Energy Storage and Delivery Systems - An Urgent Requirement for Aerospace Contingencies

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A few months ago, a major disaster at sea startled the world. The U.S.S. "Thresher" was lost with all hands, in waters which are among the best charted and best known in the whole world and a few miles only from the main base of operations. In the absence of really adequate data, it has been, so far clearly impossible to reconstruct a proper explanation of the tragedy except to learn that, at a comparatively trivial depth compared with that of the world's oceans, means of reconnaissance for the wreck and for rescue under such circumstances, have been either extremely inadequate for the task or totally lacking.

If a survey is made of the increasing toll of flying accidents both in the civil transport and in the military field it must be conceded that there are, yet, many equally inexplicable losses of life and of materiel in regions of the troposphere and lower stratosphere where the problems of flight ought to be well understood.

The nature of these experiences is such that their study and their resolution are of importance to astronautics which has profited by analogies in many fields. Criteria which are used to gauge the performance of sea going vessels and, more recently, aircraft have been expressed in standards which have been appropriately codified by marine surveyors or by aircraft inspectors, and the concepts of seaworthiness and airworthiness are well understood. As yet, however, in spite of several orbital and sub-orbital flights successfully achieved in this country and in the Soviet union, and clearly a successful medical and training programme for personnel, there is, so far, little visible evidence of a realistic or concerted drive to promote really systematic study of the many criteria which must be implied in true 'spaceworthiness of manned space vehicles.

Just as the analysis of data, on an international scale of co-operation has promoted transport successes in other spheres it should now be possible to infer that favourable results for astronautics will be achieved by properly concerted action on an international scale. A new discipline of Astrography may result which would be a counterpart of oceanography. It would be a specially analytic field in which the space sciences would be considered from the point of view of application rather than theory.

Numerous contributions have already been made some of the most significant and relevant having been studies founded on the extension of radiobiology and of radiation damage already available into the space environment, suitably amplified by newer findings. By far the most basic problem however hinges on propulsion.
Chemically fuelled rockets which have been dominating aerospace research up to the present have had the great advantage of being largely independent of their environment but this attribute which has been so valuable has tended to obscure their most serious limitations when the choice of optimum prime movers for serious and protracted voyages into deep space are under consideration. Their bulk and short endurance obviously render them obsolete for such problems.

The investigations currently proceeding over a wide front into such questions as the acceleration of electrically charged fluid masses under conditions of ionic flow, or of the transport of plasma by pumping fields point the way towards a realization of the desired techniques which would provide an adequate supply of power located midway between the extremes of the high energy high thrust chemical rockets of short duration, and the low-energy low thrust devices such as ion motors or plasma jets so far developed to cater for long endurance, cruise conditions. There is plainly a most serious 'propulsion gap' which needs to be filled before soundly conceived manned power flight in space can be contemplated.

As is usual in such problems involving transport phenomena we may divide the problem into:

a. The means by which the chosen form of energy source may be made to exert a force on its environment. This is the problem of the working substance.

b. The means by which acceleration of the working substance may be achieved.

c. Associated with the above is the question of energy storage. This may generally be considered in terms of thermodynamic potentials, of dynamic or electrical storage or, ultimately, the role of matter itself as form of energy rather than a vehicle through which it acts.

So far, one of the most impressive and, indeed, promising methods aimed at the resolution of the 'Propulsion Gap' has been the Gas Core Nuclear Rocket and consideration of this is desirable.

Gas Core Nuclear Rockets.

The present position of nuclear rocket development is dominated by the attendant technologies of civil power generation stations and naval reactors from which much useful data has become available. At the same time these also restrict the development of suitable space-borne reactors as they do a large vested interest in man-power and indeed concepts centred on quite different working conditions.

