Gaseous-core nuclear rockets

Conceivable in many forms, they seem at present mostly a field for speculation, but experiments in progress may bring them close to reality

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AN EXPLORATION of the methods leading to more efficient propulsion-system applications of the enormous energy available from nuclear reactions leads directly to the concept of a gaseous-core rocket. A gaseous-core nuclear reactor can be defined as one in which the nuclear fuel exists in the gaseous (or plasma) state. Since the technology of gaseous nuclear fuels has not yet been attempted experimentally, the gaseous-core nuclear reactor is at present only a concept. Thus, although theoretical feasibility has already been demonstrated for some gaseous-core systems, several of the practical problems may still prove prohibitive.

The basic justification for a gaseous-core nuclear rocket, as is usual with any radically new system, is that significant performance gains may be realized. Consider the well-known dependence of rocket vehicle performance on propellant exhaust velocity. All other things being equal, burnout velocity, and therefore vehicle range, is directly proportional to propellant exhaust velocity. In a thermodynamic system, this means range is proportional to the square root of the propellant "chamber" temperature. Now, in a "conventional" nuclear-rocket reactor the propellant is heated by contact with the hot reactor structure containing the fissionable fuel, limiting the maximum temperature to that at which the structural material can maintain its shape. Since the highest material *melting points* known are around 6500 F, the likelihood of propellant temperatures exceeding, or even reaching, 6000 F is rather remote.

Gaseous Core the "Fix"

The obvious "fix" is to remove the solid fuel-carrying structure, allow the nuclear fuel to become gaseous, and mix it with, or actually allow it to become, the propellant. By using a cooled container, very high gas temperatures may then be realized. This principle is in itself not at all new or different. The conventional chemical rocket, often built of a cooled dural alloy which melts at around 1400 F, utilizes flame temperatures which for some propellants may approach 9000 F.

The principal advantage of the gaseous-core system, then, is its higher operating temperatures, resulting in higher specific impulse. (The thrust level for some concepts is comparable with that of the conventional nuclear rocket.) The disadvantages of gaseous-core systems, unfortunately, appear to be quite severe. Although they vary somewhat among the several concepts, the two basic technical

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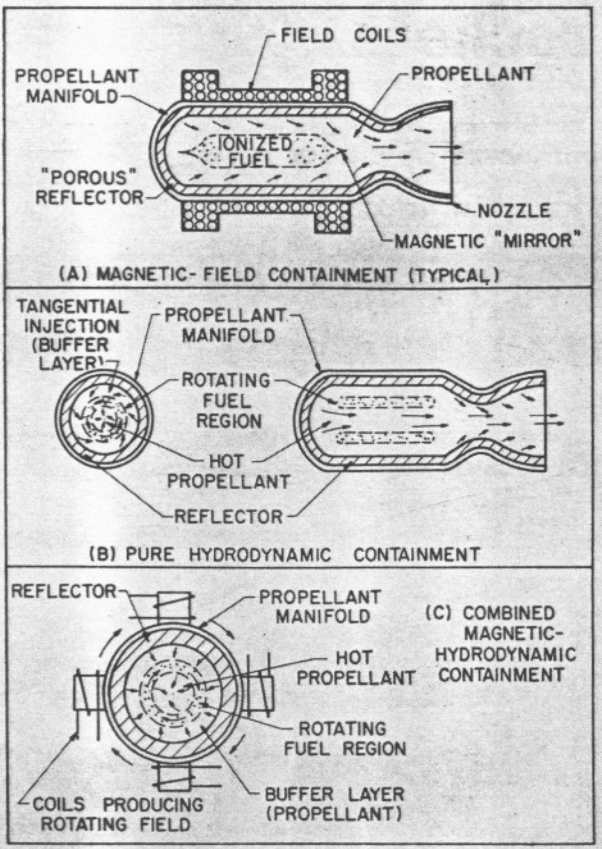
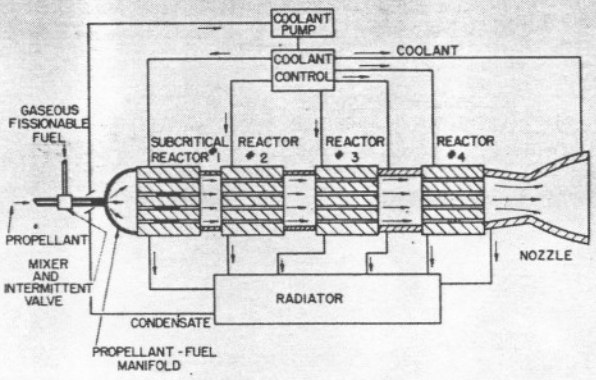
Fissionable-Fuel Containment in Cavity Reactors



