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THE SPHEROMAK FUSION MACHINE AS PROPULSION IN SPACEFLIGHT

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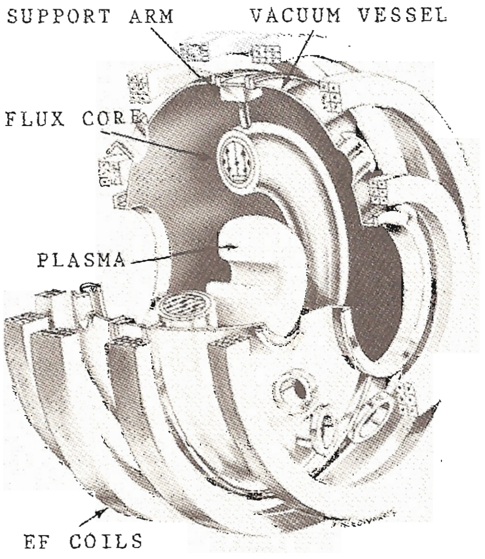
Modification of the practical lightweight spheromak produces a FUSION-ROCKET for interplanetary spacetravel.

1. THE S-1 SPHEROMAK FUSION MACHINE

The S-1 Spheromak device, the first large-scale test of the spheromak magnetic confinement concept, began operation at the Princeton Plasma Physics Laboratory early in 1983. As in a tokamak a spheromak uses toroidal and poloidal magnetic fields to confine a doughnut-shaped plasma. In a spheromak, however, the currents generating the toroidal field flow in the plasma itself, eliminating the large external toroidal field coils required on tokamaks.

Higher current densities minimize the need for supplemental plasma heating apparatus, thereby simplifying the task of reaching ignition temperatures. The spheromak's high engineering beta value (the ratio of the plasma pressure to the magnetic field pressure, measured at the coils rather than within the plasma) allows maintenance of a higher plasma energy with less stress on the coils themselves in comparison with tokamaks.

The spheromak consists of 3 main sections: the vacuum vessel, 6 outer equilibrium field (EF) coils, and a flux core, which contains a 6-turn poloidal field (PF) coil, a 90-turn toroidal field (TF) coil and one additional EF coil. Recently, addition of a loose-fitting figure-8 stabilization system has improved plasma stability and parameters.



The EF coils are powered by 2 motor-generator sets, which provide a steady-state EF field over the duration of a plasma discharge by supplying currents up to 22,300 amperes for up to 5 seconds.

