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WILD BLUE YONDER PROPULSION SCHEMES U

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This paper will include a discussion of the ORION concept, several gaseous core nuclear rockets, thermonuclear propulsion utilizing superconducting magnets, and finally a lightweight radioisotope power generation system for electric propulsion. With the exception of the latter concept, all of these schemes have much in common. The initial vehicle weights would be very large - on the order of several million pounds. The payload fractions are high - on the order of 25 to 50 percent of the takeoff weight - for near Earth missions. The development problems would be severe, and, correspondingly, the development costs would be extreme - on the order of many billions of dollars. In addition, the launching problems from Earth would be fantastic - with nuclear radiation hazards and political overtones added for good measure. However, the reward for success would be great. One can contemplate large payload fractions propelled on space missions - with thrust-to-weight ratios, at least in some cases, greater than unity and with specific impulses of several thousand seconds. The mission transportation costs would run in terms of dollars per pound of payload with clear opportunities for reasonable manned expeditions across the solar system. This is the carrot that leads the endorsement of such gigantic projects. Conf. R.D. Author

The ORION vehicle resembles a city water tower, as shown in figure 1. Rather sophisticated small nuclear bombs would be ejected at frequent intervals to a trailing position along the vehicle axis, and exploded. The explosion pressure of these bombs reacts on the pusher plate shown at the base of the vehicle. The shock load on the vehicle proper is minimized by a tuned damper system connecting the pusher plate to the cabin. Additional shock isolation beds may be required to minimize the oscillatory accelerations on the crew.

The operational sequence on the vehicle is shown in figure 2. Following ejection, the bomb is exploded when the pusher plate reaches its maximum rearward velocity. Thus, the piston inertia helps to shield the cabin from the shock load. The full explosion pressure reverses the motion of the pusher plate relative to the cabin to reset the cycle for the next explosion.

A minimum-size ORION vehicle, weighing perhaps 600 tons, is shown mounted on a Saturn booster in figure 3. The chemical first stage is required to boost ORION to a sufficient altitude in order to permit the first nuclear explosion. This altitude is perhaps above 35,000 feet. The ORION vehicle then adds sufficient velocity increment through a series of nuclear explosions to accomplish the desired mission.

The payload capability of ORION improves as the size increases, with vehicles as large as 5000 tons contemplated. Except for the nuclear bombs, the entire ORION vehicle and payload would be returned to Earth's vicinity for reuse after accomplishing the mission.

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The gaseous core reactors shown in figures 4 to 8 offer about the same kind of performance promises. To be superior to the more conventional heat-transfer nuclear rocket, the hydrogen propellant must be heated to temperatures above the melting point of most materials. This heating is accomplished in a gaseous core reactor through which the hydrogen is passed. The fluid mechanic arrangements are generally tailored in special ways so as to conserve as much of the reacting uranium gas as possible. A typical cavity might be 10 feet in diameter and 10 feet long. This cavity would be surrounded by high-temperature moderating materials to thermalize the neutrons. The propellant must cool these materials to counteract the neutron and gamma heating amounting to about 10 percent of the total energy generated. Thus, the thermal properties of the moderator set an upper limit for the specific impulse of a gaseous core reactor at about 3000 seconds.

If only uranium gas fills the core, the minimum pressure for hot criticality is about 25 pounds per square inch. With the addition of the hydrogen propellant, the wall pressures approach 1000 to 10,000 pounds per square inch.

The pressure shell to contain these pressures is sufficiently thick so that no reactor shield is required. Nevertheless, the total weight of the reactor including moderator and pressure shell is from 250,000 to 500,000 pounds. Hence, in a mission comparison with more conventional nuclear rockets, the gaseous core reactor system would likely require a fuel load of more than 500,000 pounds to capitalize on its higher specific impulse.

An early suggestion for a gaseous core reactor is shown in figure 4. Tangentially entering hydrogen passes radially inward through a gaseous uranium vortex. Hopefully, the centrifugal forces associated with the heavier uranium molecules would be balanced by the diffusion drag of the inwardly moving hydrogen. The hydrogen would ultimately move along the axis to the exhaust nozzle.

