Pulsed Plasma Propulsion

By Alfred E. Kunen

THERE are many different types of pulsed-plasma engines, or accelerators, which may be classified by the geometry of the discharge, either a sheet or a line, and by the position of the electrodes, which are either directly in contact with the propellant, or inductively coupled with the propellant. It is the author's belief that, of all the various types of pulsed-plasma accelerators, only the sheet-direct-contact accelerator will ultimately become a working engine. The arguments in support of this belief are partly of a practical nature and may even be only intuitive. There are, however, two devices which fill even this narrow description: the so-called "pinch engine" and the purely axial accelerator illustrated in Figs. 1 and 2. Note that both are characterized by coaxial geometries and require that the discharge be axisymmetric. In the "pinch" type or radial accelerator, the initial discharge formed by axial currents must be turned so that the currents become radial. No turning is apparently required in the axial accelerator. However, the magnetic-field forces are inversely proportional to the radius, and some turning will take place. It would appear that both accelerators should maintain a current sheet normal to the walls of the electrodes. This may be more easily obtained in a curved channel than in a straight one. In addition to symmetry, it appears necessary to obtain a discharge which is relatively

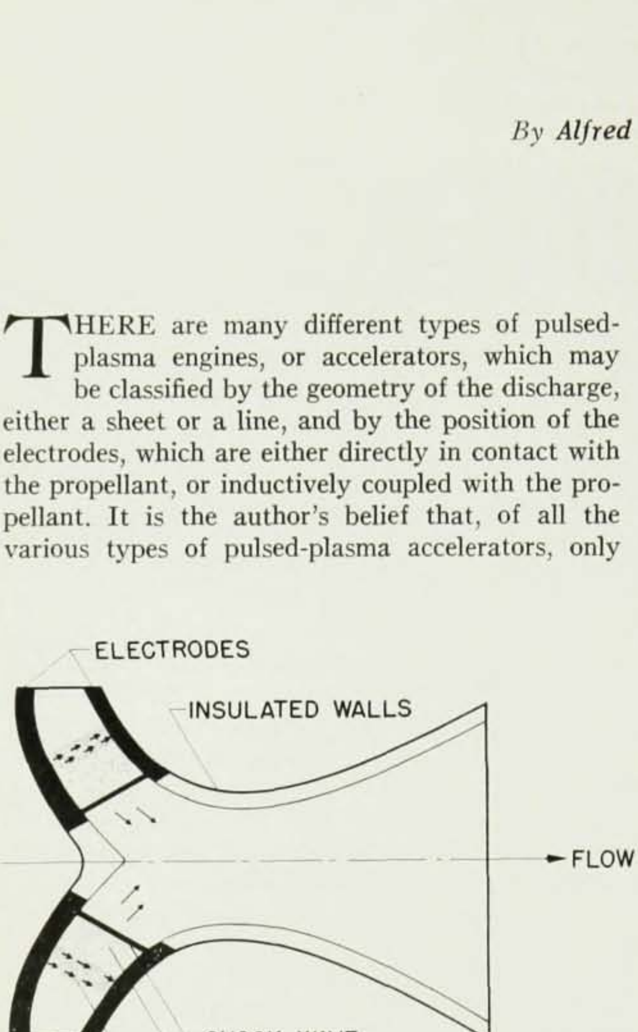

Fig. 1. A schematic representation of a pulsed-plasma accelerator employing the electromagnetic pinch effect. Direct, sheet discharge.

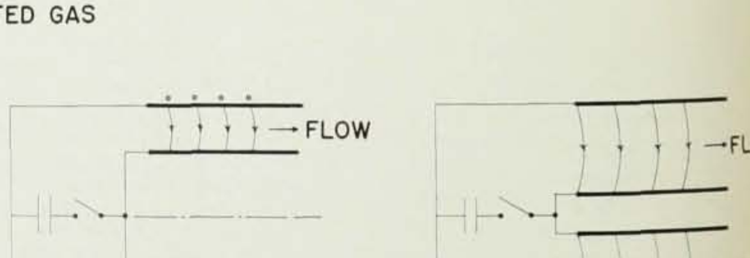

Fig. 2. Axial accelerator for pulsed-plasma propulsion: coaxial tubes; direct, sheet discharge.