Hybrid Solid-Gaseous Rocket System



difficulties generally break down to the following:

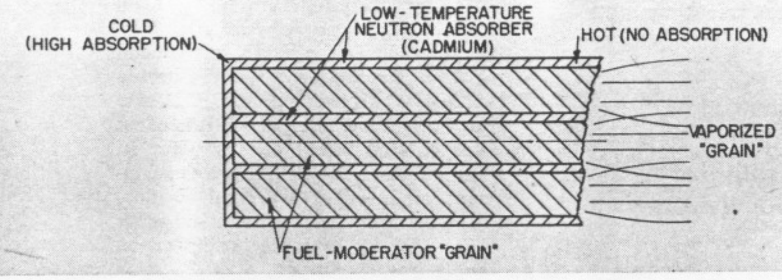
1. Limitation of attainable temperatures by wall cooling requirements, which are likely to result primarily from the enormously high thermal radiation level.
2. Economical maintenance of the conditions necessary for the controlled nuclear reaction, in terms of either weight or cost.

A third serious consideration, although not important to basic feasibility, is the amount of radioactive material expelled. Although this is actually far less than that produced by the smallest of atomic bombs, it could form the basis for political controversy. Finally, there is the environmental requirement for shielding, and the operational problems of control, instrumentation, testing, etc. These, unfortunately, will be difficult to assess until some experimental experience has been accumulated.

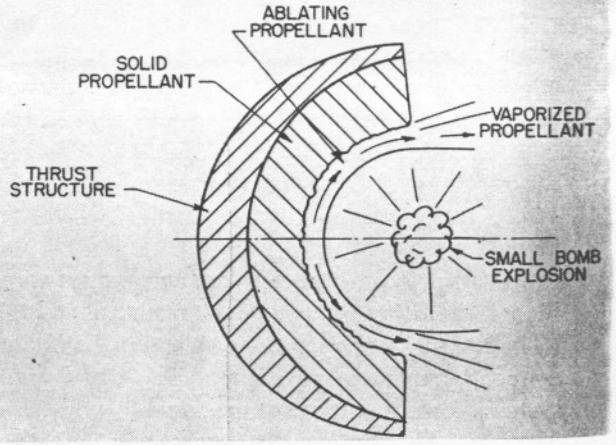
There are almost any number of conceivable configurations for gaseous-core rockets. Although all have higher performance than the solid-core reactors, some may produce better than 1-g accelerations, while others have only small thrust-to-weight ratios. The few examples to be discussed might be sketched as follows:

1. A more or less homogeneous mixture of propellant and fissionable fuel gases—usually called a "cavity reactor" because of the need for a dense neutron reflector surrounding the gaseous region.
2. A series of barely subcritical solid-fission reactors through which there passes intermittently a gaseous mixture of propellant and sufficient fissionable fuel to produce criticality.
3. A "solid-propellant" rocket utilizing fission-

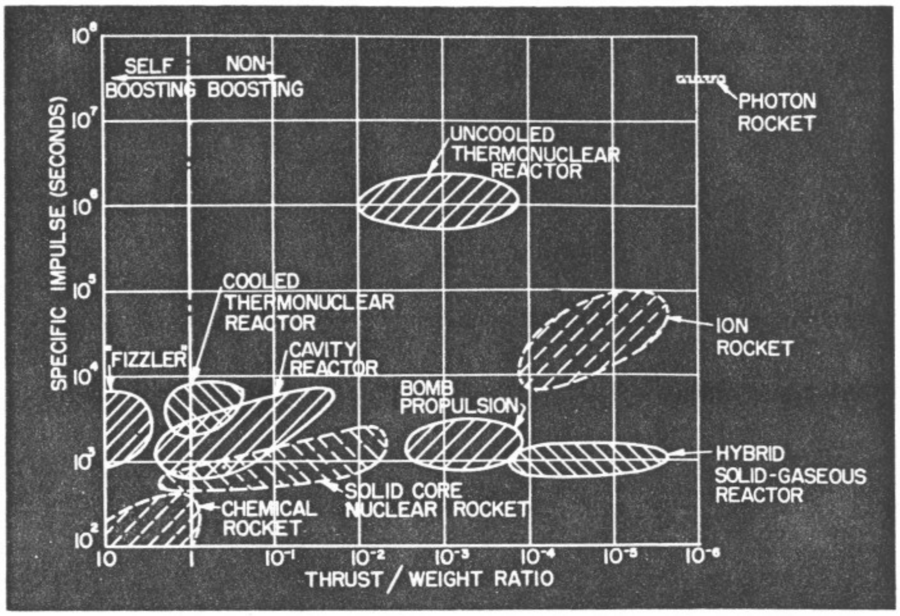
Solid-Propellant, or Fizzler, Rocket System



