Concepts for Future Nuclear Rocket Propulsion

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The fundamentals, problems and potentialities of rocket propulsion systems powered by heat exchanger nuclear reactors have often been discussed in the technical literature.[1,2,3] In such systems, a reactor with solid fuel structure is used as an energy source to heat a working fluid which is then expelled through an exhaust nozzle, in the conventional fashion. Fission energy thus supplants chemical energy in the rocket motor combustion chamber. This straightforward approach is in the present tradition of reactor development — adapting the atom to the boiler, so to speak, rather than the other way around. Unfortunately this approach places an artificial upper limit on estimates of potential nuclear rocket performance, since all conventional heat engines, whether chemical- or nuclear-powered, are fundamentally limited by the energy of the molecular rather than the nuclear bond.

The energy available from fission of U^{235} is about 10^7 times that from chemical reaction of an equal mass of high explosive or other combustible mixture. In addition, fission energy appears principally as kinetic energy of the two fission fragments, each with an energy of 60 to 100 MeV, corresponding to a kinetic "temperature" of the order of 10^{12} R. The energy released as a result of other nuclear processes, such as fusion, beta decay and alpha emission, can also give rise to very energetic (several MeV) particles. It is clear that nuclear interaction processes offer a tremendous potential advantage over chemical reactions, which can never yield more than a few eV per particle.

Fusion

First in interest, and certainly most speculative, is the application of fusion energy to rocket propulsion. Fusion reactions in deuterium gas yield a variety of low mass particles (T, He^3, He^4, p and n) with energies of several MeV each. If it were possible to expel the products of these fusion reactions rearward from a rocket vehicle, the effective specific impulse of the "propellant" would be about 3×10^6 lb_f sec/lb_m,[4] some 10^4 larger than presently attainable from chemical rocket propellants. More likely, the products themselves could not practically be constrained to move unidirectionally; however large masses of non-fusioned gas could be heated to very high temperature by collisions with the energetic fusion products, resulting in high specific impulse performance even though only a small fraction of the fusionable fuel has been "burned." For example, a gas mixture in which only one D-D fusion reaction has taken place for each 10^4 D nuclei present will reach a bulk temperature of about 7×10^6 R (neglecting all losses) and will give a specific impulse of roughly 3×10^4 sec when expelled through a proper nozzle configuration. With this specific impulse, a 100-ton rocket could take off from the earth, land on the moon and return, all under power, with the expenditure of only 5 tons of propellant.

Of course, gases at temperatures of the order of 10^6 R and higher cannot be contained by solid walls, at least at present, even with use of advanced methods of liquid cooling. However, since gases are highly ionized at these temperatures it is possible, in theory, to contain them within appropriately shaped magnetic fields. This approach is under investigation in the current thermonuclear power program[5], but no satisfactory solution to the containment problem has yet been announced.

It is evident that thermonuclear fusion reactions can yield propellant temperature and performance far beyond that available conventionally today if such reactions can be made to "go" in a controllable manner. It is equally evident that speculation on the possible forms (weight, size, performance, etc.) of thermonuclear-powered propulsion systems is fruitless until the controlled release of fusion energy is an accomplished fact.

Radioisotope Decay[6]

Many radioisotopes are found in nature (e.g., Ra, Rd, etc.), others result from the fission of uranium or plutonium nuclei (e.g., Sr^{90}, etc.) and still others can be manufactured by neutron irradiation of stable elements placed in nuclear reactors.

The prime difficulty in considering the use of fission product isotopes is that they do not appear singly, but are formed as part of a large group of "mixed" fission products. Chemical separation processes are necessary to isolate any one desired fission product from the mixture. On the other hand, radioisotope production by irradiation of a stable element results in the formation of the desired isotope mixed only with the parent target element. No chemical separation plants are required as for the extraction of single fission products; however, it is necessary to utilize reactors especially designed for irradiation usage. Some characteristics of potentially useful radioisotopes of both types are shown in Table 1.

