CONF-770706--25

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HIGH PRESSURE RESEARCH

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SUBMITTED TO: 6th AIRAPT International High Pressure Conference,
Boulder, Colorado, July 25-29, 1977

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FUTURE PULSED MAGNETIC FIELD APPLICATIONS IN
DYNAMIC HIGH PRESSURE RESEARCH

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INTRODUCTION

The generation of large pressures by magnetic fields to obtain equation of state information is of fairly recent origin. Magnetic fields used in compression experiments rise gradually, and therefore produce an almost isentropic sample compression. High pressure state points well off the shock Hugoniot can be produced, particularly for "soft" materials, and the data obtained can thus complement that obtained from shock-wave techniques.

Axial magnetic field compression is first discussed together with a few of the results obtained to date, chosen to show both advantages and limitations of the method. Magnetic compression with azimuthal fields is then considered. Although there are several potential pitfalls, the possibilities are encouraging for obtaining very large pressures, as well as for carrying out small scale experiments with modest facilities.

Improved diagnostic techniques are next considered. An x-ray "streaking camera" is proposed for volume measurements and a more detailed discussion is given on the use of the shift of the ruby fluorescence lines for pressure measurements. In the last section some additional flux compression magnetic field sources are discussed briefly.

COMPRESSION BY AXIAL MAGNETIC FIELDS

Figure 1 shows schematically a system for compressing samples by axial magnetic fields. The sample under test is placed within a good electrical

conducting sleeve such as copper and usually stoppered at both ends by nonconducting plugs. The assembly is then placed inside a magnetic field coil together with a magnetic field measuring probe. As the field builds up in the coil, the sleeve excludes the field and pressure is therefore exerted upon it with consequent compression of the sample. The sample volume at one instant of compression is determined by flash x-radiography either down the cylindrical axis or, with a sufficiently intense beam, at right angles to the axis. In a field coil such as shown, where the outer conductor is fixed, a complete time record of the magnetic field is obtained from the probe. A number of hydrodynamic calculations have been made with simulated equations of state for samples being compressed by time varying pressures derived from experimental magnetic field curves. The results show that after a few sound transit times across the sample, the sample pressure and density become fairly isotropic and that the pressure is within a few percent of that exerted by the magnetic field. The calculations also show that the samples are compressed almost isentropically. These features then allow acquisition of high pressure equation of state data. Volume is measured directly, pressure is obtained from the magnetic field, and the state path is an isentrope. With a system like that shown on Fig. 1, driven by external explosive flux compressors capable of producing fields of about 250T (25 GPa), Fowler et al.^[1] have reported data on solid deuterium up to (6.5 GPa, $0.71 \pm .10 \text{ gr/cm}^3$). Lack of x-ray beam intensity precluded measurements at higher pressure owing to increased beam attenuation from the large compression suffered by the deuterium.

It is difficult to generate magnetic fields greater than 250 T with fixed-wall coils over experimental volumes sufficient for these kinds of measurements. Hawke and his coworkers,^[2,3] who were the first to report

data of this type, employ cylindrical explosive flux compression techniques. In this case the thick walled outer coil of Fig. 1 is replaced by a thin-walled cylinder, or liner, which is surrounded by a ring charge of explosive. After an initial magnetic field is induced in the liner the explosive charge is detonated, followed by compression of the liner with a consequent increase of the magnetic field. Very large magnetic fields and pressures can be obtained this way ($> 1000 \text{ T}$, 400 GPa). These authors report, for example, compression of lucite by a factor of nearly five at a pressure of $450 \pm 150 \text{ GPa}$. This compression, approximately isentropic, can be compared to an estimated compression of about 3 under a single shock to 450 GPa . In implosion geometries of this kind, it is not possible to monitor the magnetic field to high values, because the imploding liner destroys the probe before peak fields are reached. The sample pressure is therefore determined indirectly from calculations based upon the compression observed in the liner. (Also determined from the flash radiograph). This accounts for the large uncertainty in the estimated pressure.