Unfortunately, the drag produced by the flowing hydrogen is so great that excessive loss of uranium will occur unless the hydrogen flow rates are limited to very low values. Hence, in a single-tube vortex reactor, only low thrusts could be obtained without excessive loss of uranium.

One way to avoid this difficulty is to use multiple vortex arrangements as are shown in figure 5. Criticality is achieved by the combination of many gaseous uranium cores. These may either be materially separated, as in the upper left diagram, or established by a matrix injection pattern, as shown in the square box drawing. These schemes were proposed by Jet Propulsion Laboratory and Space Technology Laboratory. Both have a major problem of cooling the enclosed hardware.

The United Aircraft Corporation uses an alternative approach to boost the hydrogen flow (fig. 6). Ninety percent of the incoming swirling hydrogen moves axially toward the annular exhaust nozzle on one end. This hydrogen would be seeded with additives to absorb the radiant heat from the core. Note, however, that the slower moving boundary layers near the end walls will not sustain the radial pressure gradients generated by the vortex. Hence, there will be a radially inward secondary flow of about 5 percent on each end wall. This hydrogen

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blends with the 0.1 percent diffusion flow and moves along the axis to the discharge nozzle.

The Lewis Research Center's coaxial jet reactor is illustrated in figure 7. The central core of uranium gas would be injected at a much slower speed than the coaxially flowing hydrogen. Hopefully, the mixing processes can be tailored to minimize the uranium loss rate. A hydrogen buffer layer would be added with an intermediate velocity profile between the uranium and outer hydrogen layer to serve this purpose. The hydrogen to uranium flow ratio should be 50 to 100 or higher for reasonable fuel conservation.

Though hidden by the vortex flow, the United Aircraft scheme (fig. 6) must have axial velocities and axial velocity ratios comparable with those of the coaxial jet. Hence, the differences in the axial velocities between the fuel and the hydrogen would produce the same kind of mixing losses of uranium as for the coaxial jet.

On the other hand, the axial velocity component can be eliminated on the vortex reactor by using tangential entry and exit of the fluid. A schematic of this arrangement is shown in figure 8. In all of these reactors, the principal heat-transfer mechanism to the hydrogen is by radiation, and the hydrogen must be continuously seeded with graphite powders and other materials to absorb the radiant heat before it reaches the containing walls.

There are, of course, grave questions concerning the stability of the boundary between the uranium and hydrogen flows. These questions would be complicated by feasible nuclear criticality interactions due to expansions, contractions, or distortions of the uranium gas regions. There are also extreme heat-transfer problems in the exhaust nozzle that would require solution before such cavity reactors are practical.

The next scheme to be discussed is the thermonuclear rocket. The approach (not yet accomplished in the laboratory) is to heat a plasma of light elements to a temperature on the order of 1 billion degrees Kelvin. At such temperatures, a portion of the ions are moving at sufficient speeds to cause fusion upon collision, accompanied by the release of large energies.

Four frequently considered fusion reactions are shown as follows:

$$D + D \rightarrow He^3(0.8\ \mathrm{Mev}) + n(2.4\ \mathrm{Mev})$$

$$D + D \rightarrow T(1.0\ \mathrm{Mev}) + p(3.0\ \mathrm{Mev})$$

$$D + T \rightarrow He^4(3.5\ \mathrm{Mev}) + n(14.1\ \mathrm{Mev})$$

$$D + He^3 \rightarrow He^4(3.6\ \mathrm{Mev}) + p(14.7\ \mathrm{Mev})$$

The amount of energy liberated to each particle is given in million-electron-volt units. One electron volt is equivalent to 11,605° K. The first two reactions occur with equal probability and are between deuterium ions. The third and fourth are between deuterium and either tritium or helium 3, respectively. The

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difficulty with using deuterium-deuterium and deuterium-tritium reactions is that a large fraction of the energy appears as high-velocity neutrons.

At the temperature ranges of interest, only magnetic fields offer promise as a means of confinement. The neutrons are unaffected by magnetic fields and are thus lost from the reaction zone. Recovery of this energy in a cooled shield would only complicate a thermonuclear space propulsion system. Hence, reactions liberating charged particles that can be trapped by magnetic fields are preferred.