Typical layouts of gas core reactors are shown in Figs 1, 2, 3. It will be noted that, as in a normal bi-fuel rocket, two gaseous components flow into a chamber consisting of a cavity surrounded by a moderating shield. The propellant generally considered to be most promising is hydrogen and a possible fuel which has received a good deal of study has been UF₆ containing the fissionable isotope of uranium.
As envisaged such a device, presupposing that flow and containment could be sustained, would operate at exhaust gas temperatures of 10,000 deg. R to 15,660 deg. R and specific impulses of up to 3,000 sec. are planned. Performance and endurance calculations by Ragadale and others have shown such a figure for specific impulse would correspond with a thrust weight ratio which would enable a vehicle designed for a round trip to a planet such as Venus with a total vehicle weight of about half of that obtaining in the case of a solid cored reactor rated for a similar mission. \(^1,2,3,4,5^\)

Because of the extremely high pressures which would obviously be necessary in a reaction of this kind, there is a body of opinion which considers that there must be an induced differential between the flow rates of the two gaseous components as they pass through the cavity which has been formally expressed in terms of 'residence times'. This implies that there is a Separation Factor which is the ratio of the hydrogen velocity through the reactor to that of the fissionable fuel.

It has been shown that:

\[
\frac{P}{1,000} = \frac{W'}{35} \quad \frac{N_p}{10^{10}} \quad \frac{T}{10,000} \quad S \text{ is Separation factor.}
\]

\(N_p\) is the critical density at/c.c.

\(T\) is the reaction temperature deg. R.

\(W'\) is the hydrogen to fuel flow-rate ratio.

With a separation factor of 100 there seems to be a theoretically feasible reactor type but the engineering problems are formidable and methods of bringing about partial separation would clearly be extremely complex.

Two methods which have been proposed which might provide a basis for operating have been;

a. Vortex containment systems which may be single or multiplex. \(^1,2,3,4^\)

b. CO-axial flow systems. \(^2^\)

In addition, some attempts have been made at JPL to analyse the conditions of operation of a plasma-core type reactor. So far the bulk of the work has been of a theoretical nature but some publications of the Russian Kikoin working in this field might indicate that the theory has been applied to an extent. Calculations by G. Safronov have shown that with a cavity radius of about 1 meter using a \(D_2O\) reflector a charge of about 2 kg would correspond to a condition of criticality.

These details of cavity and vortex stabilized cavity reactors are cited in this paper because they seem to provide the first and obvious solution to the vital problem of the propulsion gap and there can be little doubt that, in terms of feasibility, of range and of thrust these prime movers will be attainable after particularly difficult development programmes. However they would present extremely difficult problems in habitability of space-craft and of shielding in view of their high temperatures and radiation rates.
While work in this direction is seen to have promise there are a number of other directions in which enquiry should be directed, particularly those in which there seems to be promise offered by acceleration of plasma or ionised gases at relatively low magnetic Reynolds numbers at which high temperature, containment and radiation problems are much less formidable. As an introduction to these it is profitable to study the applications of MHD drive to vortex systems such as those suggested by the work of Rozenzweig and his collaborators, noting, however, that their goal has been a different one. (3)

There is also the work of Gross and Kessey, who have examined the theory of an MHD plasma centrifuge. (4). In this the plasma is contained between two co-axial cylinders. Fig. ( )

MHD Equations and Analysis of the Plasma Vortex.

Continuity $\nabla \cdot V = 0$

Momentum $\mathcal{M}(\frac{dV}{dt}) + \nabla p = J \times B$

Faraday's Law $\nabla \cdot E = -(dB/dt)$

Ampere's Law $\nabla \times B = -\mu J$

Ohm's Law $J = \sigma(\mathcal{E} \times V \times B)$

Divergence Law $\nabla \cdot B = 0$

$V =$ fluid velocity
$B =$ magnetic field vector
$E =$ electric field vector
$\mathcal{M} =$ bulk fluid density
$\sigma =$ conductivity
$\mu =$ magnetic permeability.