COMPRESSION BY AZIMUTHAL FIELDS

S. J. Bless^[4], in a significant paper, was apparently the first to report on azimuthal magnetic field compression. Using a modest capacitor bank (96 kJ peak energy) he was able to generate sample pressures estimated as high as 30 GPa . He also demonstrated the utility of the technique for "recovery" experiments, in which some recovered materials were found to have undergone structural changes after compression.

Figure 2 shows an arrangement in which the magnetic compression fields are azimuthal. Power is supplied symmetrically to the system and the current, shown by the arrows, flows radially through the base plate, then

through the sample sleeve and returns through the outer heavy cylinder. The cylindrical sample under investigation is assumed to be a nonconductor. To simplify the analysis, the thickness and mass of the sleeve are ignored, and currents are assumed to flow on the inner radius of the outer cylinder, which is assumed not to vary. Then the value of the magnetic field acting upon the sample, the magnetic pressure it generates, and the inductance of the compression system may be written

$$B = \mu I / 2\pi r \quad (1)$$

$$p = B^2 / 2\mu = \mu I^2 / 8\pi^2 r^2 \quad (2)$$

$$L' = (\mu \lambda / 2\pi) \ln (R/r) \quad (3)$$

We consider two types of power sources: a capacitor bank and an explosive flux compression generator for which circuit schematics are drawn in Fig. 3. An explosive flux compression generator^[5-8] consists basically of a cavity defined by surrounding metal conductors, some or all of which may be overlaid with explosives. After an initial magnetic flux is introduced in the cavity, the explosives are detonated, forcefully reducing the inductance of the generator in a prescribed fashion. If the generator is part of a completely conducting system, the magnetic flux in the system is conserved.

The circuit equations for the two cases are:

$$\frac{d}{dt} \left[(\ell_0 + L') I \right] + q/C = 0 \quad (4)$$

$$\frac{d}{dt} \left[(L_G + \ell_0 + L') I \right] = 0 \quad (5)$$

Equation (4), after multiplication by I , yields an energy relation while Eq. (5) can be integrated directly. The solutions are written only

for the case of maximum compression. These correspond in the first case to no charge left in the capacitors, and in the second, to reduction of the generator inductance to zero.

$$1/2 (L_0 + L') i^2 + 1/2 \int_0^T \dot{L} i^2 dt = q_0^2 / 2C + 1/2 L_0 i_0^2 \quad (6)$$

$$(L_0 + L') i = (L_{G0} + L_0) i_0 \quad (7)$$

The integral of Eq. (6) represents work done on the sample. The initial energy in the circuit then finally appears as this work and as energy stored in the final circuit inductance. Although not apparent, the work term is implicitly contained in Eq. (7).

When the sample equation of state along the isentrope is known the equations can be solved. To get some idea of the maximum compressions predicted we use the following very approximate form for the equation of state that leads to relatively simple solutions to the equations.

$$pV^\gamma = p_0 V_0^\gamma \quad \text{or} \quad 1r^{\gamma-1} = 1_0 r_0^{\gamma-1} \quad (8)$$

Substitution of Eq. (8) into Eqs. (6 and 7) leads to Eq. (9) for both solutions

$$w \ln w = \alpha \quad (9)$$

subscripts 1 and 2 for w and α , given in the notation section pertain respectively to the capacitor powered and the flux compression powered solutions. Initial parameters for a problem are embodied in both the values of w and α , and the solutions for w yield the values of the maximum compression ratios, r_0/r .