Deuterium and helium 3 might be provided as the fuel utilizing the fourth reaction. If the reactor temperature is held at a sufficiently high value, the probability of a deuterium-helium 3 reaction is much greater than the deuterium-deuterium reaction so that only about 5 percent of the energy would be liberated as neutrons.

The reacting plasma would be contained in a magnetic bottle as shown in figure 9. The charged particles are reflected back toward the reactor interior by the stronger fields on the ends. The plasma pressures of more than 1000 pounds per square inch suggest confining field strengths of over 100 kilogauss. These fields would be provided by superconducting magnets to minimize the power losses associated with containment. The field on one end of the reactor would be weaker than on the other end, which would allow propellant to flow through the magnetic nozzle to space to produce thrust.

The cryogenic magnet must, of course, be cooled to low temperatures with a liquid-helium system. To minimize the heat load on the magnet due to bremsstrahlung and neutron radiation, shields are provided, as shown in figure 10. The thermal capacity of the hydrogen cools the cryoplant and the neutron shield (secondary). This hydrogen is ejected by the reactor-exit jet. Additional cooling through a radiator system is required for the primary bremsstrahlung shield.

The performance of such a thermonuclear rocket is pretty spectacular. Thrust to engine weight ratios as high as 0.01 are feasible and correspond to about 1 or 2 kilowatts of jet power per pound of engine weight. The specific impulse would be on the order of 10,000 seconds. The performance of such a system would therefore be about an order of magnitude better than that predicted for a nuclear fission electric propulsion system.

The Lewis Research Center is investigating the feasibility of using ion cyclotron resonance as the means of kindling the thermonuclear reactor. For this scheme to be effective, magnetic field strengths in the 100-kilogauss range are required. Hence, the Center also has a modest effort devoted to the production of intense magnetic fields; several water-cooled magnets (fig. 11 shows one of these) in the 100-kilogauss range have been tested. Lewis also has the liquid-helium production capacity to support major projects with superconducting magnets. However, no one has yet sustained a controlled thermonuclear reaction in the laboratory either here or elsewhere. Hence, it is far from timely to get enthusiastic about the mission capabilities of thermonuclear systems - the understatement of the conference.

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The final idea to be discussed is the radioisotope balloon shown in figure 12. Concentric conductors are arranged in either spherical or cylindrical geometry from the electrodes of a radioisotope battery. The inner shell would be coated with either an α-emitting or a β-emitting radioisotope. The high-energy charged particles that are ejected through radioactive decay generate the electrode potential to form a nuclear battery.

Because of the potential difference, there will be an attraction between the inner and outer electrodes. This attractive force must be canceled by rotating the outer balloon. If spherical geometries are used, the poles have no centrifugal forces. Hence, a yoke is also required.

The voltage output for a radioisotope battery is high - on the order of 1/2 million to 1 million volts setting a minimum size for the battery of a few feet in diameter. This high voltage would be used to accelerate colloidal charged particles to speeds corresponding to specific impulses in the thousands.

The overall weight of the system including powerplant and accelerator is estimated at a few pounds per jet kilowatt. The mission potential of such a lightweight system is, of course, very good. However, the optimism toward using such a system is not very high.

The problem is traceable to a combination of properties of the isotopes. The α-emitters are desired but are in very short supply. They also must be carefully contained, for they are toxic and are deposited in the bone marrow of animals, where the radioactivity does irreparable damage. The β-emitters are much more plentiful, but the high-speed electrons generate X-rays on impact with materials. Hence, 3 to 6 inches of lead would be required at the launch pad to shield the crew. Also, the heat generation of the radioisotope decay process cannot be shut off. Hence, a major cooling problem might be faced during launch on any high-power radioisotope system.

Research is being conducted on the radioisotope systems as well as on the other Wild Blue Yonder propulsion schemes discussed in this paper. None has progressed to the point of sufficient confidence to justify a development program, and some may never reach that point. The chemical rocket still looks like the work horse for missions to be flown in the next 10 years.

