sarily ignores polarity). The orientations so determined (Fig. 3) show a distinct clustering about ω, indicating that most of these features do indeed form parallel $\{10\bar{1}3\}$. To my knowledge, there is no evidence indicating that deformation lamellae in tectonites form preferentially parallel to ω, and the data in Fig. 2a certainly cannot be interpreted to support this notion. Deformation lamellae, identical with those in tectonites, have recently been produced in static experiments on oriented quartz crystals (*12*), and these clearly are not parallel to ω.

A detailed study with optical and electron microscopes of the planar features parallel to $\{10\bar{1}3\}$ reveal that individual bands commonly comprise several very thin planar features (*7*). Replication electron microscopy of polished surfaces showed no discontinuities, the indication being that the features are not open fractures as was suggested (*13*). Replicas of planar features etched in HF vapor show thin, nearly linear, but discontinuous ridges. Electron micrographs of the area of intersection of two sets of the features (Fig. 1, e and f) show slight mutual offset of the features, indicating small shear displacements along them. Therefore, inasmuch as the shear strength of quartz is very high, these features are probably reliable indicators of intense deformation by shock.

Interferometry (*14*, *15*) and x-ray studies (*15*) have indicated that the material composing the features is silica having a short-range order. Apparently the crystal structure along these planes was severely distorted and partly reduced to glass during small shear deformations accompanying the passage of the shock wave. Planar features parallel to $\{10\bar{1}3\}$ have also been observed in quartz from the Ries Kessel (*16*), Sudbury structure (*17*), and many other cryptoexplosive structures (*8*).

Thus it appears that both deformation lamellae parallel to $\{0001\}$ and planar features parallel to $\{10\bar{1}3\}$ are reliable criteria for shock due to impact by meteorite or comet. Both the optical characteristics and frequency (distribution of orientations with respect to the *c*-axis) of a statistically sound population serve to distinguish these structures from those produced by tectonic deformation. It seems that studies of microstructures in tectonically deformed quartz have been sufficient to preclude the probability that these structures could be produced during tectonic deformations. The possibility (unlikely, in my opinion) remains, however, that these features could be created by shock due to volcanic explosions. No such features have been reported, but no careful search has been made that I know of.

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Direct High-Temperature Ohmic Heating of Metals as Liquid Pipes

Abstract. *When a sufficiently high electric current is passed through a liquid metal, the electromagnetic pressure pinches off the liquid metal and interrupts the flow of current. For the first time the pinch effect has been overcome by use of centrifugal acceleration. By rotation of a pipe of liquid metal, tin or bismuth or their alloys, at sufficiently high speed, it can be heated electrically without intermission of the electric current. One may now heat liquid metallic substances, by resistive (ohmic) heating, to 5000°K and perhaps higher temperatures.*

The electromagnetic pinch effect was first described by Hering (*1*) in 1907 as a practical limitation for electrical-resistance furnaces. Northrup (*2*) established the simple relation between pinch pressure (P_{el}), current (c), and cross-sectional area (a) of the liquid conductor (in centimeter-gram-second units throughout):

$$P_{\mathrm{el}} = c^2/a \tag{1}$$

If the current is measured in amperes (I),

$$P_{\mathrm{el}}\ (\mathrm{dyne/cm^2}) = I^2/(100 \cdot a) \tag{2}$$

Earlier the pinch effect was overcome in liquid-metal tubes (*3*) by application of hydrostatic pressure to them in a U-tube type of furnace. We shall now show that the pinch pressure can be easily overcome [as was suggested (*4*)] by centrifugal pressure P_{cent}. The centrifugal force F (in dynes), in a liquid tube having an inside radius R (centimeters) and rotating at r revolutions per minute, equals

$$F = 4\pi^2 R \cdot r^2 \cdot M/3600 \tag{3}$$

M being the total mass in grams.

The force per unit area of the tube (P_{cent}) in dynes per square centimeter is

$$P_{\mathrm{cent}} = 4\pi^2 \cdot R \cdot r^2 \cdot M/3600 \cdot 2\pi R \cdot L \tag{4}$$

where L is the length of liquid metal in centimeters. If D is the density of the liquid metal in grams per cubic centimeter and θ is its thickness in centimeters,

$$M = 2\pi R \cdot L \cdot \theta \cdot D \tag{5}$$

Therefore, from Eqs. 4 and 5,

$$P_{\mathrm{cent}} = \frac{4\pi^2 \cdot R \cdot r^2 \cdot \theta \cdot D}{(60)^2} = \frac{1.0966 \cdot R \cdot r^2 \cdot \theta \cdot D}{100} \tag{6}$$

The hydrostatic pressure in a liquid is exerted equally in all directions. In Eq. 2 the cross-sectional area a is

$$a = 2\pi \cdot R \cdot \theta \tag{7}$$

(we ignore the term $\pi\theta^2$ for $R \gg \theta$).