Nuclear-Bomb Rocket System



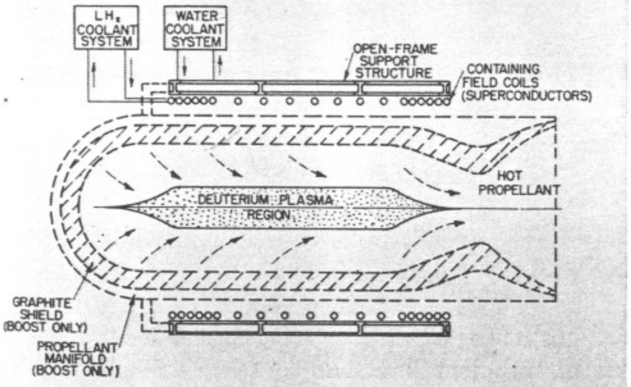
Performance of Gaseous-Core Propulsion Systems



able material mixed in a solid "grain" with a moderating propellant, and "ignited" by removal of a control rod; often called a "fizzler".

4. A series of small fission bomb explosions, the impacts in the forward direction being absorbed preferably by a good propellant material which is thereby itself vaporized and exhausted (Project Orion).
5. A fusion-powered (thermonuclear) reactor used to heat a separate propellant (somewhat similar to the fission-powered cavity reactor).
6. A thermonuclear-powered reactor using fusion products themselves as propellant, together with the hot fuel plasma.

Thermonuclear Rocket System



Note: Propellant system, including shield, tankage, and nozzle, shown within dashed lines, is jettisoned after boost.

Let's look at each of these schemes in more detail.

A *uniform* critical mixture of gaseous fissionable fuel and propellant is impractical from a cost viewpoint. Shepherd and Cleaver pointed this out as early as 1951, showing that even the most elemental of space missions would require the expenditure of prodigious sums for the uranium expelled from the nozzle. Some preferential retention of the fissionable fuel is thus essential.

Two Methods for Retaining Fuel

Fortunately, the nature of the system provides two obvious methods for accomplishing this retention. The first of these depends on the basic high-temperature requirement for high performance: At any temperature sufficiently high to be of interest, the heavy fuel atoms will become almost completely ionized, and may be retained by a "magnetic bottle" of some sort. A low-molecular-weight propellant is then selected which will *not* be appreciably ionized at the desired operating pressure and temperature, and therefore may flow unimpeded out of the nozzle to produce thrust. Because of its high ionization potential, helium would be a good propellant for this application.

The second method for achieving fuel retention is based on the fact that fissionable fuels have very high atomic mass numbers, whereas the best-performing propellant gases are those with the lowest mass numbers. Thus there is the possibility of utilizing some sort of hydrodynamic "centrifugal separator."

A third mechanism, utilizing both of these properties of the fuel-propel- (CONTINUED ON PAGE 110)

Gaseous-Core Rockets

(CONTINUED FROM PAGE 25)

lant mixture, would be to use rotating magnetic fields to spin the mass of hot ionized fuel, thus providing the centrifugal acceleration necessary for fuel separation.

The figure on page 24 shows diagrams of these three means to contain fissioning fuel. A "centrifugal separator" device seems theoretically feasible, and also more practical than those using the magnetic containment principle, primarily because of the massive electrical equipment needed for the latter. Reactors of the centrifugal type have been the subject of considerable theoretical study, and some of the crucial fuel-separation experiments are now in process at a number of laboratories in this country. It is likely that conclusive demonstration of operational feasibility (positive *or* negative) will be available shortly.

The principal stumbling block for these cavity reactors, however, still seems to be heat transfer, i.e., keeping the cavity walls from melting or eroding away. It appears that the usual conductive and convective heat-transfer components, which give the biggest headaches in chemical rockets, will be far overshadowed by thermal radiation at the high temperatures of interest here.

The only possible loophole in this apparently serious heat-transfer limitation is the chance that the effective thermal emissivity of these gaseous cores may be quite low. Unfortunately, the theoretical analysis of radiation from an energy-producing gas is quite complicated, having perhaps its closest parallel in the astrophysical study of stellar interiors, and this question is not likely to be resolved definitely until some experimental work has been done.