Alfred E. Kunen, manager of the Plasma Propulsion Laboratory of the Republic Aviation Corporation, presented the paper on which this article is based at a symposium on plasma physics held in Tarrytown, N. Y., on April 13 and 14, 1962. Organized by the New York State Section of the American Physical Society, the symposium was one of a series of meetings on single topics in physics to be arranged by the Section primarily for the benefit of physicists in fields other than the one under discussion. Several of the papers on plasma physics were printed in the December 1962 issue of Physics Today, *and another from the same symposium begins on page 31 of this issue. Three additional papers from the Tarrytown meeting will appear in a future issue.*

thin and impervious to neutral particles by virtue of the high degree of ionization in the discharge. The accelerating sheet, driven by Lorentz forces, should then drive out the propellant situated in the interelectrode region. In general, the thickness of the sheet and its degree of ionization is affected by the energy available to the discharge. Low energy per discharge coupled with a high pulse rate is desirable for low capacitor weight, but is detrimental to the formation of a good driving "magnetic piston". Experimentally, lower energy per discharge appears to be required in the radial than in the axial accelerator in order to obtain symmetric and nonporous sheet discharges or "pistons".

It is possible to obtain rather efficient conversion of stored electrical energy to kinetic energy of the propellant in a single pulse of accelerated gas. The current trace will look like a critically damped sine wave, and the piston will sweep the electrode region in the same period as the half-cycle current oscillation. In some cases, however, it may not be desirable to sweep out the propellant mass with one pulse. The circuit can be designed to ring out, and each half cycle of current oscillation will be associated with a new discharge originating at the position of minimum circuit inductance. Figs. 3 and 4 are streak photographs illustrating two different

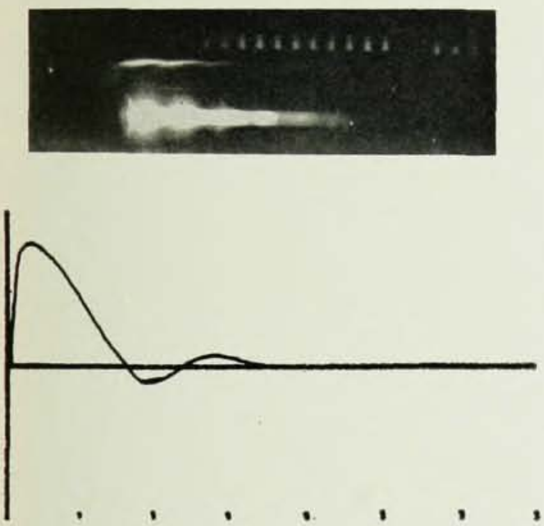

Fig. 3. Streak photograph depicted above shows only one distinct streak of radially inward moving discharge sheet.