Therefore P_{cent} equals the pinch pressure when (from Eqs. 2 and 6)

$$I = 2.625 \cdot r \cdot R \cdot \theta \cdot D^{\frac{1}{2}} \tag{8}$$

or

$$r = 0.3809 \cdot I/(R \cdot \theta \cdot D^{\frac{1}{2}}) \tag{9}$$

Thus, whenever the speed of rotation is greater than that required by Eq. 9 for a given amperage (I), the liquid conductor will conduct the current. If the current rises above the value given by Eq. 8 it will pinch, with interruption of the current. A pipe of liquid tin for example, with $R = 3.5$ cm, $\theta = 0.3$ cm, $D = 7.00$ g/cm^3 (*5*), must be rotated at 275 rev/min for counteraction of a pinch pressure equivalent to 2000 amps. The true value of P_{el} is

$$(2000)^2/100 \cdot 2\pi \cdot 3.5 \cdot 0.3$$

or 6063 dyne/cm^2 or 4.55 mm-Hg.

A modification of the centrifugal ohmic heating furnace (*6*) is sketched in Fig. 1. It has four basic parts: (i) a drive mechanism to rotate the furnace; (ii) a power supply, current leads, and rotary contacts; (iii) a furnace shell lined with thermal insulation and electrically insulated at one end for provision of a current path through the liquid pipe; and (iv) a support tube to contain the liquid-metal pipe.

The electromechanical variable drive unit of 7.5 hp permits rotation of the furnace at speeds between 100 and 1300 rev/min. One important aspect in the design of the drive apparatus is the critical rimming speed, which we shall describe.

A variable autotransformer having a maximum output of 80 amps at 220 volts controls the secondary of a step-down transformer having a maximum output of 3000 amps at 5 volts. The resistance of the load or liquid pipe can be approximately matched to the transformer by adjustment of the resistance of the liquid pipe to 1.6 mohms. The current is carried by copper bus bars (1.2 by 15 cm) and 12 short lengths of 4/0 welding cable. A set of 12 copper brushes (*7*) (90 percent Cu, 10 percent C), each fitted with two double strands of copper wire 6 mm in diameter and positioned around each drum with cast-bronze holders, transfers the current from the bus bars to the current drum and furnace shell. Silver plates 1.5 mm in thickness are soldered to the faces of the brushes to reduce contact resistance (from 50 to 2 mohms or less) caused by buildup of carbon on the brushes during rotation. The so-called current-pickup drum (Fig. 1) functions as a means for transferring current to one end of the liquid-metal pipe through a copper bar that is insulated electrically from the furnace shell. Current is supplied to the other end of the pipe from the furnace shell—through the aluminum end plate and thence to the liquid metal through the graphite connector.

Table 1. Experimental and calculated speeds of rotation (r) for liquid tin at two current densities. A, 1.04 cm^2; θ, 0.048 cm.

Temp (°K)	Volts	Amps	Density (amp/cm^2)	Minimum r (rev/min)	
				Exp.	Calc.
600	3	635	607	570 ± 20	560
600	4	835	798	720 ± 30	740

The furnace shell is 78 cm long and 35 cm in outer diameter; the wall is 4 mm thick (Fig. 1). Carbon felt (a woven carbon fabric from National Carbon Company) around the inside of the furnace shell provides thermal insulation. Thermal conductivity of the felt is 3.36×10^{-4} cal/cm·sec·°K at 1000°K; for comparison, the thermal conductivity of Thermax carbon black at 1000°K is 1.35×10^{-4} cal/cm·sec·°K.

The support tubes for the liquid-metal pipes are made from 50-cm-long graphite or quartz tubes, 7.0 cm in inner diameter and 7.5 cm in outer diameter, push-fitted at each end into graphite caps which in turn are push-fitted into the graphite current connectors. An argon flush is provided inside the support tube through a hole in the bearing shaft. The graphite tube holders (Fig. 1) allow a liquid level 1 cm in depth to be held in the support tube.

We calculated the speeds of rotation required for various current densities for several metals (Fig. 2), choosing the metals tin and bismuth for experiment because of their low melting points, resistivities, and ease of handling.