Once the maximum compression ratio is known, other parameters are easily determined: the volume follows immediately; the pressure and

and current from Eqs. (8); the final coaxial inductance from Eq. (3) which, with the source inductance, allows calculation of the final stored magnetic energy; and finally the work done on the sample, which with Eq. (8) reduces to

$$W = p_0 V_0 [(V_0/V)^{\gamma-1} - 1] / (\gamma-1) \quad (10)$$

A number of solutions are given in Table I for both capacitor bank and explosive flux compression generator power sources. The first five columns give initial conditions, which include: γ ; initial sample pressure; which prescribes the initial current; and the total initial energy in the system. For the capacitor bank solutions, the initial energy assigned to the bank is the total energy less that in L_0 , the initial circuit inductance. For the flux compressor solutions, the remaining initial energy is assigned to the generator, thus specifying its initial inductance.

The last five columns of the table give at maximum compression the volume compression ratio, pressure, final current, work done on the sample and energy stored in the residual circuit inductance. Several conclusions can be noted from the data: the bulk of the energy delivered appears in the inductance, seldom more than a few percent appearing as compression work on the sample; softer materials (lower γ) compress more and at somewhat higher pressures; larger initial system energy results in greater compression.

Clearly the extreme values given in the table are not realistic. Expansion of the outer wall radius can be significant for both power systems, and more realistic sample equations of state, particularly at the lower pressures, should be used. Allowance for the mass and compression energy of the sleeve could be important, particularly for the capacitor bank sources, since their available energy is fixed. The most significant questions, however, deal with the stability and current carrying capacity of the

sample sleeve. It is probable that parts of the sleeve would have to be in a plasma state when the magnetic pressures get as large as several hundred GPa's^[9]. Whether or not the sleeves pass through regions of unacceptable resistivity during such a transition can, at present, only be established experimentally. E. W. Salmi has suggested using a cesium plasma to carry large currents^[10]. Z-pinch plasmas, of which this would be an example, are notoriously unstable, and this question will also have to be examined.

We feel, however, that pressures of 100 GPa can probably be obtained now, and that eventually several hundred GPa pressures could be generated with some existing capacitor banks, and perhaps more easily with small explosive flux compression generators now under development.

DIAGNOSTICS

The most important need in future magnetic compression measurements is to make the measurement of pressure and volume continuously throughout the compression. We first discuss briefly the feasibility of a streaking x-ray system for continuous volume measurement, but devote the bulk of this section to a study of the feasibility of using ruby fluorescence for continuous sample pressure measurements.

The technology needed to make continuous measurements of sample boundaries is possible by use of an x-ray pulse that is longer than the compression time, a scintillator, a low-light-level image intensifier, and a streaking camera.^[11] Fig. 4 shows the schematic layout of such a system. The particular x-ray source needed would depend on the materials used in the experiment, method of compression (amount of material surrounding the experiment to be penetrated), and whether a transverse or longitudinal measurement is to be made. Plastic scintillators have short enough

fluorescence decay times ($\sim 2-3$ nsec.) and acceptable x-ray to visible light conversion efficiency. Several commercial image intensifiers have already been used to amplify scintillation converted photons. The streaking camera can be the conventional rotating mirror and film type or the electronic type if necessary. It therefore appears that such a system is within the state of the art.

A number of papers describe the application of ruby fluorescence wavelength shift to the measurement of pressure in static press experiments. Barnett, Block and Piermarini^[12] provide a detailed discussion of their technique as well as the comparative merits of many materials as optical fluorescence pressure sensors. Mao and Bell^[13] extend the use of this method to about 1 megabar. Upon application of pressure, the wavelength of each component of the fluorescence doublet of ruby shifts with a coefficient

$$\frac{d\lambda}{dp} = + 0.365 \frac{\text{\AA}}{\text{kbar}}$$

Also, spectral line-broadening and wavelength shift occur with temperature rise, causing the R_1 and R_2 fluorescence lines to merge at a temperature of about 490°K . These effects degrade the accuracy of the pressure measurement. However, the consequences should be minimal when applied to magnetic flux driven, isentropic compression experiments due to the small increase of temperature with pressure.