From the above basic equations, equations for mass flow in a long cylinder may be derived, using a single fluid density;

$$E_r = \left( \frac{I_r}{4\pi h_o \sigma} \right) - V_0 B_o$$

$$-\frac{G_r}{r} \left( \frac{2V_0}{r^2} + \frac{V_0}{r} \right) + \eta \frac{3}{r} \left[ \frac{1}{r^2} \frac{d}{dr} \left( r V_\phi \right) \right] - \frac{B_o I_r}{4\pi h_o r} = 0$$
For a complex fluid such as a partially ionized, incompressible plasma (electrons, light and heavy ions, light and heavy neutral particles);

\[
\frac{\partial}{\partial t} \frac{2}{\mu} \left[ \frac{1}{r} \frac{2}{3r} (\nabla \cdot \mathbf{B}_o) \right] - \frac{G_o}{\mathbf{B}_o} \left( \frac{\partial \mathbf{B}}{\partial t} - \frac{\mathbf{B}_o}{\mathbf{r}} \right) = 0
\]

\[
\frac{2}{\mu} \left( \mathbf{B}_o \right) = - \frac{\mathbf{B}_o}{\mathbf{r}} \frac{\partial \mathbf{B}_o}{\partial t}
\]

\[
\frac{2}{\mu} \left( \frac{\mathbf{B}_o}{\mathbf{r}} \right) = \mathbf{B}_o \frac{2}{\mathbf{r}} \left( \frac{\mathbf{r} \cdot \mathbf{B}_o}{\mathbf{r}} \right)
\]

For a complex fluid such as a partially ionized, incompressible plasma (electrons, light and heavy ions, light and heavy neutral particles);

\[
\mathbf{F} = \sum_{j=1}^{5} \mathbf{n}_i \mathbf{m}_i = \text{const.}
\]

\[
\mathbf{n}_i = \text{number density of species } i
\]

\[
\mathbf{m}_i = \text{mass of particle of the } i\text{th species}
\]

A solution is obtainable from detailed consideration of the above relationships defining the electric power required to rotate plasma per unit mass, which is;

\[
\frac{P_m}{\mathbf{R}_o^4 / \mathbf{B}_o \mathbf{r}_o^4} = \frac{4 \left| \mathbf{R}_N \right|}{1 - \mathbf{R}}
\]

where

\[
\left| \mathbf{R}_N \right| \text{ is radial Reynolds no}
\]

\[
P_m \text{ is total electric power input}
\]

\[
\mathbf{R}_o \text{ is absolute coefficient of viscosity}
\]

\[
\phi_e \text{ is electrical potential difference across electrodes.}
\]

\[
\mathbf{F}_o \text{ is applied axial magnetic field}
\]

\[
\mathbf{r}_o \text{ is radius of outer electrode}
\]

\[
\mathbf{r} \text{ is } \mathbf{r}_o / \mathbf{r}_o
\]

and

\[
\mathbf{R} = \frac{2 (m + 1)}{[m + 1] [3^{2} - 1 + 2 (\frac{2 \mathbf{R}_N}{m^2} - a) \ln 3] - 2 q (3^{m+1} - 1)}
\]

while

\[
m = 1 + \mathbf{R}_N
\]
Typical results which have been obtained from studies on gaseous core rockets are represented by the following data:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust gas temp.</td>
<td>11,000 deg. R.</td>
</tr>
<tr>
<td>Average gas press.</td>
<td>500 atm.</td>
</tr>
<tr>
<td>Reactor volume</td>
<td>10.3 cubic metres</td>
</tr>
<tr>
<td>Total power</td>
<td>$1.21 \times 10^8$ Kw.</td>
</tr>
<tr>
<td>Reactor radius</td>
<td>1 metre</td>
</tr>
<tr>
<td>Radial current</td>
<td>348 amperes.</td>
</tr>
<tr>
<td>Voltage diff.</td>
<td>50 volts.</td>
</tr>
<tr>
<td>Axial magnetic field</td>
<td>$10^4$ gauss.</td>
</tr>
<tr>
<td>Mass flow</td>
<td>5.63 lb. sec.</td>
</tr>
<tr>
<td>Thrust</td>
<td>16,900 lbs.</td>
</tr>
</tbody>
</table>

The thrust is still comparatively small and would have to be considerably increased in order to justify the effort that will be needed to realize serviceable equipment working on these principles.