The decay of a radioactive isotope is generally accompanied by the release of fairly large amounts of energy carried by beta particles (electrons), gamma photons or alpha particles. Energetic photons are highly penetrating and must pass through large masses of material in order to lose their energy. Alpha particles and high energy electrons have mass and are charged, and lose their energy quickly by ionization processes in passage through matter. As a consequence, gamma. emitters are not as useful for radioisotope heat sources as are alpha and beta emitters. The decay energy for potentially useful beta emitters averages about 1 MeV per disintegration, while alpha emitters yield about 4 MeV apiece. Each fission :process yields two radioisotopes and about one excess neutron. Thus about 6 MeV of decay energy can be obtained per fission if the two fission product isotopes are beta emitters yielding 1 MeV each, and the excess neutron is used to produce a 4-MeV alpha emitter from some stable parent element, such as bismuth (yields alpha-active Po). Since the initial kinetic energy of the two fission fragments is about 160 MeV, only some 4 percent of the total energy of the fission products can be converted for use as decay energy. Practical considerations reduce this to less than 0.5 percent for most cases[7].

Table 1a — Artificially Produced Radioisotopes

Parent Element	Daughter isotope	KW/ lb	KW/10^3 MW yr
Tm^{169}	Tm^{170}	10	1400
Cs^{133}	Cs^{134}	6.9	550
Tl^{203}	Tl^{204}	0.17	140

Production conditions: *(Thermal power available at initial use)* Material weights include both parent and daughter. Production by irradiation in large thermal reactors for two half-lives. Initial use assumed at end of irradiation period.

Table 1b — Chemically Separated Fission Products

Fission Product	Production rate lb/10^3 MW yr	KW/ lb	KW/10^3 MW yr
Mixed	880	0.58	510
Sr^{90} / Y^{90}	25	0.32	8
Ru^{106}/ Rh^{106}	40	4.2	19
Cs^{137} / Ba^{137}	93	0.15	14
Ce^{144} / Pr^{144}	84	2.4	200

Production conditions: *(Thermal power available at initial use)* Weights include weight of all chemically similar isotopes. Fission products produced in large thermal reactors with a fuel cycle time of 180 days (assumed). Initial use assumed at 90 days following removal from production reactors.

The most obvious use of decaying radioisotopes is as heat sources, replacing fission reactors or chemical combustion used to heat a propellant gas to high temperature. One disadvantage of this application is that no control is possible over the rate of energy production; thus auxiliary cooling systems (heat dumps) are required to prevent melting or vaporization of the source while not in use. Another disadvantage is the present limited production capability (3) for radioisotope sources. This is a result of the low energy conversion ratio obtained when using the fission process to produce active isotopes. For an assumed conversion efficiency as high as 1 percent, an installed production reactor capacity of the order of 10^6 MW would be required to provide the heat sources for one large rocket vehicle per month. This is about twenty times the present power plant capacity of the United States. Still another disadvantage is that the specific power output of almost any of the useful radioisotopes is very low by rocket motor standards. It has been shown (1b) that a rocket reactor specific power of the order of 0.5 MW/lb or higher is required for satisfactory missile propulsion by nuclear reactor heat-exchanger rocket motors. In contrast, the best isotope listed in Table 1, Tm^{170}, yields only 0.01 MW/lb at initial use. The use of radioisotopes as heat sources for rocket propulsion thus does not appear very attractive.

The possibility remains of using directly the momentum of the energetic decay particles[8]. Unfortunately these are emitted isotropically, and at least half of the total decay energy will be deposited within the vehicle if half is assumed to go rearward. This latter assumption implies a thin layer of radioisotope "painted" on the flat base of the vehicle to be propelled. For such a configuration it has been shown[9] that about 100 MW must be dissipated by the vehicle for every pound of thrust produced by alpha emission, For beta emission the heat dissipation must be about 3500 MW per pound of thrust. Clearly, such a scheme is impractical.

In general, it does not appear possible to make practical use of radioisotopes for rocket propulsion.

Fission Energy

Many possible applications of fission energy and reactor systems have been suggested for propulsion aside from the obvious direct-heat-exchanger approach mentioned previously[1,2,3].