Estimation of the Fluorescence Intensity

The coupled, nonlinear differential equations which describe the energy level population dynamics and photon transport in ruby must be solved by numerical methods using a computer. We can, however, obtain reasonably close estimates of the fluorescence photon flux rate and the excited state population density by assuming that^[14]

1) equilibrium conditions prevail for the level populations.

2) stimulated emission is not significant.

These are good assumptions for the case of a continuous pump source. In this approximation, the fluorescence photon flux rate is:

$$\dot{\phi} = n_2 / T_f ; \frac{\text{photons}}{\text{cm}^3 \text{ sec.}} \quad (11)$$

$$n_2 = n_0 \frac{W_p T_f}{1 + W_p T_f} ; \text{cm}^{-3} \quad (12)$$

Here, T_f is the excited state fluorescence lifetime, W_p the pump rate from the ground state to the excited state, and n_0 the density of chromium ions.

Calculation of Optical Pump Rate

Consider a parallel beam of light incident upon an optically thin ruby crystal. Let P_0 be the optical power in the beam (Watts) and ν_p the center frequency of the pump light (sec^{-1}). Then the flux rate of pump photons is

$$\phi_p = \frac{P_0}{h\nu_p} ; \frac{\text{photons}}{\text{sec.}} \quad (13)$$

where h is Planck's constant. If σ_p is the absorption cross-section of the pump transition (cm^2) and A is the crystal area normal to the pump beam (cm^2), then the pump rate is given by: [15]

$$W_p = \frac{\phi_p \sigma_p}{A} ; \text{sec}^{-1} \quad (14)$$

Example Calculation

Consider a cylindrical crystal of laser ruby ($0.05\% \text{Cr}^{3+} : \text{Al}_2\text{O}_3$) illuminated by a 5 Watt, multiline, cw argon-ion laser through an end

face, with a polarization parallel to the c-axis of the crystal. Let the temperature of the crystal be 77°K so that the fluorescence line is narrow.

We shall assume a crystal diameter $d = 0.1\text{ cm}$ and length $l = 0.1\text{ cm}$. The total fluorescence flux rate produced by this ruby cylinder is given by Eq. (11) multiplied by the volume of the ruby, i.e.,

$$\dot{\phi} = \frac{n_2}{T_f} \left(\frac{\pi d^2}{4} \right) l = 7.85 \times 10^{-4} \frac{n_2}{T_f} ; \frac{\text{photons}}{\text{sec.}} \quad (15)$$

Let the crystal occupy the focal region of a lens of diameter D and focal length f . Neglecting internal reflections, these photons are radiated through 4π -steradians. Thus the fraction captured by the lens is

$$\frac{\pi(D/2)^2}{4\pi f^2} = \frac{1}{16F^2} \quad (16)$$

where $F = \frac{f}{D}$ is the focal ratio, or f-number, of the lens. The total flux through the lens is therefore

$$\dot{\phi} = \frac{7.85 \times 10^{-4}}{16} \frac{n_2}{T_f F^2} = 4.9 \times 10^{-5} \frac{n_2}{T_f F^2} ; \frac{\text{photons}}{\text{sec.}} \quad (17)$$

The corresponding intensity is obtained upon multiplication of this by the photon energy, at the fluorescence wavelength ($h\nu = 2.86 \times 10^{-19} \frac{\text{J}}{\text{photon}}$ at 6943 Å)

$$I = 2.86 \times 10^{-19} \times 4.9 \times 10^{-5} \frac{n_2}{T_f F^2} = 1.4 \times 10^{-23} \times \frac{n_2}{T_f F^2} ; \frac{\text{J}}{\text{sec.}} \quad (18)$$