Rosa has pointed out in a recent study of a combination of a cavity reactor with an MHD generator, that the cavity reactor as discussed above, suffers from the rather important disability that a good deal on unfissioned uranium would be dumped in the exhaust and that full efficiency could only be maintained if this could, somehow, be recovered and recycled. This rather difficult task could be obviated, he believes, by the use of the combined cavity reactor and MHD generator. (8). Figs.

As illustrated, the installation also includes an MHD generator of a kind now considered to be practicable after a good many development difficulties have been resolved. It would produce, in conjunction with a cavity reactor about 300 tons of thrust and operate with a specific impulse of about 1,000 seconds. The operating chamber pressure and temperature would be 100 atmospheres and 300 deg. K., using a working fluid consisting of hydrogen containing 1% $^3$He and 1% Potassium vapour. For criticality, it would require a diameter of about 2 metres and would need a $D_0$ blanket of about 7 tons weight. Gas escape temperature would be about 2,000 deg. K. and pressure would be atmospheric after a 100/1 expansion. The MHD generator working from these exhaust gases would be designed for a gas flow of $1.45 \times 10^7$ mols/sec and for a power output of 14,000 megawatts. This is, of course, high compared with existing power generating plant but is not high compared with output achieved with chemical rockets for short periods. It should be quite adequate to put a 100 ton satellite into close orbit and would be invaluable on longer space missions on which there would be a requirement for substantial power to deal with contingencies.

Study of MHD generators of the above type is leading to new approaches to the study of plasma and highly ionized gases both as a source of energy through fusion reactions and as means of storing energy which may be drawn off for propulsion. It is becoming better understood that the properties of plasma in a magnetic field in which it behaves as a diamagnetic medium ($k < 1$) depending for its conductivity on the
Energy as it may be used for purposes of propulsion may be stored in the following ways:

1. As chemical energy, fuels; phenomena of combustion dissociation etc.
2. As nuclear energy, fission, fusion or other processes.
3. Momentum as in flywheels.
4. Electromagnetic energy, currents flowing in inductances.
5. Electrical energy in condensers or capacitors.

If \( W_0 \) represents energy density, i.e. Joules / cm\(^3\), we have been able to obtain from chemical explosives \( W_0 \sim 10^4 / \text{cm}^3 \). In order to obtain a similar density in a magnetic storage system, the field strength \( H \) would need to be \( \sim 1.6 \times 10^6 \) gauss. If one considers the rim of a flywheel made of steel moving at the periphery at sonic speed, the kinetic energy at the rim is 500 Joules / cm\(^3\). There would be an upper limit here imposed by the strength of the material. In condensers, one may have an energy density of about \( 10^{-2} \) Joules / cm\(^3\), much below the value appertaining to a flywheel. Much attention has been paid recently to the improvement of electrical engineering materials and with improved oxides of titanium with exceptionally high dielectric constants it is hoped to be able to produce condensers with the capability of storing a charge of over 1 Joule / cm\(^3\). It would appear that the discovery of the optimum conditions of conferring energy of motion to charged gases probably in the comparatively stable configuration of the vortex presents one of the best alternatives needed to resolve the propulsion problem. It would also involve means of converting and diverting the momentum thus stored into linear acceleration. A survey of the principal natural processes of large scale transport phenomena such as movements of air masses or of portions of the solar corona would seem to stress the ultimate feasibility of the concept.

Electromagnetic Plasmoid 'Whirls'

It is well known from the established theory of magneto-hydrodynamics that;

\[
J = \sigma \left( E + \mathbf{V} \times \mathbf{B} \right)
\]

Where \( J \) = Current density

\( \sigma \) = Conductivity of the gas
\[ \mathbf{B} = \text{Magnetic field vector} \]
\[ \mathbf{V} = \text{Velocity}. \]
\[ \mathbf{E} = \text{Electric field vector}. \]

This is a special form of Ohm's law applicable to plasma transport.

In addition, the Magnetic Reynold's Number \( R_m \) is defined by

\[ R_m = \frac{\mu_0 \mathbf{V}}{\mathbf{E}} \]

\( \mu_0 \) is permeability of free space

\( \mathbf{V} \) are as above; \( l \) is a linear dimension.