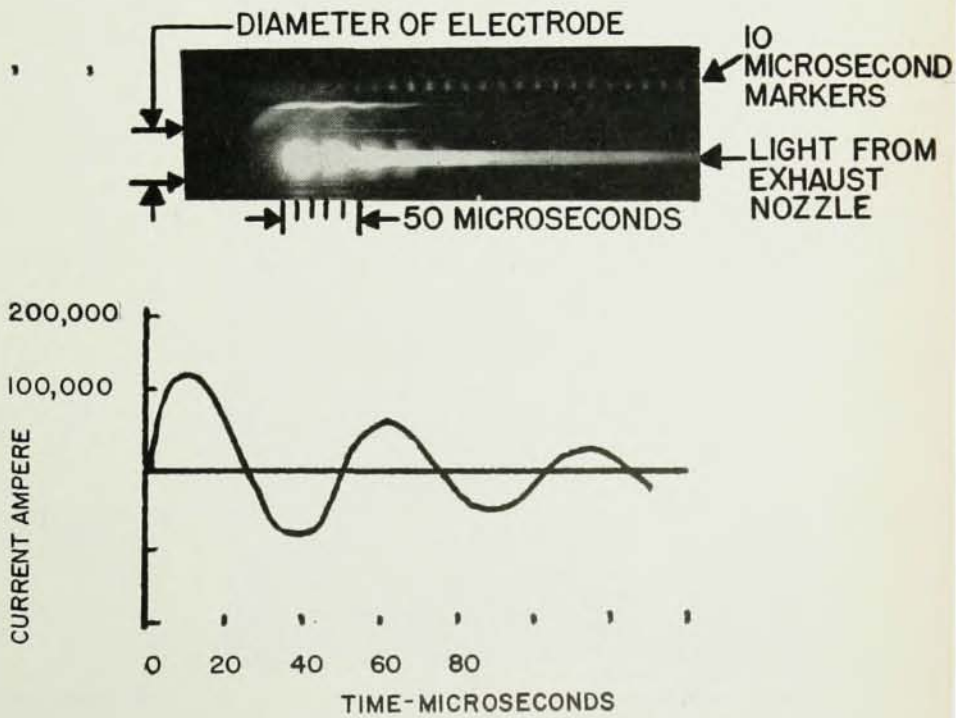

Fig. 4. The photograph on the right shows four distinct streaks of radially inward moving discharge sheet.

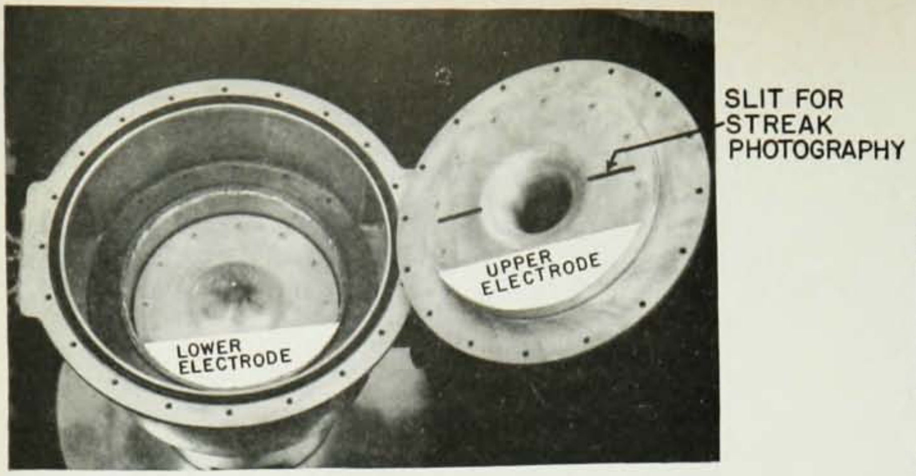

Fig. 5. Nozzle electrodes.

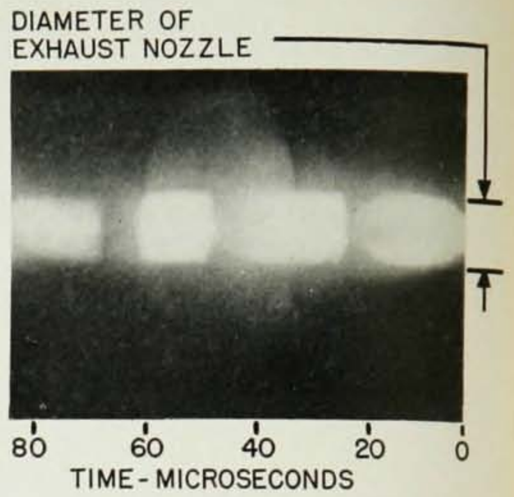

Fig. 6. Discrete slugs of light from exhaust nozzle.

types of discharge as discussed above in nozzle-shaped electrodes designed as in Fig. 5. The ringing-out condition of Fig. 4 is associated with discrete light slugs of propellant issuing from the nozzle exhaust and illustrated in Fig. 6. The axis of the rotating mirror is normal to the efflux velocity. The time scale of each slug of light is approximately equal to the time for one-half cycle of current oscillation.