A typical 5 Watt, cw laser radiates its power in 9 lines in the wavelength region between 5145 Å and 4545 Å . Comparing this with a plot

of pump band absorption cross-section vs wavelength,^[16] T_f and ϕ_p can be found. Then, w_p can be evaluated for each line, using Eqs. (13) and (14). The pump rate is the sum of the spectra contributions, yielding the result

$$w_p = 50 \text{ sec}^{-1}$$

For 0.05% ruby, the chromium ion density is:^[17] $n_0 = 1.6 \times 10^{19} \text{ cm}^{-3}$ and at a temperature of 77°K, the fluorescence lifetime is: $T_f = 4.3 \times 10^{-3} \text{ sec}$. Therefore, from Eq. (12), we calculate the excited state population density: $n_2 = 2.83 \times 10^{18} \text{ cm}^{-3}$. Substituting these values of n_2 and T_f into Eq. (18), we obtain

$$I = \frac{9.23}{F^2} \times 10^{-3}; \quad \frac{J}{\text{sec.}}$$

An identical calculation for room temperature conditions shows little change.

This value of the fluorescence intensity should be derated to take into account reflection losses, slit losses, and filter factors. A more representative value would be

$$I = \frac{3 \times 10^{-3}}{F^2}; \quad \frac{J}{\text{sec.}}$$

If we record the time-changing spectrum using a rotating mirror streaking camera behind a grating spectrometer, assume a system effective f-number of $F=10$, and a record time of 10 μs , the energy delivered to the emulsion is

$$E = \frac{3 \times 10^{-3} \times 10^{-5}}{10^2} = 3 \times 10^{-10} \text{ J}$$

which must be distributed over an emulsion area of many square cm.

Kodak Spectroscopic Analysis Film No. 1 is sensitive to the ruby fluorescence wavelength region. A typical value of the energy per unit area required to provide a density of 0.6 is

$$E' = 2 \times 10^{-9} \text{ J/cm}^2$$

Comparing E and E' we see that even with substantial increases in optical pump power (obtained, for example, from a pulsed argon-ion laser), the fluorescence intensity is marginal. These figures are predicted on a system f-number of 10, which is very optimistic.

However, the intensity is more than adequate for use with electronic image converter streaking cameras because these provide a system gain of 10^3 to 10^4 . Therefore, the shift of fluorescence wavelength is a very feasible time-resolved pressure measurement method for use with magnetic compression experiments.

OTHER FLUX COMPRESSION SYSTEMS

The device of Fig. 2 requires a heavy-walled outer cylinder to offset radial expansion. This system can, however, be adapted to explosive cylindrical flux compression. Here, the outer conductor wall would be reduced to a thickness just sufficient to withstand the forces produced on it by the initial magnetic field. This conductor would be overlaid by a ring charge of high explosive, initiated at such time as to start compression at peak system flux. Mechanical provisions are easily made so that the implosion also shorts the coaxial assembly at the input end. Calculations with a sample polytropic equation of state lead to results similar to those of Eq. (9). This system has some advantages not possessed by the externally driven system, but sample recovery is clearly not possible.

It is occasionally suggested that a 2 or 3 stage gas gun be used to accelerate a projectile with a metal disc on the face, which in turn can be used to compress a magnetic flux to a high field intensity. Table II summarizes the present and near future state-of-the-art possibilities for flying metal plates of various metals, thicknesses and diameters. [18]

Figure 5 shows a side view of a flying plate flux compression device. There are 3 basic factors which limit the maximum field attainable in such a configuration. The first limit is the available kinetic energy in the flying plate reduced by losses caused by resistive heating in the metal and subsequent magnetic diffusion loss. By comparison with previous cylindrical implosion efficiencies, the limit on the first two projectiles in the table (Ta and Cu) are approximately 8 MG. The second limiting factor is the ratio of the initial to final area of flux entrapment. If there were no coil expansion, the limit in the geometry of Fig. 1 would also be approximately 8 MG. The third and most important limitation is that the coil melts, vaporizes, expands and axially jets as the field exceeds about 1 or 2 MG. Past experiments where a capacitor bank was used to energize a coil in a few microseconds have never exceeded approximately 3-4 MG due to the abovementioned problems. [6,7,19] The same limitation has been found when high explosives have been used to compress flux into a coil, [20] and would also be expected with gas gun accelerated flying plates.