The PF and TF systems are powered by separate capacitor banks; power is

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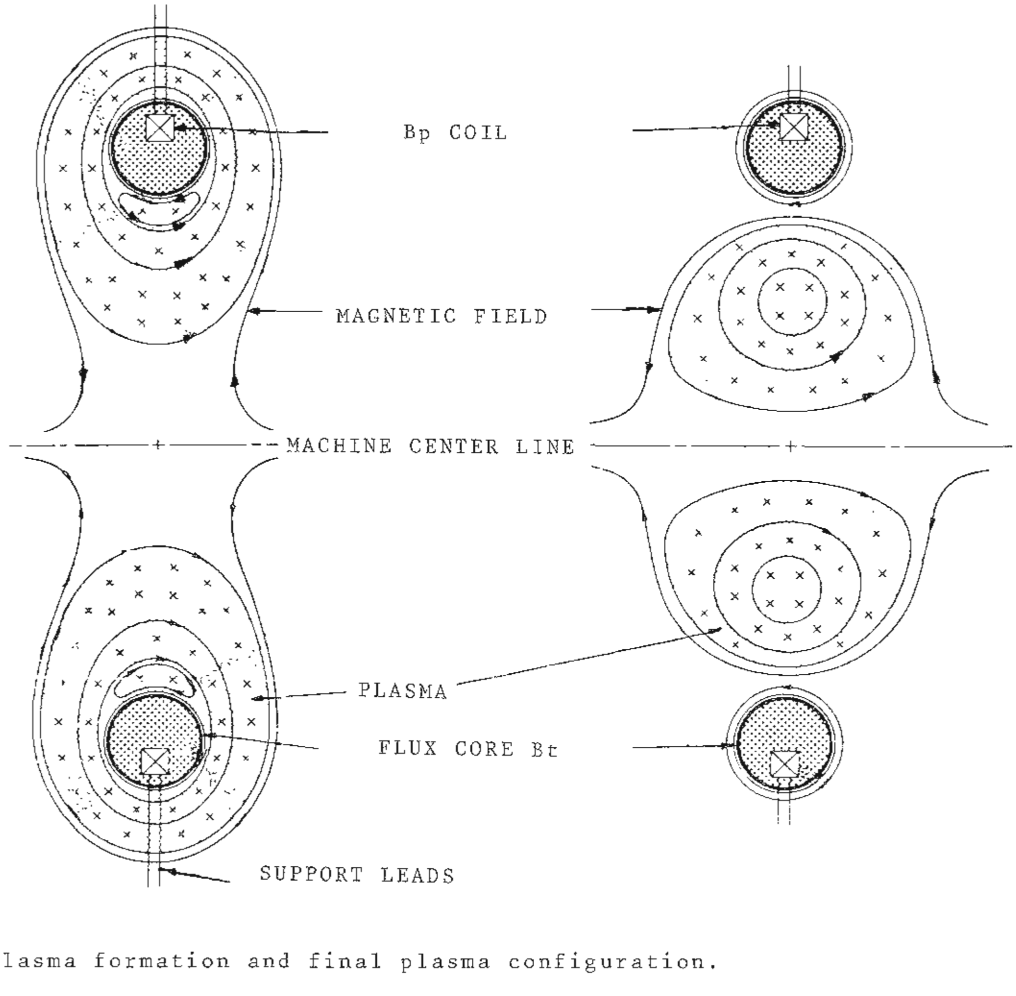
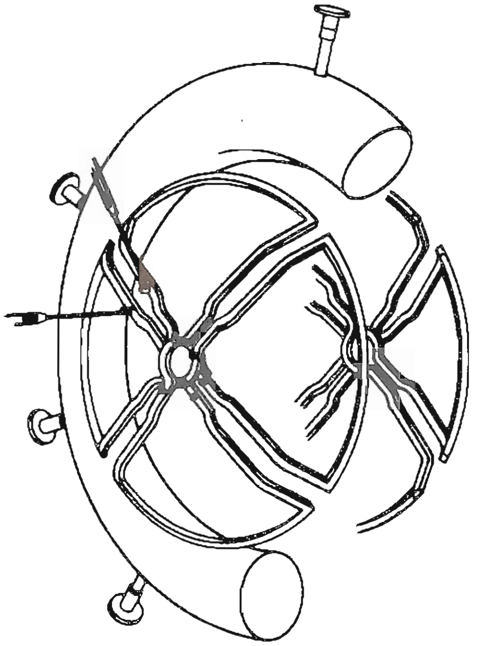
switched from the banks to the coils by ignitron tubes.

A 1/8-inch-thick aluminum shell covers the coil and fiberglass combination. This shell helps smooth the magnetic fields generated by the PF and TF coils, thereby reducing field errors and plasma-core interaction. The shell also helps stabilize the plasma during formation. The flux core is covered by a metallic "liner", which functions as a clean vacuum vessel wall. Since the liner must allow the magnetic fluxes from inside the core to be transferred to the plasma, Inconel, a very resistive nickel-based alloy, is fabricated into a thin (0.010-inch thick) cover.

Creating the flux core liner began when 0.125-inch thick Inconel sheets were shaped into 2 "half-toroids" by explosion forming (an improved method over the previously used spinning formation process). The thickness was reduced by chemical milling, a process whereby the liners were dipped into an acid bath. The acid removed material from areas not masked off, thus achieving a final product of uniform thick-



Initial plasma formation and final plasma configuration.



Passive figure-8 coil stabilization system and S-1 flux core

ness. The process has recently been used for the fabrication of the Space Shuttle's liquid fuel tanks.

2. MAKING AN S-1 SPHEROMAK PLASMA

In the S-1 Spheromak, plasmas are formed by using the flux core's coils to induce plasma currents.

At the start of an experiment, a neutral gas surrounds the flux core. The outer EF coils are switched on, generating a magnetic field that is strongest at the outer edges of the core.