Efficient utilization of the total mass of propellant consumed (high specific impulse) has been achieved only with the use of a fast-acting valve to inject a desired mass of propellant into the interelectrode region for each pulse or discharge. When operating the accelerator as an engine, capacitors are directly coupled to the electrodes, the capacitors are charged, and the discharge is initiated by the introduction of a predetermined mass of propellant by means of a fast acting valve. The discharge occurs on the left side of the Paschen curve, and the discharge voltage is generally between 1000 and 5000 volts. (See Fig. 7.)

It is possible to build a device with no valve, permitting a continuous bleeding of propellant into the interelectrode space. The propellant in gaseous form, expanding into a vacuum, would take about 100 microseconds to reach the exhaust. A discharge would have to be triggered every 100 microseconds to avoid leakage—that is, 10^4 discharges per second would be required to prevent leakage between discharges. At present it appears that a capacitor energy no less than 250 joules is required to create a symmetrical sheet discharge, relatively nonporous, in the geometries that have been subjected to test. At 10^4 discharges per second, the total power consumption is 2500 kW, a power level not yet avail-

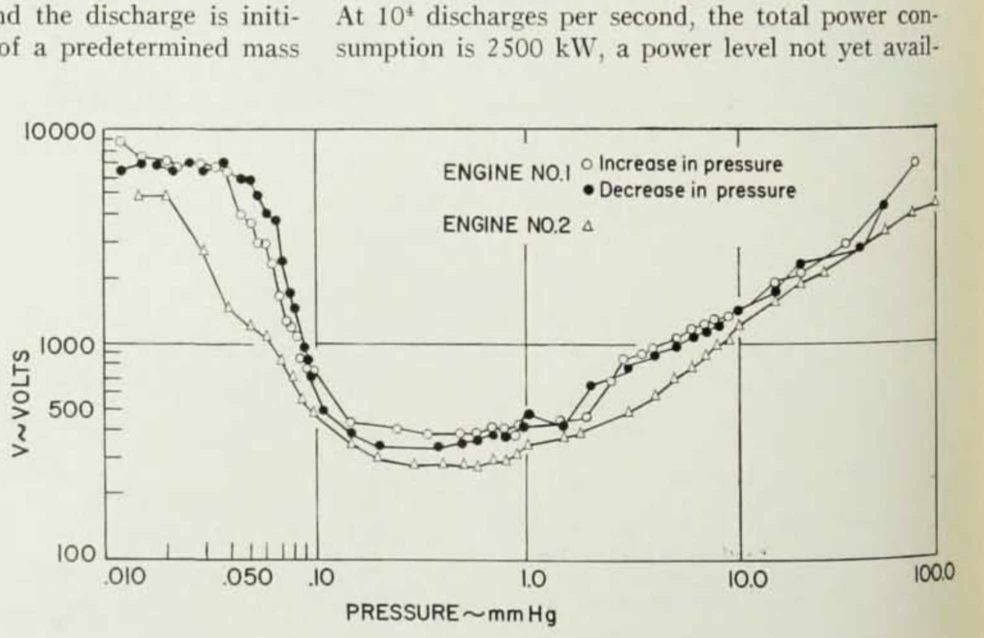

Fig. 7. Voltage breakdown curve for nitrogen.

able for electrical propulsion in space. For efficient operation without a valve at power levels now contemplated, the pulse rate must be very high and a symmetric sheet discharge, with a very high degree of ionization in the sheet, must be obtained with initial energy values of about 10 to 25 joules.