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TYPICAL ENGINE CONFIGURATION

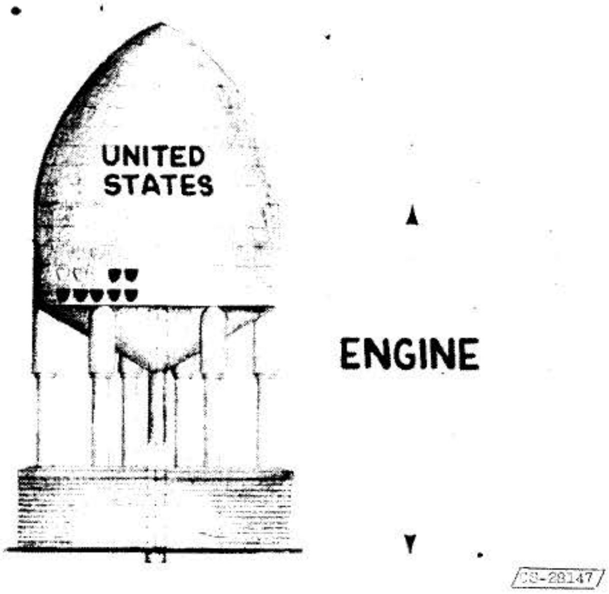

Figure 1

VEHICLE OPERATIONAL SEQUENCE

Figure 2

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SATURN BOOSTED

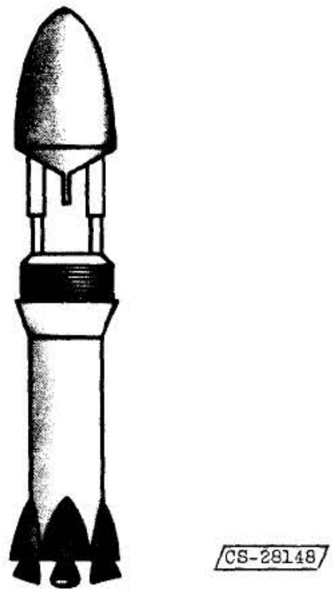

Figure 3

VORTEX GAS CORE REACTOR

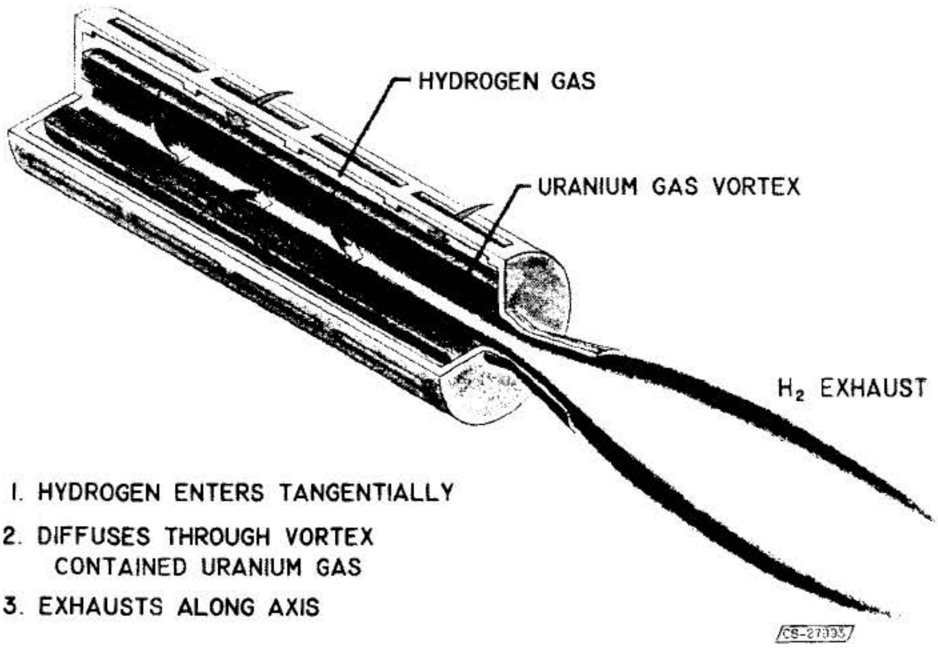

Figure 4

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VORTEX TUBE AND VORTEX MATRICES