The diagram on page 24 illustrates the principle of a hybrid solid-gaseous system. The purpose of this scheme is to reduce the amount of fissionable fuel which must be mixed with the propellant to provide criticality. This is done by using a sequence of subcritical "conventional" reactors, which are temporarily rendered highly supercritical when a slug of propellant gas containing some gaseous fissionable fuel passes through them. The gas is heated as it passes through each succeeding reactor, becoming hotter and hotter, until it finally issues from the cooled nozzle at a very high temperature.

The two principal drawbacks to this scheme are obvious: First, the crucial radiative wall-heating problem still exists, although it is somewhat relieved by the intermittent nature of the hot gas flow. Second, and more important, it is clear that the solid reactors must also become hot. In fact, because of their higher relative gross mass and much higher cross-section with respect to the gaseous slug of propellant, the solid reactors must necessarily absorb the lion's share of the energy released. The prohibitively large mass of the separate cooling system required (together with the mass of the solid reactors themselves) thus eliminates this scheme from practical consideration.

Shown in diagramatic form on page 24, the "solid-propellant" nuclear fizzler, like its chemical namesake, appears attractive principally because of its simplicity. The "grain," composed of fissionable fuel and a moderating propellant, is kept subcritical before operation by a neutron-absorbing control rod. The system is "ignited" by removing a sufficiently long section of control rod at the nozzle end. This end of the reactor thus becomes sufficiently supercritical to vaporize itself, raising the temperature of the adjoining section, and thereby reducing the neutron absorption cross-section of its control rod sufficiently to produce criticality. A zone of criticality thus propagates up the grain, vaporizing the fuel and moderator as it moves. Unfortunately, however, it turns out that the stable "burning rates" of these configurations are extremely high, approaching those of a bomb rather, than that of a fizzler. Thus, since there is little control possible without a prohibitive degree of complication, the fizzler also appears to be ruled out by practical considerations.

Project Orion Scheme

The diagram on page 24 illustrates the principle of the nuclear bomb-powered rocket, now being studied actively by General Atomic under Project Orion. Rough preliminary analyses indicate the system is penalized by comparatively low average specific impulse, enormous size, and low thrust-to-weight ratio. However, there has been much recent interest in Project Orion, indicating that some solution to these problems may be in the offing.

Finally, although a controlled fusion reaction has not yet been produced even in an experimental configuration, it will nevertheless be an important factor in future propulsion-system considerations. In fact, the "thermonuclear rocket" is considered by some the ultimate rocket powerplant with an operating principle lying within the concepts of present scientific knowledge. Thus, although it is certainly pointless to discuss detailed engineering aspects of the as yet unknown reactor configuration (estimates of operational target dates for *stationary* powerplants range from 15 to 100 yr), some basic ideas relating to thermonuclear propulsion systems are of interest even at this early date.

Very briefly, the exothermic nuclear fusion process, which eventually forms helium from reactions between deuterium nuclei (the most likely fuel for rocket applications), may be induced by overcoming the electrical Coulomb repulsion between the deuterium's protons. This requires heating the fuel to energies in the range of 10,000 to 100,000 electron volts—a *hundred million* to a *billion* degrees centigrade.

The basic problems involved in the construction of thermonuclear reactors result directly from this temperature requirement, e.g., how to heat the deuterium to these temperatures, how to keep the resulting plasma intact until sufficient time has elapsed for the reaction to occur (of the order of 0.01 to 1 millisec), how to keep impurities out of the deuterium (tiny fractional percentages of heavy nuclei radiate away much of the plasma energy), how to maintain control of the reaction, how to absorb the enormous amounts of radiated energy, etc.

The diagram on page 25 shows one possible form for a fusion rocket, suggested by the author in 1956. The fully-ionized, billion-degree deuterium plasma is held in a longitudinal configuration by the linear magnetic field of a solenoid, the ends being closed off by "magnetic mirrors" of the type now under investigation both in Russia and at the Lawrence Radiation Laboratory here in the U.S. The mirror at the "back" end is, say, 100 times less effective than that at the "front" end, so that the hot ions effuse preferentially out the back. The axial ion velocity component out the exit of this magnetic nozzle is of the order of 10^9 cm/sec. (The effusing electrons would be relativistic, but their thrust contribution would probably be small.)