Some important problem areas of interest will be discussed. Perhaps the oldest problem is that of the initiation of the discharge, and the literature on this subject is voluminous. In the case we are considering, there are several reasons why the discharge is altogether different from those described in many of the previously published studies. First of all, the inductance of the discharge electrodes is a good part of the total inductance of the circuit, and therefore the growth of current in the discharge is very much affected by the location of the glow-to-arc transition. It would be interesting to know the form of the arc discharge when transition first occurs—is the arc formed along a line which then distributes itself into a symmetric sheet or is the sheet already formed prior to transition? Second, we are generally dealing with a highly overvolted discharge or impulsive breakdown, and are much concerned with the repeatability of characteristics from discharge to discharge. There are considerable effects, in some cases, attributable to the presence of the insulator. Test runs of millions of consecutive discharges indicate that erosion of certain insulator materials is large during the first few thousand discharges and then becomes negligible in subsequent discharges. The same is true of electrode erosion. The exact processes occurring in the early phases of the discharge are not well understood.

Once the symmetrical sheet discharge is formed, the electro-gas-dynamical processes of propellant acceleration must be considered. This problem is generally treated by coupling the circuit equations (of moving media) with certain assumptions as to the behavior of the gas being accelerated or, in other words, with a particular assumed gas-dynamic model. Several analytical models have been used to study the acceleration process. In the case of a plasma of constant mass (sometimes called the "slug" model), the work done on the accelerating constant mass is equal to the time rate of increase of kinetic energy. The internal energy of the propellant is considered constant; joulean heating is neglected. In addition to varying inductance, the circuit is sometimes considered to have varying resistance. In general, the constant-mass model is not considered to be representative of the situation in which a plasma is accelerated experimentally. The well-known snow-plow model does not conserve dynamical energy as in the slug model, and the increase in internal energy of the propellant is a result of the inelastic collision of the moving gas with the preceding stationary gas. In the case of a plasma engine, the snow-plow model is assumed to move into a region of varying density and velocity; the efficiency of conversion is affected primarily by density changes. The snow-plow model assumes that all of the fluid overtaken by the infinitely conducting current sheet is piled up in a very thin layer at the sheet and is moving at the same speed. Gas-dynamic models include the nonsteady motion between the unaffected gas and the "piston" and can become as complicated in the computation as one chooses, without adding any real knowledge to the actual behavior.

The relationships for a circuit with moving media are illustrated in Fig. 8. The rate of doing work, dW/dt, is proportional to the product of the current squared, and the rate of change of inductance, dL/dt. In the radial accelerator, the value dL/dt is inversely proportional to the radius of the discharge, and hence greater efficiency can be achieved by combining the current peak with the region near the nozzle exhaust. This favorable condition is difficult to achieve in practice and leads to the unfa-

$$U_M = \frac{1}{2} L i^2 \qquad (1)$$

Faraday's (Kirchhoff's) Law for the Circuit

$$iR - \frac{q}{c} = -\frac{d\phi}{dt} = -\frac{d(Li)}{dt} \qquad (2)$$

$$\text{or } i^2 R + \frac{d}{dt}\left(\frac{q^2}{2c}\right) = -i\frac{d(Li)}{dt}$$

$$\text{with } i = -\frac{dq}{dt} \qquad (3)$$

Energy Equation

$$i^2 R + \frac{d}{dt}\left(\frac{q^2}{2c}\right) + \frac{dU_M}{dt} + \frac{dW}{dt} = 0 \qquad (4)$$

From Equations (1), (3), and (4)

$$\frac{dW}{dt} = \frac{1}{2} i^2 \frac{dL}{dt} \qquad (5)$$

With i = Constant

$$\left(\frac{dU_M}{dt}\right)_{i\ \text{constant}} = \frac{1}{2} i^2 \frac{dL}{dt} = \frac{dW}{dt}$$

Fig. 8. Equation for Faraday's law.