There are generally two main regions to be considered when the question of moving ionized gases or plasmas are under consideration. They are those in which:

1. \( R_m \gg 1 \) and \( E^\alpha \)
2. \( R_m \ll 1 \).

(1) This is the region of thermal or equilibrium ionization occurring at high temperatures and is typical of the conditions obtaining during the investigation of fusion devices.

(2) This is the region of extra-thermal or non-equilibrium ionization and which has long been known in connexion with investigations on low pressure gas discharges.

There would appear to be a region on the general curve (Fig. 0) lying below the point of inflexion of the curve which has not received much attention but which has been under consideration in connexion with the setting up of rotating plasmoid systems which have been named 'whirls' by Japolsky who has carried out an extensive investigation on their properties. Their conception and relationship with e/m wave systems rotating in vacua arose from analysis of propagation from a wave guide under particular conditions. They are particular solutions of the Maxwell equations.

The Maxwell equations may be set out as follows:

\[ \mathbf{E} = \mathbf{E} = \nabla \times \mathbf{B} ; \quad \mathbf{B} = \nabla \times \mathbf{E} \]

\[ \text{div}\mathbf{E} = 0 ; \quad \text{div}\mathbf{B} = 0 \]

\( \mathbf{E} \) is electric field intensity vector (e.s.d.)
\( \vec{B} \) is the Magnetic field intensity vector

\[
\text{dot over vectors indicates } \frac{d}{dt} \text{ in fixed coordinates and } c \frac{d}{dt} \text{ in invariant coordinates.}
\]

In addition, solutions of Maxwell's equations must always satisfy the 'wave equations'

\[
\Box \vec{E} = 0 \quad ; \quad \Box \vec{B} = 0
\]

where \( \Box \vec{L} = \nabla \vec{L} + \frac{1}{c} \frac{\partial}{\partial (i \omega t)} \) in fixed coordinates

\[
= \nabla \vec{L} + \frac{1}{c} \frac{\partial}{\partial (i \omega t)} \quad \text{in invariant coordinates}
\]

\( \nabla \vec{L} \) = curl curl + grad div.

\( c \) is the ratio between the absolute electrostatic and absolute electromagnetic units of field intensity and is usually referred to as the velocity of light.

In the theory we are obliged to take account of two kinds of solutions to the Maxwell equations. These are (1) An elementary solution ('simple whirl'). (2) Integral solutions ('compound whirls')

For the 'simple whirl'

\[
\begin{align*}
\vec{E} &= A \beta \gamma \vec{b}_0 \vec{R} \left( e^{i (\omega t + n \theta)} + \frac{e^{i (\omega t - n \theta)}}{2} \right) \\
\vec{B} &= A \beta \vec{b}_0 \left( \frac{e^{i (\omega t + n \theta)}}{n} - \frac{e^{i (\omega t - n \theta)}}{2} \right)
\end{align*}
\]

A is the amplitude constant

\( R \) is a symbol indicating that only the real portion of the complex expression in the brackets need be taken.

is a non-dimensional constant

\[
\beta = \left( 1 - \frac{V^2}{c^2} \right)^{-\frac{1}{2}}
\]

V is the velocity of motion of the 'whirl' with reference to a coordinate system taken as fixed.

\[
\frac{q_0}{\lambda_0} = 2 \pi V = \frac{\Omega}{c}
\]

\( \lambda \) is the wave length of the 'whirl.'

\( n \) is its frequency

\( \Omega \) is its angular frequency with respect to the moving coordinates.
where \( x \) is the axial coordinate with reference to the moving coordinate system and may be called an invariant axial coordinate \( x \), by the relationship:

\[
x = x_1 + vt
\]

\( t \) is time in seconds

\( \tau \) is the invariant time coordinate

\( \beta \) is a non-dimensional constant which characterises the exponential fall in the field intensity in the axial direction \( r \).

\[
\gamma = \frac{|k|}{\beta q_0} = \text{exponential decrement fn.}
\]

The upper sign \((-\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\·
\[ H \Phi = \sum (J_{n+1} - J_{n-1}) H \theta \]
\[ = \sum (J_{n+1} - J_{n-1}) \]

where \( J_n = \int_n \left( \frac{x}{\sqrt{x^2 + 1}} \right) \)

These are Bessel functions of the first kind (Bessel coefficients) of the order \( V_n \) of an argument:

\[ J_n = \int_n \left( \frac{x}{\sqrt{x^2 + 1}} \right) \]

which is the same in all cases when \( S = q \omega \nu \) is an invariant coordinate.