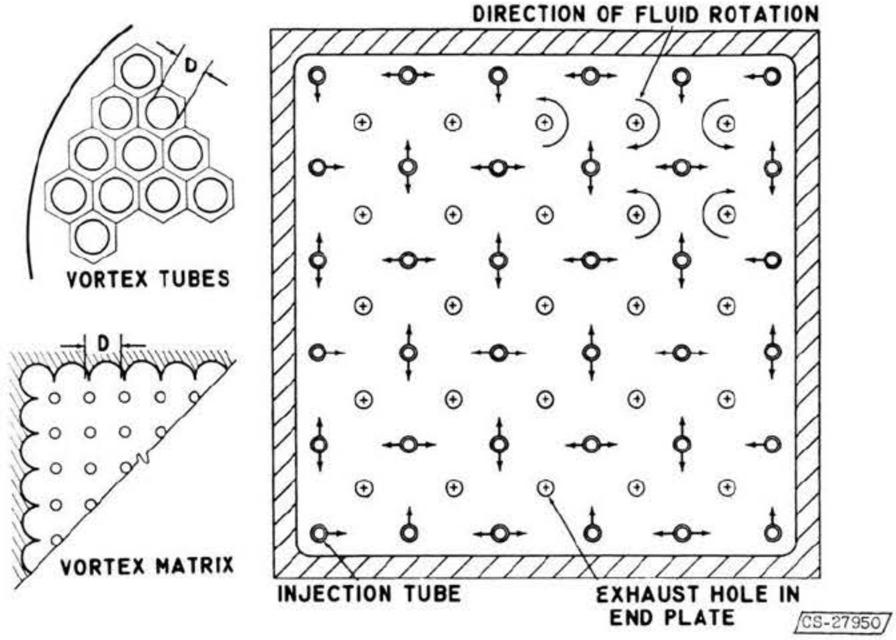


Figure 5

UNITED AIRCRAFT REACTOR

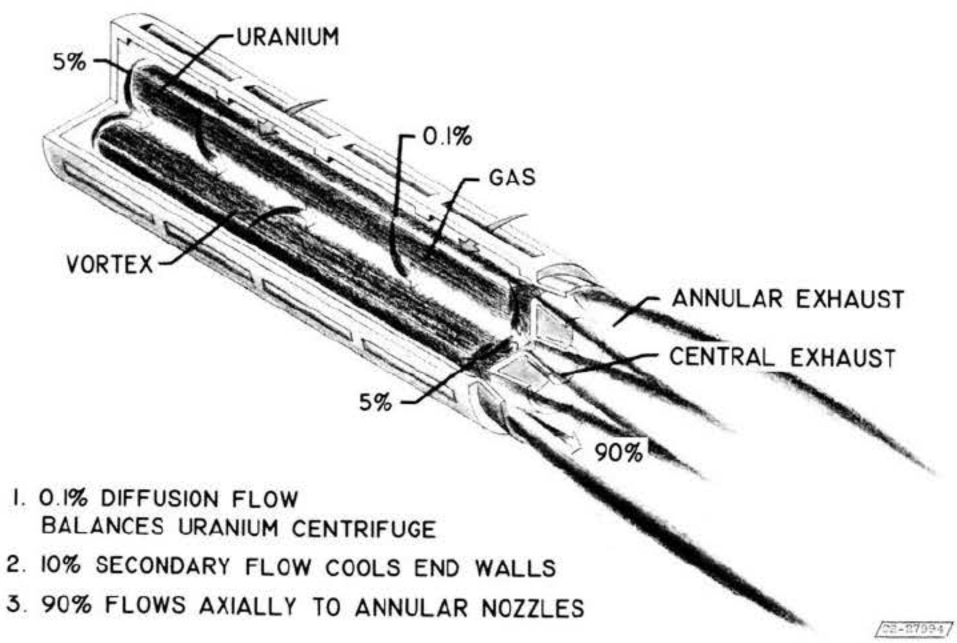
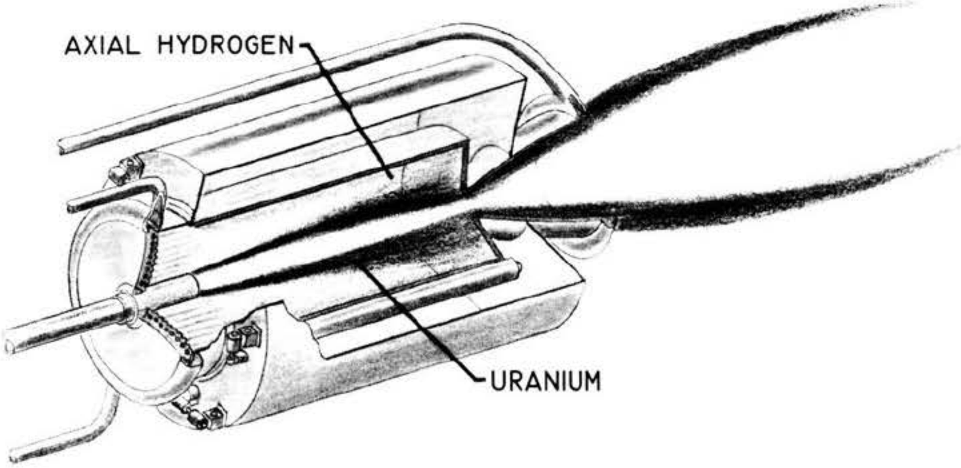