The possibility of using fission fragment momentum directly suffers from the objections given previously to use of radioisotope decay-product momentum. The ratio of kinetic energy to momentum is about the same for fission fragments as for energetic (several MeV) alpha particles, and the specific heat dissipation which must be achieved is about 80 MW per pound of thrust produced.

Fission fragments lose their energy by ionization of the material through which they pass while slowing down. If fissions can be made to occur in a reactor in such a way that the fragment slowing down takes place in the propellant gas rather than in structure (i.e., solid fuel elements), it would be possible to heat the gas above the limiting temperatures of containing structural materials. In principle, this can be done if fissionable fuel can be applied in thin films to the outer surfaces of fuel elements in a reactor core. If the fuel film is thin enough ($<10^{-4}$ cm) very little self-absorption will take place, and half of the fission fragments will travel away from the fuel element to heat the surrounding gas directly, while half will lose their energy in the element structure, which thus requires internal cooling. In the limit, if the propellant gas is used both as the internal coolant and the external flowing gas (in series flow),[10] an increase in specific impulse of about 40 percent appears possible over that attainable from the conventional high temperature heat exchanger system. Consideration of the practical reactor design problems associated with the exploitation of this phenomenon leads to the general conclusion that the potential propellant performance gain is outweighed by increased complexity, size and weight of the reactor system.

Another line of attack is by making most of the fissions occur in the gas phase itself in a reflector-moderated "cavity" reactor[11]. Here an intimate mixture of fissionable material and diluent (propellant) is fed into a large void space surrounded by a neutron moderating material such as D_2O. Fissions take place in the mixture within the void, principally by thermal neutrons returned from the reflector-moderator, and heat the mixture to a temperature limited only by pressure-temperature-stress limitations of the container. A convergent-divergent nozzle must be located at one end of the void core to allow the escape of hot gas. An annular nozzle is preferable in order to minimize neutron leakage or streaming from the core. Figure 1 shows a schematic outline of such a device[12], similar to those proposed as early as 1949.

In order to achieve super-performance, temperatures of interest in this system must be much higher than those reached in the combustion process in conventional rocket motors.

Since rocket motor combustion temperatures are within a few thousand degrees of the boiling points of most structural materials, it is clear that all super-performance reactors operating on the principal of interest here can be analyzed as gaseous reactors, whether the fissionable fuel and diluent are introduced in solid, liquid or gaseous form.

For a gaseous reactor operated at a temperature sufficiently high to assure that all core gases are monatomic, a simple, approximate relation can be found between various parameters describing the reactor and vehicle operating conditions. Neglecting ionization effects and assuming perfect gases this is:

$$P_c = 0.045(I_{sp})(I_{tot})(\frac{S_{pf}}{W_f}) \quad (1)$$

Here Pc is core gas pressure in lb/in.^{2}, p_f is critical fuel density in lb/ft^3, I_{sp} is propellant specific impulse in seconds, and W_f is the weight in pounds of fissionable material expended during operation; I_{tot} is the system total impulse, and is simply the product of rocket motor thrust F in pounds and operating time t_b in seconds. It is certainly desirable to retain as many of the unfissioned atoms of fuel as possible to prevent their escape from the system with the outflowing diluent gas. The factor S in Equation [1] is a measure of this retention or weight separation ability, defined here as the ratio of fuel mass expelled during operation to that which would have been expelled if no separation had taken place.

The only nuclear requirement on Equation [1] is that the fuel density be sufficient to ensure reactor criticality. Figure 2 shows the critical fuel density, taken from the work of Safonov[11], required for cavity reactors within reflector moderators of neutronically "infinite" thickness. In practice "infinite" means 5 to 10 neutron slowing down lengths, so that reflector thicknesses of several feet are of interest.