The solutions for the "magneto-polarised whirls" would be expressed in exactly the same way but with the sole difference that the functions \( G \) and \( H \) in the above would be interchanged.

The characteristic expression for the "compound whirl" may now be written:

\[ E = A \rho q \int \left( \sum f(x) \left( \frac{x}{\sqrt{x^2 + 1}} \right) \right) \]

\[ \beta = A \beta q \int \left( \frac{x}{f(x)} \right) \]

where \( f(x) \) is an arbitrary function insofar as this is consistent with conditions of physical reality.

There is an important case in which:

\[ f(x) = \exp \left( \alpha x + \frac{2}{x} \right) \]

Here, the second term of the Right Hand expression indicates the dispersion of the centres of elementary "simple whirls" which together constitute the compound one.

When the upper limit of the integral

\[ \left( \sum \frac{f(x)}{f(x)} \right) \]

is finite i.e. when \( x \) is substituted for \( x \), the type of 'whirl' which would result is defined as a 'fragment.'

This would be a relatively unstable entity.
Properties.

From the above formulation, it should be appreciated that a 'whirl' forms waves (in the azimuthal direction) which rotate about the axis with an angular velocity:

\[
\Omega_n = \frac{\partial}{\partial t} / \frac{\partial}{\partial \theta} = \frac{\beta_n \Omega}{n} = \frac{\beta_n \theta}{n}
\]

Hence, in the radial direction, there result standing waves corresponding with the nodal circles of the Bessel functions outlined above, or of their appropriate integrals. In a 'simple whirl' the loci of the nodal circles i.e. the nodal surfaces will be cylinders, in a compound whirl' or 'fragment' they will be surfaces of revolution with curved generating lines.

The total energy of the 'whirl' system may be determined to be:

\[
\hat{E} = \frac{1}{8 \pi} \int \int (E \cdot \vec{E} + \beta \cdot \vec{\beta}) \, d\omega
\]

( the dots indicate scalar multiplication).

Extended over all space the above quantity becomes:

\[
\hat{E} = \frac{1}{8 \pi} \int \int \int (E \cdot \vec{E} + \beta \cdot \vec{\beta}) \, dx \, dy \, dz
\]

The energy of a compound whirl being finite, its existence in a complete form within a confined space is physically possible. On the other hand, a 'simple whirl' or a fragment, for which could only be partially realized in a limited space.

For a compound whirl where energy is finite,

\[
\hat{E} = \beta \hat{E} = mc^2
\]

\[
\kappa = \frac{\hbar}{2 \pi} = \frac{\hbar}{2 \pi} \frac{x^2 + 1}{x}
\]

\[
\kappa = \frac{\hbar}{2 \pi} = \frac{\hbar}{2 \pi} \frac{x^2 + 1}{x}
\]

\[
\Omega K = \frac{\Omega x^2 h}{2}
\]

\[
\kappa
\]

is a constant which has the dimensions of angular momentum which remains invariant for a given 'whirl'. It corresponds to Planck's constant although it might not be equal to it numerically. The angular momentum of the 'whirl' is \(2\pi \kappa\). Thus the invariance of \(K\) represents the law of conservation of angular momentum imparted to the system.
If the electrodynamic 'whirl' system is generated not in vacua but in a conducting medium such as an ionized gas (seeded or unseeded) or a plasma with a resistivity \( \rho_w \), the dielectric constant \( \varepsilon \) both in e.s.u. and permittivity \( \varepsilon_\text{m.u.} \).

