major portion of the noise from the propellers of a ship is a result of cavitation, a fact which was made use of extensively in both our submarine and anti-submarine warfare.

Not only is cavitation disturbing from the standpoint of the noise produced, but it is one of the most destructing phenomena confronting the hydraulic engineer. It is impossible to completely eliminate cavitation by proper design but there is no better way to reduce the disturbing and destructive effects of cavitation than by proper design. After the design has been carried as far as possible in the elimination of cavitation, then one can consider the selection of the proper material to resist the erosion and insulate against the noise. In considering the most important points for the elimination of cavitation from the standpoint of design let us analyze one of the simplest hydraulic mechanisms in use today: The Hydraulic pressure reducing valve.

The pressure reducing valves in the water systems on some of the longer steam generation plants have water velocities in excess of 2,000 ft. per sec. Is it any wonder that they erode badly? Cavitation erosion occurs only on the low pressure side of the valve. It is not uncommon for serious erosion to occur at a distance of as much as ten feet from the reducing valve if there is an elbow in the line at that point. The centrifugal force of the water as it makes the turn in the elbow tends to bring any remaining cavities to the inside of the turn where they collect and collapse. It is not uncommon for a pipe to be badly eroded just around and on the inside of the turn in an elbow down stream. Such a reducing valve is likewise a serious offender in that it is extremely noisy.

In Fig. (2) is shown a disc cut from the body of such a valve on the low pressure side.

There are five important points which have not been given proper consideration in the design of such a valve:

(1) The maximum velocity of the water is too high.

(2) The rate of change of kinetic energy of the water as it goes through the valve is too great.

(3) The velocity of the fluid at the point where the pressure has reached the desired minimum is too great.

(4) The decrease in velocity is too abrupt.

(5) The curvatures in the valves are too sharp.

FIG. 2

Since these are the same factors which control the existance or non-existance of cavitation and the resulting raise and erosion even on the most complicated hydraulic mechanism, let us consider what is to be desired on each of these points.

(1) Wherever possible the velocity of the fluid should not exceed a few hundred feet per second.

(2) The velocity changes effected in the fluid should be such as to change the kinetic energy of the fluid at as nearly a uniform rate as possible.

In other words, $\frac{dv^2}{dt}$ should be as nearly constant as possible along the path of the fluid through the valve.

(3) The velocity of the fluid at the point where the fluid pressure has been reduced to its desired minumum should be substantially equal to the velocity in the pipe as it leaves the valve.

(4) The rate of decrease in velocity must never exceed a value such that the change in velocity head exceeds the pressure head.

(5) Any curvature in the fluid path must be of sufficiently great radius that the resulting centrifugal force acting on the fluid at any point does not exceed the fluid pressure at the point. In other words: $\frac{Mv^2}{Ra} \leq P$. If these five conditions are met, the pressure drop along the path of the fluid can be represented as follows:

$$\frac{dP}{dS} = KW^{-1.3} v^{1.7}$$

P = Pressure

S = Distance along path of flow

K = A constant for the particular fluid at a given temperature (for water at 100° C, K = 0.0000355.

W = Clearance space for the fluid on distance between the two surfaces between which the fluid is passing.

v = Velocity of the fluid at the point in question.

A valve design in which an attempt to meet the above requirements is shown in figure 3.

The trend in hydraulic equipment is to higher pressures and higher rates of flow and this is going to make it more and more necessary that the Hydraulic Design Engineer do a good job.

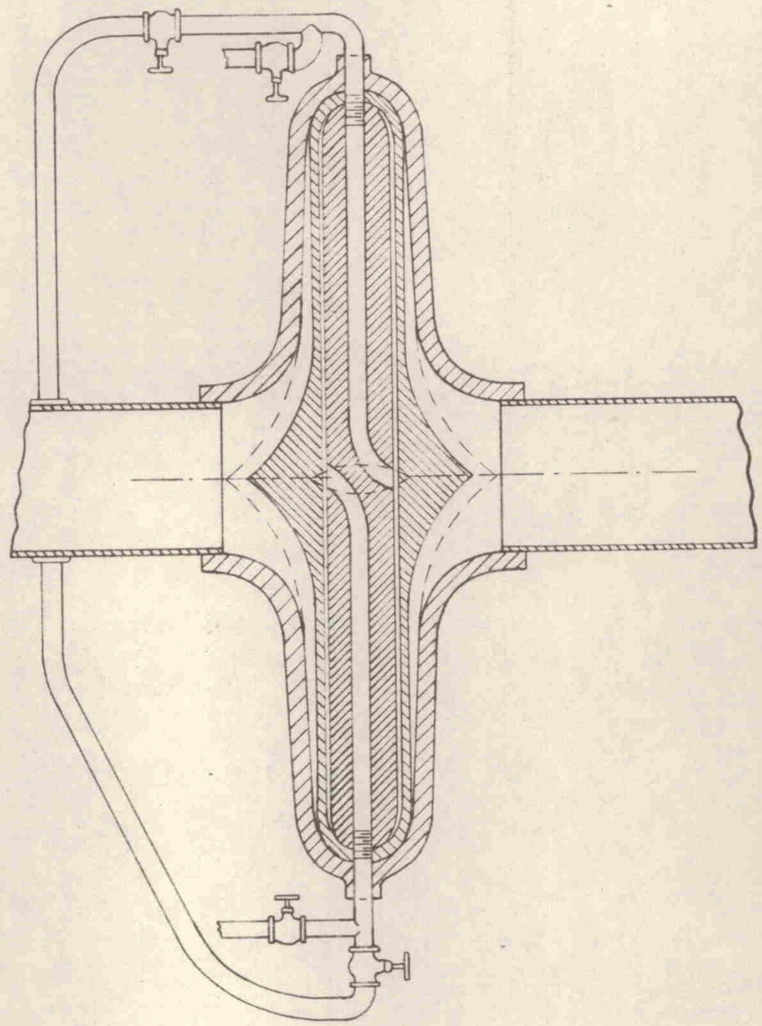

FIG. 3