TABLE I*

CAPACITOR BANK POWER SOURCE

γ	P_o (GPa)	I_o (kA)	E_o (kJ)	L_o (nH)	V_o/V	P (GPa)	I (MA)	W (kJ)	E_H (kJ)
9	.01	125	100		2.511	39.7	4.97	3.1	96.9
5	.1	396	100		3.447	48.7	4.71	5.5	94
7	.1	396	100		2.327	36.7	4.98	4.1	95.4
9	.1	396	100		1.899	32.1	5.15	3.3	96.7
11	.1	396	100		1.677	29.5	5.26	2.8	97.2
5	.1	396	1000		5.963	754	14.1	50	950
7	.1	396	1000		3.366	489	15.1	38	962
9	.1	396	1000		2.510	395	15.7	31	969.
11	.1	396	1000		2.099	348	16.1	26.	974

MAGNETIC FLUX COMPRESSION GENERATOR POWER SOURCE

9	.1	396	100	1267	3.498	7840	59.3	440	15000
9	.25	627	100	503	2.818	2800	39.5	195	6300
9	.5	886	50	121	2.012	271	14.5	26	780
9	.5	886	25	58	1.731	70	8.0	7.7	324
5	.5	886	100	249	5.230	1960	24.2	147	3000
7	.5	886	100	249	3.133	1480	27.2	124	3100
9	.5	886	100	249	2.395	1290	29.1	106	3300
11	.5	886	100	249	2.028	1200	30.4	93	3400

* For all solutions, $R = 0.8$ cm, $r_o = 0.5$ cm, $\lambda = 2$ cm and $L_o = 4.12$ nH

TABLE II

<u>Number Stages</u>	<u>Metal</u>	<u>Projectile Diameter (cm)</u>	<u>Projectile Thickness (mm)</u>	<u>Maximum Velocity (mm/μs)</u>	<u>Kinetic Energy (kJ)</u>
2	Ta	5	2	5	815
2	Cu	5	2	5	440
2	Ta	2.5	2	7	400
2	Cu	2.5	2	7.5	250
2	Al	2.5	3	7.5	110
3	Ta	2.5	.25	10	100

NOTATION*

μ	free space permeability
I	current
L_G	inductance of flux compression generator
L'	inductance of compression assembly
ℓ_o	circuit source inductance
$L_o = L'_o + \ell_o$	
r	sample radius
λ	sample length
R	outer radius of sample assembly
q, C	charge and capacitance
p	pressure on sample
V	volume of sample
γ	polytropic exponent in isentrope of sample
β_1	$4\pi(\gamma-1)L_o/\mu\lambda$
w_1	$(r_o/r)^{2(\gamma-1)} \exp(\beta_1 + 1)$
α_1	$(1 + \beta_1)[1 + (\beta_1 q_o^2/2C)/(1 + \beta_1)(1/2 L_o I_o^2)] \exp(\beta_1 + 1)$
w_2	$(r_o/r)^{\gamma-1} \exp[2\pi(\gamma-1)L_o/\mu\lambda]$
α_2	$(\gamma-1)(R/r_o)^{(\gamma-1)}L_o/L'_o \times (L_{G0} + L_o)/L'_o \ln(R/r_o)$

* Unless otherwise stated MKS units are used throughout, and initial values of variables are indicated by subscript zero.

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FIGURE CAPTIONS

Fig. 1. Axial magnetic field compression system.

Fig. 2. Azimuthal field compression system, cylindrically symmetric about the center line.

Fig. 3. Schematic circuits for powering magnetic compression devices with a) capacitor bank and b) explosive flux compression generator.

Fig. 4. X-ray streaking camera schematic layout.

Fig. 5. Side view of gas gun flying plate flux compression device.