Then, the electric and magnetic vectors would be expressible in the form:

\[
\vec{E} = \frac{C_n}{c} \vec{E}_\text{c}, \quad \vec{B} = \vec{B}_\text{c} + \vec{B}_\text{r},
\]

and the current density may be expressed in the form:

\[
\vec{I} = \frac{C_{12}}{c} \cdot \frac{\vec{E}_\text{r}}{\rho_w},
\]

where

\[
\frac{C_{12}}{c} = \frac{1}{N\varepsilon\mu}, \quad \frac{C_n}{c} = \frac{\sqrt{\mu}}{4\pi\varepsilon M}.
\]

The expressions for \( \vec{E}_\text{c} \) and \( \vec{B}_\text{c} \) and for \( \vec{E}_\text{r} \) and \( \vec{B}_\text{r} \) will be the same as those previously given for \( \vec{E} \) and \( \vec{B} \), but with \( C_{12} \) and \( C_n \) substituted.

The resistivity of the air \( \rho_w \) depends upon the degree of its ionization and this depends mainly upon \( \varepsilon_\text{c} \), which represents the intensity of the electric field. The component \( \varepsilon_\text{c} \) is analogous to the local "e.m.f. of ohmic resistance" per unit length, the product of resistivity \( \rho_w \) and current density. Quantitatively \( \varepsilon_\text{c} \) would be >> than \( \varepsilon_\text{r} \).

When \( \varepsilon_\text{c} \gg 3,500 \text{ volts/cm} \), complete ionization in most gases results and the condition of plasma is realized.

In order to generate the highly energetic plasmoid systems described a special vortex tube wound with a sheath helix with a geometry conformable with the boundary conditions demanded by the system. Electric power supply would be available as polyphase current and a pumping field acting on the gas would set up a lag between the linear and angular velocities of the gas and the linear and angular velocities of the field. The imbalance resulting from this would favour ionization. Over and above the energy thus expended entrainment would also take place as a result of coupling effects together with a substantial compression of the gaseous core or kernel represented by the 'whirl.'

The total energy output required to ionize \( F \) particles under normal conditions would be:

\[
e F v_i / n_i \text{ per particle.}
\]

\( e \) is the electric charge
\( F \) is the number of particles ionized
\( v_i \) is the ionizing potential
\( n_i \) is the ionizing efficiency.

The amount of energy transferred to a plasma more fully ionized than that envisaged in the above theory is given by Miller (12) in terms of a propagation constant \( k \).
$k^2 = \left( \frac{\omega}{c} \right) \left[ 1 - \left( \frac{\omega_p e}{\omega} \right) \right] \left( 1 + \frac{\omega_p e}{\omega} + \frac{\nu}{\nu_0} \right)$

where:

- $\omega$ is electromagnetic field frequency,
- $\omega_p e$ is plasma electron frequency.

It should be noted that in communications on applications of 'whirl' theory to deflection of light in the Sun's gravitational field on theories of nuclear structure and of the nature of fundamental particles, Japolsky has claimed confirmation by the calculation of fourteen physical constants applying in his formulae only five well known and established factors (c, h, e, m+ and ) the velocity of light, Planck's constant, the electronic charge, the protonic mass and the gravitational constant respectively. His data derived from the above includes the mass ratio of the electron and proton, the mass of the neutron and of the light nuclei $^1H$, $^2H$, and $^4He$. It is remarkable to note that these conceptions have permitted a calculation of the period of rotation by pure theory for the planet Venus on 20 hrs and 45 minutes. Radioastronomical data published after that gave 22 hrs, 16 minutes. There are, in addition, some interesting and speculative proposals for the realisation of nuclear power from a different route than fission and fusion resulting from this analysis. Consideration of this, however, is outside the scope of this paper.

A certain resemblance may be detected to 'whirl' theory in the interesting work of Dr. Bostick on 'Plasmoids'. In his experiments which have given rise to some thought-provoking analogies between the behaviour of small slugs of plasma generated by electrostatic means and that of fundamental particles. He has briefly examined the behaviour of a hydromagnetic model of toroidal configuration analogous to an electron or a proton. In his analysis Bostick has related rest mass energy for the toroidal electron model with its electromagnetic field energy, which he finds to be

$E = \int \frac{1}{s} \left\{ \left| \nabla \right| + \left| \phi \right| \right\} dV = \frac{\xi}{R} \left( 1 + \frac{1}{n} \sqrt{\frac{k^2}{\nu e}} \right)$

where:

- $V$ is volume
- $R$ is the major radius
- $r$ is the minor radius.