Figure 6

COAXIAL JET REACTOR



1. URANIUM AND HYDROGEN FLOW AXIALLY
2. URANIUM FLOWS MUCH SLOWER THAN HYDROGEN
3. TURBULENT MIXING GRADUALLY CONSUMES URANIUM
4. LOW SPEED HYDROGEN BUFFER LAYER MINIMIZES URANIUM LOSS

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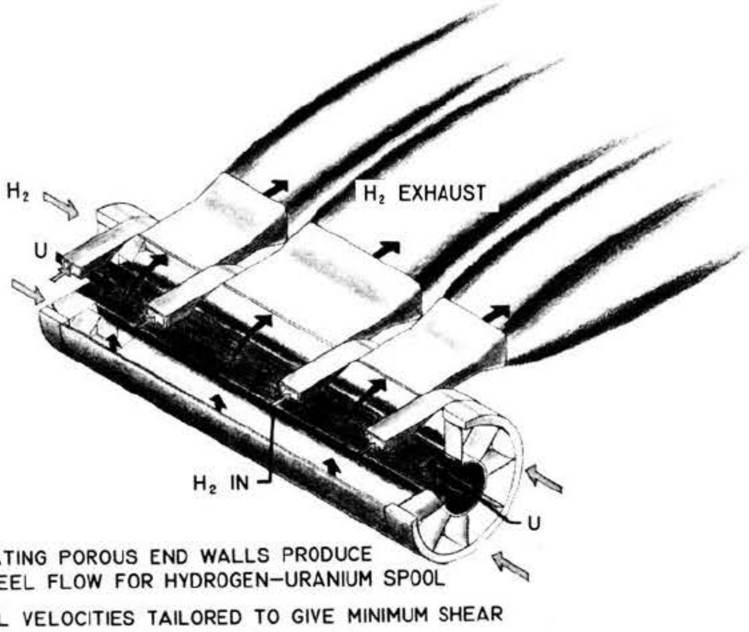
Figure 7

WHEEL FLOW REACTOR



1. ROTATING POROUS END WALLS PRODUCE WHEEL FLOW FOR HYDROGEN–URANIUM SPOOL
2. AXIAL VELOCITIES TAILORED TO GIVE MINIMUM SHEAR
3. PRINCIPAL HYDROGEN FLOW ENTERS AND LEAVES TANGENTIALLY