The critical rimming speed is defined as the rotational velocity that must be reached to cause a pool of liquid, ini-

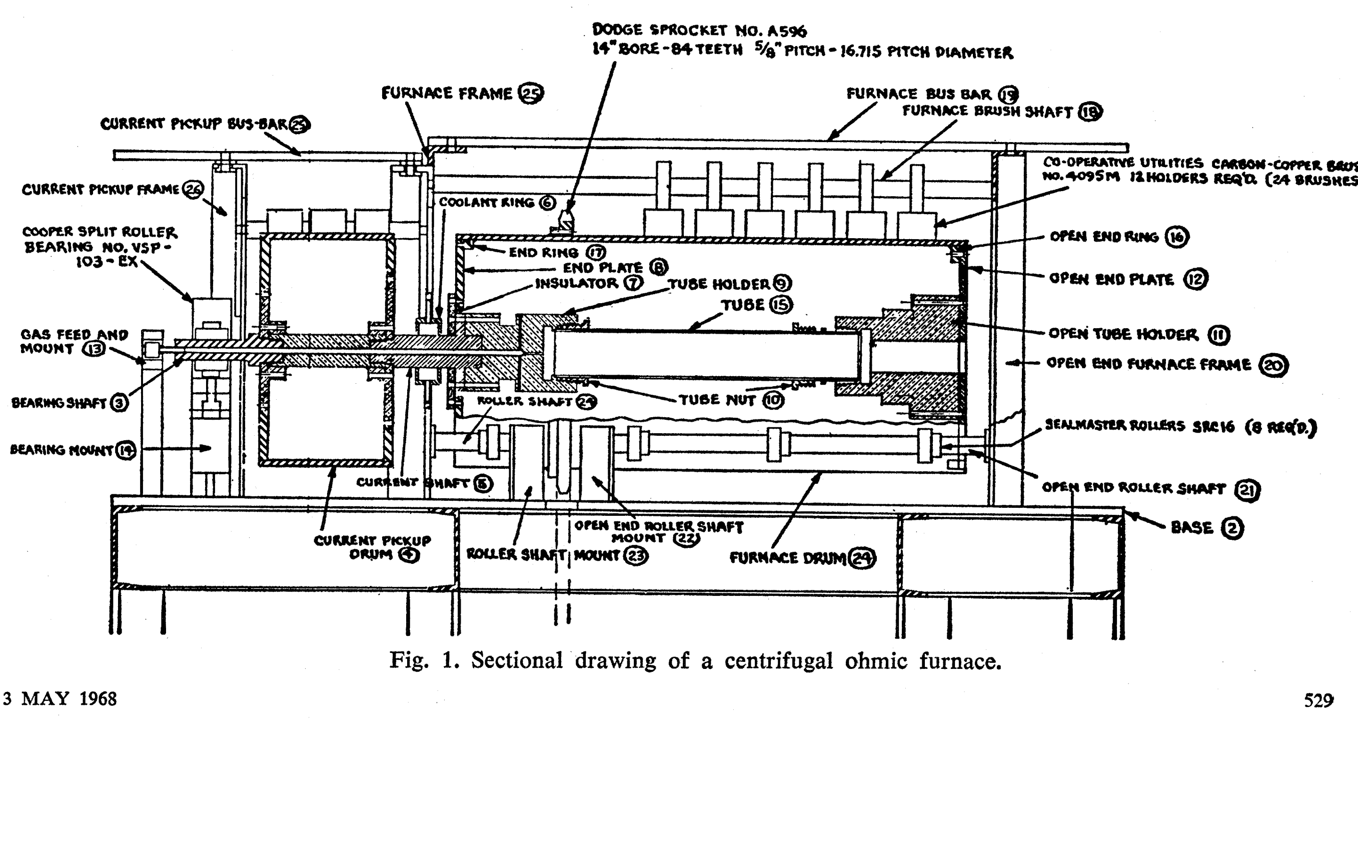

Fig. 1. Sectional drawing of a centrifugal ohmic furnace.

tially resting along the bottom surface of a tube, to form a liquid layer of uniform thickness over the entire inner surface of the tube and so rotate at the same angular velocity. The critical rimming speed is unnecessary when solid pipes are melted while rotating at $1g$; once a pipe has been rimmed, the centrifugal force may of course be reduced to $1g$. To test these points, a Wood's metal pipe, $\theta = 0.3$ cm, $R = 3.5$ cm, was machined to snug-fit a graphite support tube and rotated at $1.3g$; a liquid pipe formed that was dimensionally stable both during and after melting. The critical rimming speed V (centimeters per second) has been related to variable parameters in the following equation:

$$V = 9.1\ (\theta \cdot g)^{\frac{1}{2}}\ (R/\theta)^{0.2} \times (\eta/\rho \cdot \theta^{3/2} \cdot g^{\frac{1}{2}})^{-0.026} \quad (10)$$

where g is acceleration of gravity in centimeters per square second, η is absolute viscosity in poises, and ρ is the density of the liquid pipe in grams per cubic centimeter; R, r, and θ are defined in Eqs. 3 and 5. Equation 10 may be so expressed in terms of the principal variables r, θ, and R:

$$r = 2985 \cdot (\rho/\eta)^{0.026} \cdot (\theta^{0.34}/R^{0.80}) \quad (11)$$

since by definition

$$V = (2\pi rR)/60$$

For example, tin at its melting point, with $\theta = 0.3$, $R = 3.5$, $\rho = 7.00$, and $\eta = 2.0 \times 10^{-2}$, must rotate at 845 rev/min, according to Eq. 11.