Consideration of two examples serves to illustrate the practical difficulties which confront useful gaseous reactor propulsion systems:

(1) Assume no separation takes place, so that $S = 1$, and that criticality can be achieved with $\rho_f = 0.11$ lb/ft³. Assume further that it is desired to fly a vehicle which requires 100,000 lb thrust for 200 seconds with propellant of performance comparable to that from present chemical rockets; hence $I_{tot} = 2 \times 10^7$ lb sec and $I_{sp} = 300$ sec. For these conditions Equation [1] becomes:

$$W_f P_c = 2.7x10^7 \quad (1a)$$

Here a system pressure of 1000 lb/in² will result in the loss of 27,000 lb of fissionable fuel; this is clearly impractical. However, for an allowable fuel loss of 300 lb the system pressure must be 90,000 lb/in² which is equally impractical.

(2) Approaching the problem from another viewpoint, assume an allowable fuel expense of 300 lb and a specific impulse of 3,000 sec, some tenfold better than for present conventional rockets. With the vehicle impulse previously postulated, the system pressure is related to the separation ratio by:

$$P_c = 9x10^5 S \quad (1b)$$

For a system pressure of 1,000 lb/in² the factor S must be 1.11×10^{-3}, implying retention of all but one fuel atom in 900 of those which would normally escape by being swept out with the diluent gas.

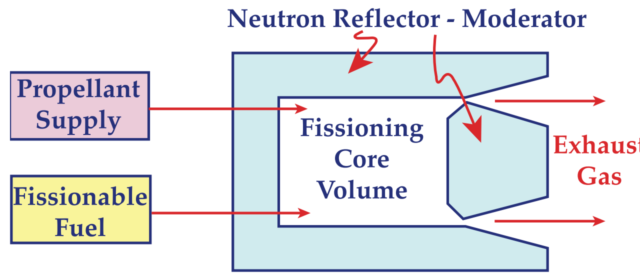


Figure 1 — Gaseous "Cavity" Reactors

Steady-state gaseous reactors thus appear practical for rocket propulsion only if separation ratios of the order of 10^{-3} can be achieved. Although it is not clear at present how this can be done, the enormous potential value of a rocket propulsion system capable of producing both very high specific impulse and high thrust-to-weight ratio makes it imperative that serious consideration be given to the problem of gas-phase separation of atomic species.

Reactor Systems

Aside from the more or less exotic and novel schemes previously discussed, fission energy can play another role in the rocket propulsion systems of the future. For this, interest is in the application of conventional nuclear-powered heat engine equipment for the production of relatively small amounts of very hot gas, on a pulsed or steady-state basis.

Two general classes of such systems are the "thermo-mechanical" and "electrical" open cycles. The first of these typically makes use of a succession of nuclear-powered heat engines to heat a working fluid to successively higher and higher temperatures by use of conventional thermodynamic cycles. The resulting hot gas is expelled through a nozzle to produce the thrust output of the system. Of course, a great deal of waste heat must be dumped in the primary reactor circuit in order to produce a small amount of high temperature, high specific impulse exhaust gas from the secondary circuit.

The cost of dumping this waste heat is reflected only in fixed equipment weight, not in increased propellant flow rate. Thus it appears possible to achieve high propellant performance at the expense of low overall propulsion system thrust-to-weight ratio. An illustrative example of a possible thermo-mechanical cycle is shown in Figure 3.