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Figure 8

THERMONUCLEAR ROCKET

BASIC COMPONENTS

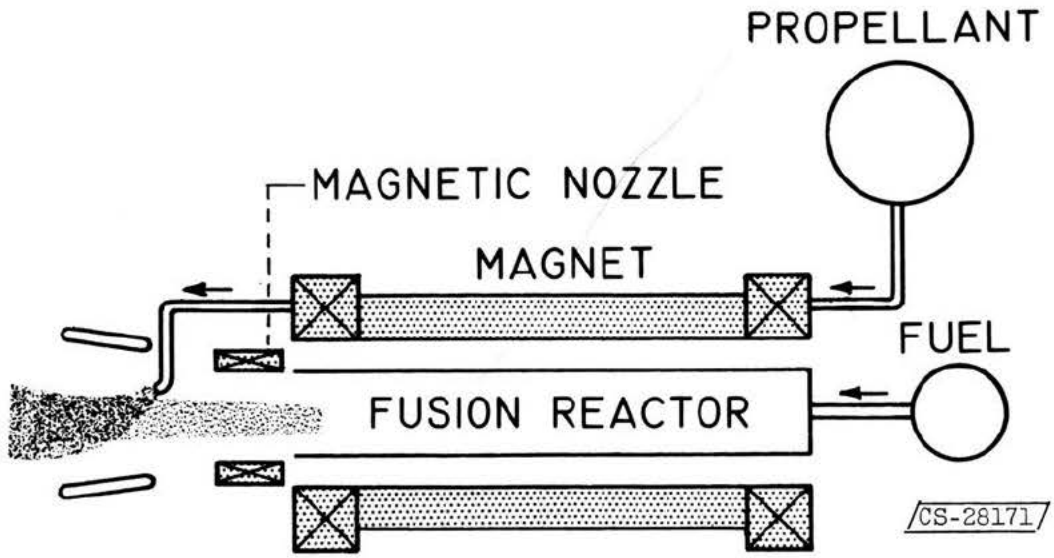

Figure 9

THERMONUCLEAR ROCKET

INCORPORATION OF SHIELDED AND
CRYOGENICALLY COOLED MAGNET