Approximately 350 g of tin (99.8 percent Sn) was heated to 600°K in a quartz tube, 48 cm long and 7 cm in inner diameter (θ, 0.048). The liquid pipe that was formed was alternately pinched several times with an excess of current input and restored to a continuously conducting state by increase in the centrifugal force (Table 1 and Fig. 3). The values yielded when the pinch force was just overcome by centrifugal pressure (by increase in speed of rotation) at a set amperage (Table 1) are within experimental error (5 percent) of values calculated from Eqs. 8 and 9.

In trace *2* (Fig. 3) the current runs smoothly, with no pinching; in trace *1* the current is too great for the centrifugal pressure, and one sees the typical trace of a current being continually interrupted.

The measured amperage was corrected for contact losses of 4 and 6 percent at 570 and 720 rev/min, respectively. The temperature was measured with a standard chromel-alumel thermocouple checked at the normal boiling point of mercury. Agreement with the literature value for Hg, 630°K, was within 0.5°K.

In several experiments we heated Wood's metal and alloys of bismuth and tin in rotating and nonrotating graphite and quartz tubes in which the pinch pressure was overcome by an increase in the hydrostatic pressure by means of simple addition of more metal (*6*); maximum temperature reached in these tests was 1200°K. The temperature of the liquid metal when rimmed (about 600°K) was always lower by a few hundred degrees than that of the same liquid at rest. A decrease in electrical power supplied to the metal, caused by increase in contact resistance during rotation, and an increase of about eightfold in the surface area (that is, of the rimmed liquid relative to liquid at rest) are the obvious reasons for the temperature drop.

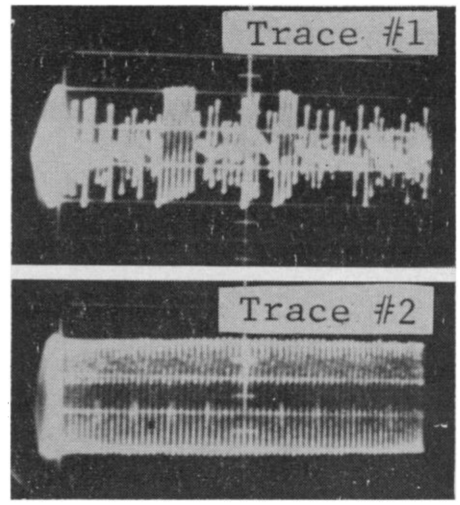

Fig. 3. Oscilloscope traces of current through a pipe of liquid tin in a rotated furnace. Trace 1, current interrupted, or pinched; trace 2, current normally continuous.

Our successful ohmic heating of low-melting metals (*9*), held in tubular form by centrifugal force by which the magnetic "pinch" effect is overcome, suggests that higher-melting metals, carbides, salts, and oxides may be similarly heated to high temperatures—perhaps to 5000°K (*10*).

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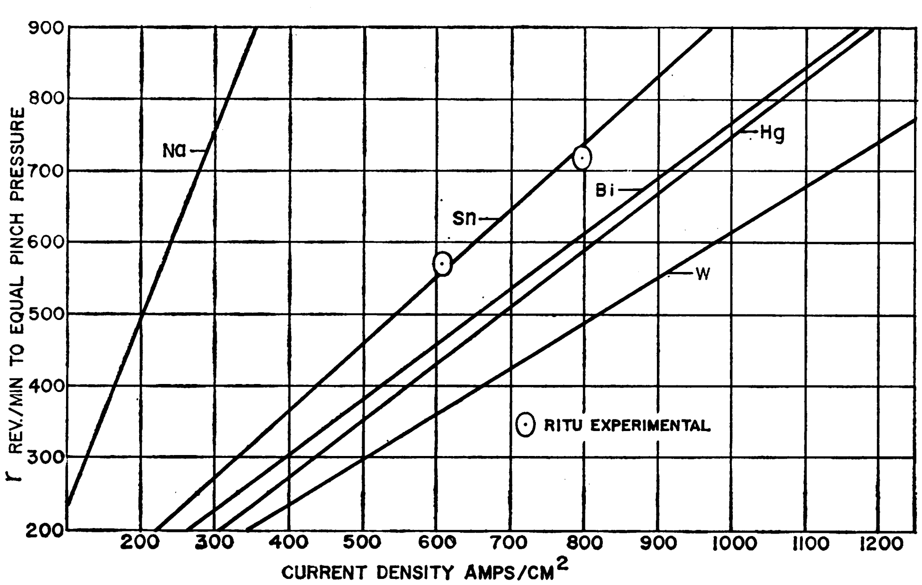

Fig. 2. Rotational speed versus current density.

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