This author has pointed out that in any force-free configuration involving plasma or magnetic fields such as those which assume a toroidal form, there are helicoidal enveloping field lines which thread the system such that their pitch angle varies from 90 deg. at the annular axis to approximately zero at the periphery. This led him to postulate self-gravitational forces with such a particle model comparable in kind but not, of course, in degree of magnitude with similar self-gravitational effect within force-free electrically conducting plasmas occurring on a galactic scale within the stellar universe.
The problem of designing suitable accelerator and divertor equipment may at first sight appear formidable particularly when the exceedingly massive nature of most acceleration equipment is visualized even when these are designed to operate under conditions of high vacua. However this type of equipment is not always massive and the work of Budker and Naumov in the Soviet Union may be noted in this connexion.

These workers have published accounts of their development of such devices as an impulsive noniron (air cored) synchrotron for which a stabilised beam of relativistic electrons is set up and in which a small addition of ions is needed to compensate for decay of the electron beam through coulomb interaction. With this beam magnetic fields of $10^5$ Oersted and electric fields of $10^5$ v/cm would result. The beam in question which is described as transparent for ions and for e/m waves and which can be sustained for several hours has been designed specifically to act as a focusing system for the light cyclic resonance accelerator for which Budker has been responsible. In this, the beam can be sustained in circular form using a current of 100,000 amps with a ring radius of 3 metres producing energy of 100 B.ev. One accelerator operating on the principle with a ring radius of 17 has been able to furnish a beam of 200-300 m.e.v. The installation would have an installed weight of only 150kg. Acceleration is produced by means of R.F. techniques using millimetre waves (2-4 mm). It can thus be seen that extremely high energy particles can be made available using only medium weight equipment. The adaptation of some of the principles used in design and of data gained by such accelerators would be most useful in constructing thrusters for space propulsion. In addition, an open mind will need to be maintained about new methods of realising nuclear energy and it will be the task of the astrophysicists to assist in this field armed with the newest data being acquired through the space programmes.

If the states of matter be categorised as $W_1$, $W_2$, $W_3$ are solid liquid and gaseous states and $W_4$ categorised as the plasma state chemical phenomena ($W_5$, $W_6$ and $W_7$) would come within the energy range of say 5 e.v., corresponding to valence bond forces. Radioactive phenomena would be placed at the level of about 10 m.e.v. and cosmic ray phenomena at about 10,000 m.m.e.v. There has been suggested that a fifth state of matter $W_5$ 'nugas' may exist composed of electrons and free nucleons. This would be a common state in galactic processes. It is not easy to rate the energy absorbed in the production of this but it would not, in all probability, be of a very different order to the quantities associated with fission or fusion processes involving $W_1$, $W_2$ and $W_3$ as energy levels. This would be $5 < W_5 < 200$ m.e.v. There is also thought to be a sixth state $W_6$ possible within the ranges $0.2 < W_6 < 4G.e.v$. This would contain a good many free mesons, decayed nucleons as well as electrons. Since it is now commonly recognised that upward of 99% of matter in the cosmic universe is within the last two categories, the attainment of energy in new forms and the application of these to interplanetary transport can only be a matter of time and it may be found that neither fission nor fusion processes are particularly suitable to resolution of the problem.
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VORTEX CONTAINMENT CAVITY

FISSION REACTOR
Combined Cavity Reactor and MHD Generator.

Propellant

REACTOR

Fuel.

Propellant and uranium
High Temp. and Press.

MHD Generator

Propellant and uranium
Low Temp and Press.

POWER

COLLECTOR

Propellant

ACCELERATOR

385
ENERGY

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PLASMA

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LOAD.

THE PLASMA TRANSFORMER
Regions of Ionization.
Energy Source

High Frequency Polyphase Current

Energy Storage Converter

Divertor

Storage and Diversion Propulsive System