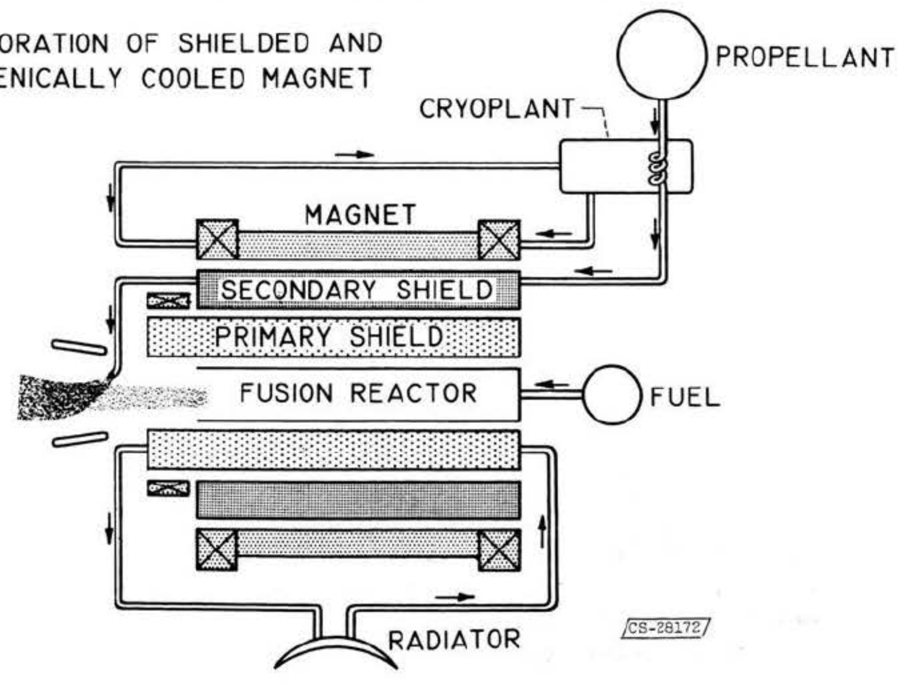

Figure 10

100,000-GAUSS WATER-COOLED ELECTROMAGNET

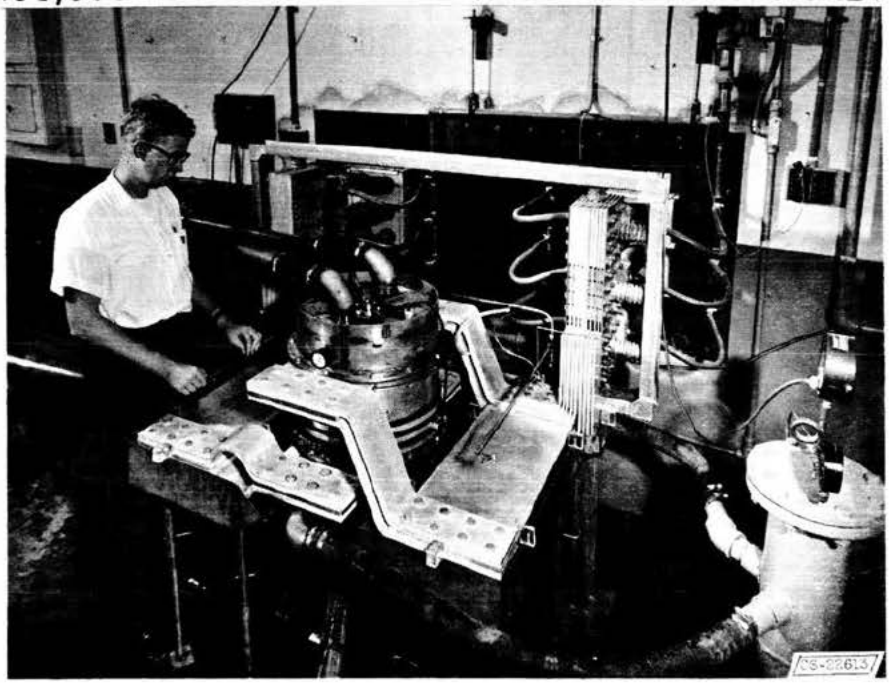

Figure 11

ELECTROSTATIC PROPULSION SYSTEM WITH DIRECT NUCLEAR ELECTROGENERATOR

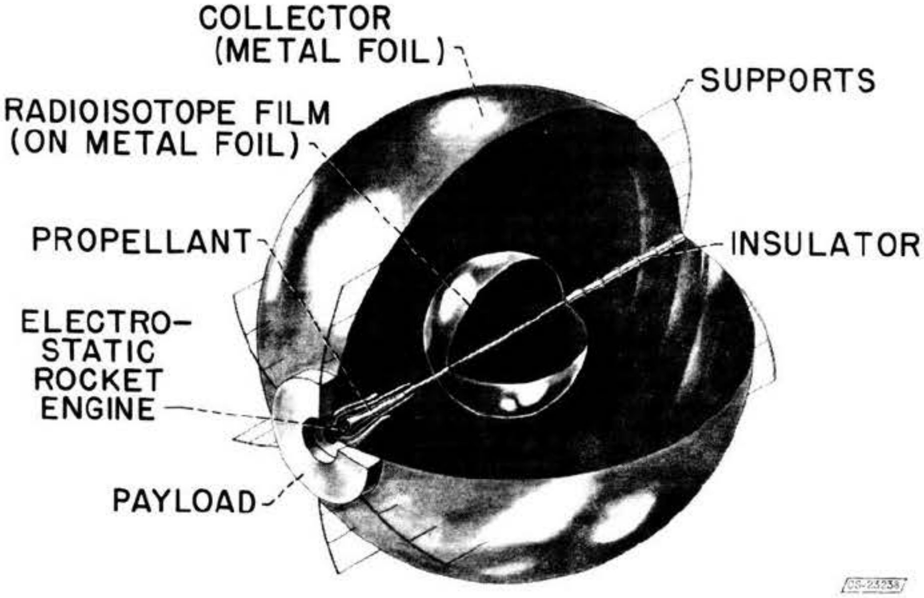

Figure 12