The PF coils are then energized as is the TF coil about 75 micro-seconds later. This creates a high voltage near the surface of the flux core, initiating the ionization that creates the plasma. The current in the PF and TF windings is changed, inducing poloidal and toroidal currents in the plasma. Simultaneously, the equilibrium fields from the EF coils push the ionized gas to the center of the machine. Here the plasma's self generated fields, aided by those of the external coils, keep it confined.

The S-1 device reached in 1986 the milestones established when the S-1 project was proposed in 1979: attainment of hot (100 eV) plasmas with stable lifetimes of 1 msec or more. The plasma has a temperature of approximately 1 million degrees Kelvin.

The S-1 device forms spheromak plasmas with major radii ranging from 45 to 60 cm, and minor radii of 25 to 50 cm. Toroidal plasma currents of up to 350 kA have been achieved at moderate powerlevels. Measured peak electron temperatures range from 40 to 110 eV.

3. FUTURE EXPERIMENTAL PROGRAM

Preliminary experiments indicate betas from 5 to 50% are possible.

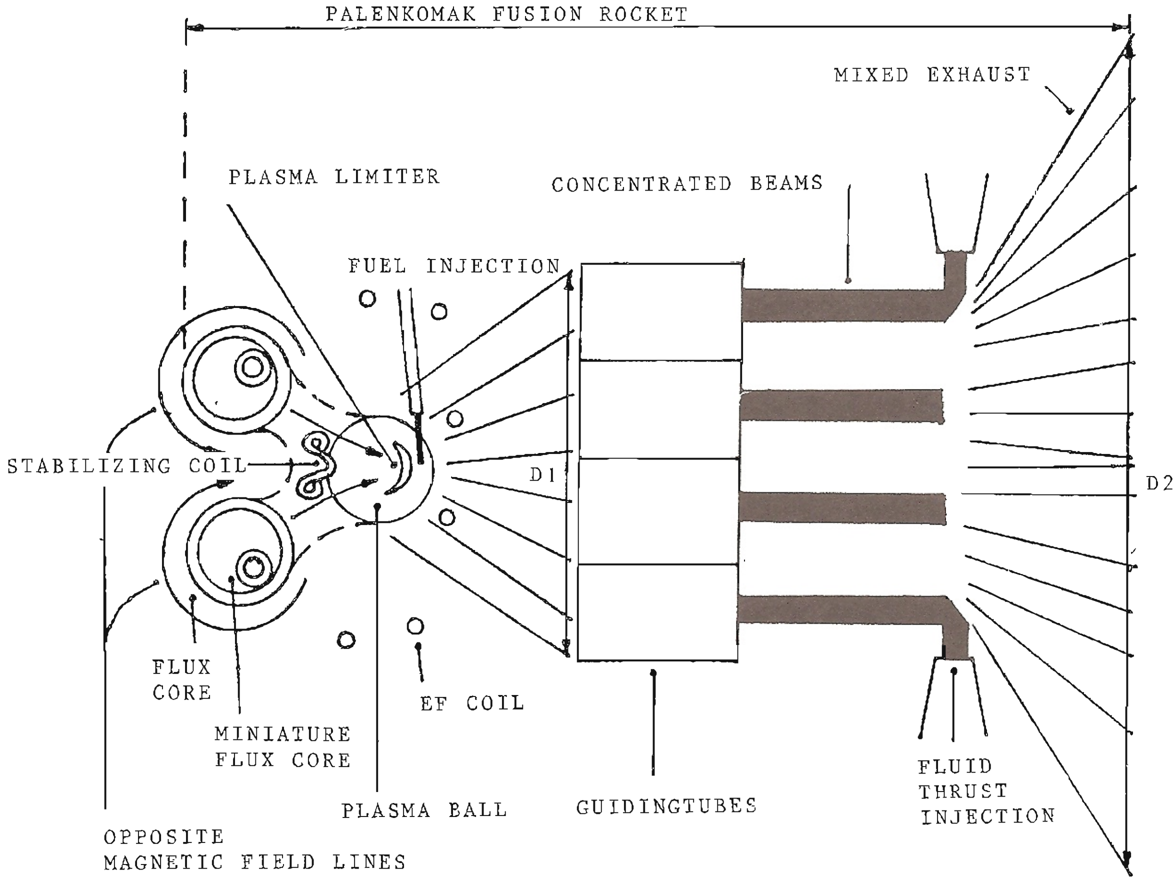
Another major emphasis of S-1 research will be the inductive sustainment of spheromaks. Sustainment is any method of actively driving plasma currents to extend the plasma lifetime, maintain a steady-state discharge, or increase plasma currents.