Although the weight of the "ignition" system necessary to initiate the reaction may be enormous (no really successful method has yet been developed), this does not affect the rocket system weight, since the reactor would probably be started on the ground. One eventual possibility for reducing the enormous mass of magnetic field-generating equipment, suggested by the author in 1956, and recently publicized by Edward Teller of the Lawrence Lab, would be the development of superconducting materials, for the containment field coils, having magnetic field breakdown thresholds higher by an order of magnitude than those presently known.

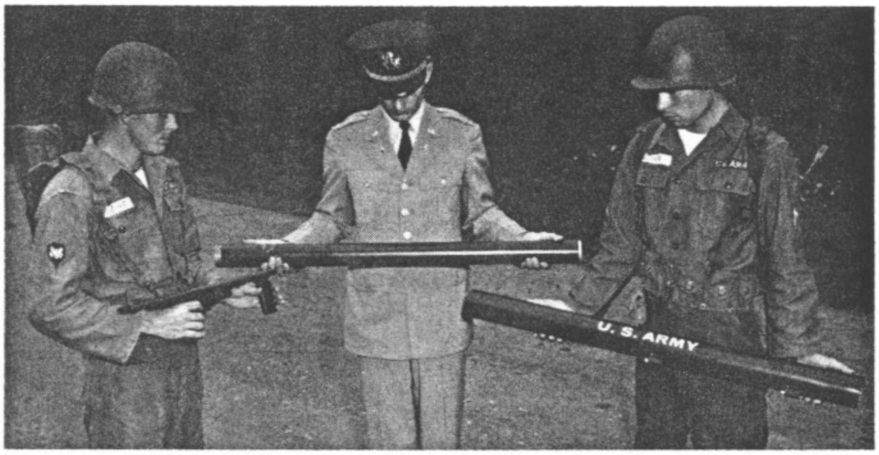
The configuration shown on page 25 could be used as a "furnace," heating by its neutron and gamma radiation a thick "porous" wall or shield cooled by ordinary hydrogen propellant. The cooled system would have high thrust; but, as in the somewhat similar cavity reactor, propellant "chamber" temperature is fixed by wall cooling limitations. Here, however, in contrast to the cavity reactor, the neutron and gamma radiation (actually hard X-rays called "bremsstahlung") are predominant, the extreme plasma particle velocities and low density resulting in a relatively low level of thermal radiation. This has the effect of improving the wall-cooling situation, since the radiated energy can penetrate the thick wall instead of all being released at the inner surface.

Boost and Sustain Stages

The cooled-wall arrangement, because of its high thrust, could constitute a "first-stage," or boost, powerplant. A "second-stage" interplanetary sustainer would then be formed by dropping the shield, pumps, and hydrogen propellant tanks. No pressure shell is required, since the high plasma pressure is transmitted to the field coils through the magnetic field, and thence to an open framework. The radiated energy would be discarded to space, the comparatively thin field coils and structure absorbing only a tiny fraction. Of course, the coils and structure would require cooling by a rather highly loaded refrigeration system, probably employing two separate fluid loops, e.g., water and liquid hydrogen.

Sustainer thrust is obtained, as indicated earlier, by effusion of the plasma out one end of the reactor. The level of this "second-stage" thrust would, of course, be rather low—one estimate which optimistically assumes superconducting field coils places sustainer thrust-to-weight ratios in the range 10^{-2} to 10^{-3}—but the specific impulse, corresponding to the billion-degree plasma temperature, exceeds a million seconds.

Some idea of the relative potential performance of the systems discussed is indicated by the estimates given in the graph on page 25. The superiority of the thermonuclear system, especially the uncooled "sustainer," is clear. It must be remembered, however, that the science, not to mention the engineering, of fusion reactors is in its pre-infancy. On a much lower level in *both* performance and difficulty, but with feasibility likely to be demonstrated shortly, is the cavity fission reactor. Again, however, it is essential to point out that the large size and operational complexities of these reactors may be prohibitive. This could be especially true when they are compared with somewhat lower performance but much simpler concepts, such as the conventional low-pressure, solid-core reactor or, perhaps, the very promising solid-core reactor which utilizes an isothermal nozzle. ◆◆



Red-Eye—Footsoldier's Anti-aircraft Missile

The three Army men hold components of Red-Eye, the new tube-launched, rocket-powered, infrared-homing missile that will give footsoldiers a weapon against low-flying aircraft. Being jointly developed by the Army, Marine Corps, and Convair-Pomona, the Red-Eye system weighs about 20 lb, has an effective range of up to a mile. A single soldier holds and fires the weapon like a bazooka. Major components of Red-Eye system—left, pistol-grip firing mechanism; middle, the missile; and right, the launching tube.