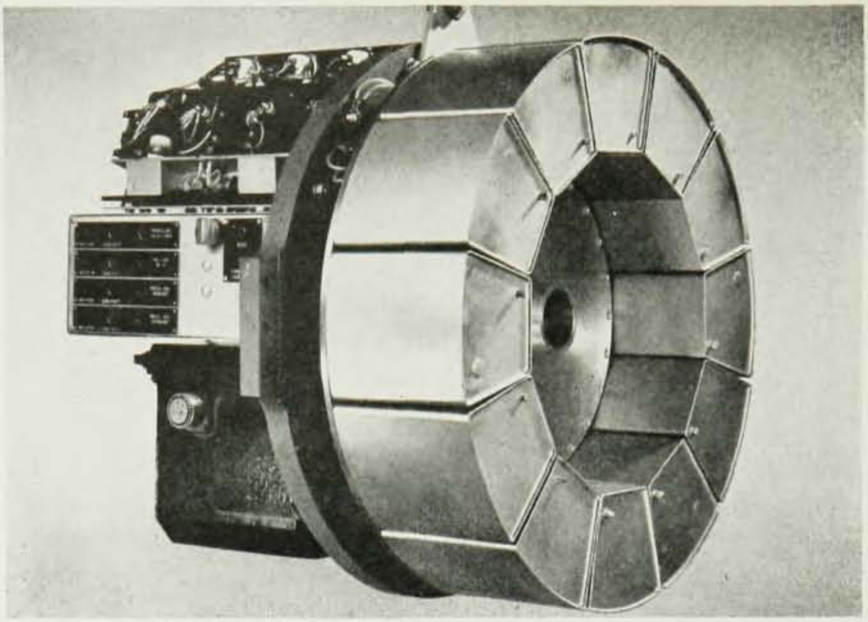

Fig. 9. Pulsed plasma engine.

vorable possibility that the plasma will leave the electrode while high currents are still in existence. It is also interesting to note that, in contrast to the case of mechanics where kinetic energy is derived at the expense of potential energy, the rate of change of magnetic energy (at constant current), dU_M/dt, is actually equal to the rate at which work is being done. The capacitors must give up electric field energy at a rate twice that of the work being done.

An early engine that has operated for hundreds of hours is illustrated in Fig. 9. To the left of the bulkhead is the power package, which, in this case, contains a 28-volt battery, a power converter and charger for charging the capacitors, a propellant system, and necessary controls. To the right of the bulkhead are the capacitors in a ring around the nozzle-shaped electrodes. These capacitors operate at 1500 to 5000 volts. The device is a nominal 1-kW, 10-millipound thrust engine. Thrust is optained by mounting the entire package on a reaction thrust stand, and specific impulse is obtained by measuring the total amount of propellant consumed in a propellant storage bottle.

Questions and Answers . . .

Q: I think it might be worth while to mention, with respect to the theory, that many of us have used the snow-plow and slug model, that some of the experimental work that has been done at Los Alamos recently by Lovberg and some of the other people, and the theoretical work that has been done by Mawardi at Case, seem to suggest that the slug and snow-plow models are not as good or as valid as they might be expected to be in all geometries. In fact, $\mathbf{J} \times \mathbf{B}$ acceleration doesn't necesarily hold. The consequences seem to be rather unfortunate in certain kinds of plasma applications. One doesn't know yet, because these new concepts are rather in their infancy.

A: If you don't have a certain minimum energy in the capacitors and a sheet discharge does not develop, then you are not getting $\mathbf{J} \times \mathbf{B}$ acceleration. A line arc discharge will take place; any acceleration could very well be due to arc heating. The specific impulse will be limited to low values, which is what one might expect from the order of magnitude of the estimated temperature. One can determine in any of these accelerators whether $\mathbf{J} \times \mathbf{B}$ acceleration or arc heating is the major factor. Certain experiments during the formation of the sheet discharge also indicate that electromagnetic acceleration is the overbearing feature.

Q: Did you say you had gotten an efficiency figure?

A: We can get into a long argument on the meaning of efficiency. We have gotten more than 50% efficiency when kinetic energy is obtained from thrust and mass flow. The effective velocity used in calculating efficiency is the ratio of thrust to mass flow, and that is how we get $\frac{1}{2}mv^2$; that is, we change v to t/m and the efficiency is given as $(\text{thrust})^2$ divided by two times the mass flow rate times the power.