One scheme for sustainment is the use of a poloidal-flux transformer along the major axis. Toroidal plasma currents of 1MA are expected to be achieved with this system. Preliminary experimental evidence from a prototype device and preliminary theoritical evidence from numerical simulations demonstrate the successful use of a poloidal-flux transformer for sustaining a spheromak by increasing and prolonging not only the toroidal plasma current but also the toroidal magnetic flux in the plasma.

A further upgrade of the spheromak system would be aimed at achieving 0.5 to 1.0 keV plasmas. This would involve moving the spheromak plasma away from the plane of the flux core by use of a magnetic field, followed by compression by a factor of approximately 2.5. In a power reactor, this would allow a non-reacting plasma to be formed, moved away from the flux core, then ignited; the core would thus be protected from neutron exposure.

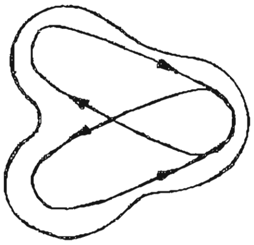
4. THE PALENKOMAK FUSION ROCKET

In the modified spheromak only the right halve of the external EF coils is used to serve as a "magnetic catchnet" for the plasma ball. The left halve of the EF coils is replaced by a flux core with a small diameter. A miniature flux core is placed inside the flux core. This PF coil with TF windings moves the plasma directly 30 degrees into the "magnetic catchnet" of 3 EF coils. A small stabilizing PF coil with opposite windings pushes the plasma towards the plasma limiter. The 2 opposite ellips



The Palenkomak fusion rocket for interplanetary spacetravel.

shaped plasma currents come together in the plasma ball and confine the plasma ball as a bi-polar complimentary unity. The number of revolutions of the opposite ellips shaped plasma currents determine the final stability by creating opposite magnetic moments.



Opposite ellips shaped electron currents confine the plasma ball.

In the balanced plasma ball a fuel injection takes place emitting a plasma flux of particles creating an outlet with a diameter of D1. The particles from the plasma are concentrated in 14 guidingtubes creating 14 beams of particles. A fluid injection of thrust material takes place in the 14 beams creating a mixture of plasma- and thrust particles to increase the final thrust and rocketspeed. This "mixed exhaust" has a diameter D2, which is 2.5 times larger than the first outlet diameter D1. After the "expansion treatment" the "mixed exhaust" will be shot into space to provide the thrust for the fusion rocket. This happens according to the third law of Newton: action = reaction.

5. PALENKOMAK PARAMETERS

The escape velocity for earth is 11.2 km/s.

The fusion rocket has a plasma temperature of 100 million degrees Kelvin, a low fuel consumption with a high specific impuls Isp = 100,000 seconds and a high exhaust speed of thrust particles. The fusion rocket can work for a long time, because of the low fuel consumption. A low fuel consumption however is not favourable for the thrust, so that a thrust injection in the second outlet is necessary. This increase of thrust material results in a higher thrust and rocket speed.

If we have the power available P, the mass flow rate through engine $\dot{m}$ and the exhaust speed c, then

$$P = \frac{\dot{m}}{2} c^2 \quad \text{and thrust } T$$

$$T = \dot{m} c \text{ . From this}$$

$$P = \frac{1}{2\dot{m}} T^2 \text{, or } T = \sqrt{2\dot{m}P}$$

We see that T will go up if we increase $\dot{m}$, at constant power. Increasing T is of advantage, because time requirement to accumulate some speed increment Δv decreases.

A chemical rocket has a gas temperature of 3573 degrees Kelvin in the combustion chamber (Space Shuttle thruster), a high fuel consumption with a low specific impuls Isp = 450 seconds and a low exhaust speed. The disadvantage of a chemical rocket is the high fuel consumption or low specific impuls, so that the payload is always very low compared to the lift-off weight. A chemical rocket travels in 9 months to the important planet Mars.

The Palenkomak fusion rocket can travel in the future to Mars in a few months, involving the machine losses.