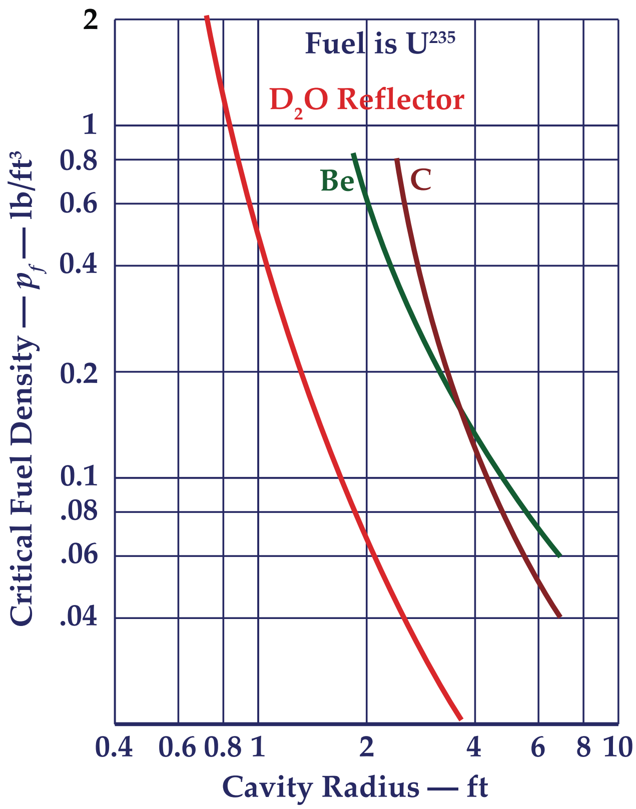


Figure 2 — Critical Fuel Density in "Cavity" Reactors (Data from Reference 6.)

Here a conventional closed-cycle gas turbine system drives a series set of positive displacement gas compressors, each one fed from the preceding unit. The propellant is vaporized and heated by cooling the compressor bank and is then supplied to the first stage pumps. The high temperature outlet gas is exhausted to space to drive the vehicle. Waste heat in the turbine drive circuit is dumped to space by thermal radiation. Although not shown, an auxiliary circuit may be needed to dump exhaust circuit waste heat in excess of that which can be absorbed by the propellant within structural temperature limitations of the compressor bank.

Electrical open cycle systems follow a pattern similar to that just described for the thermo-mechanical cycles. Here, however, two basic methods of utilizing electrical energy are evident. First is that of heating gases in the bulk by passing a current through a flowing gas stream, causing dissociation and ionization, followed by recombination in the expansion. process. This process is exemplified by the system shown in schematic outline in Figure 4. Here a nuclear-electric generating system is used to drive a d-c arc maintained within a flowing, centrifugally stabilized cylinder of liquid propellant. Propellant vaporized from the liquid-walled cylinder feeds the arc plasma and is exhausted from the plasma core through a hole in the cathode. Russian experimental work[13] on such arcs has produced plasma temperatures as high as 90,000 R, capable of yielding exhaust gas specific impulse an order of magnitude higher than that attainable today from chemical rocket motors.

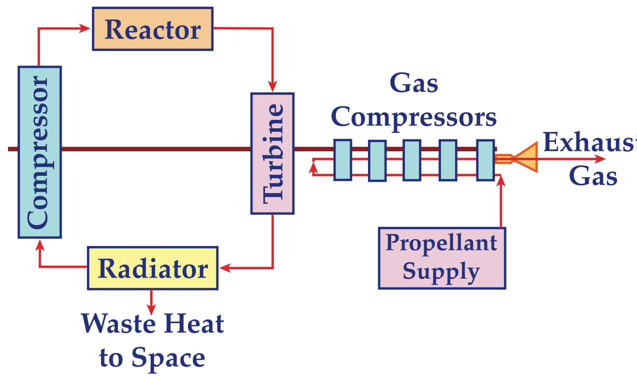
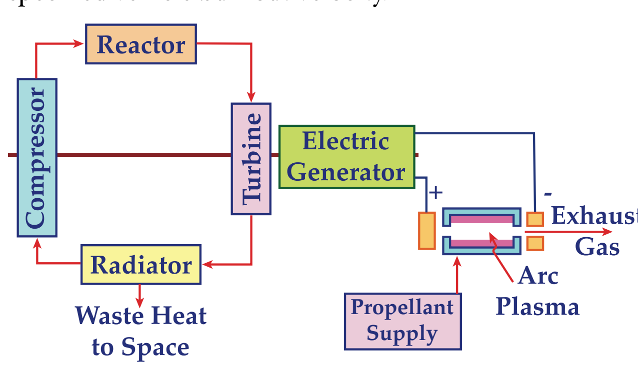


Figure 3 — Thermo-mechanical Gas Compression Systems

The second method of interest (first proposed by H. Oberth in 1929) is that of accelerating charged particles, using electrical energy to produce directed motion of the individual particles of propellant gas. This acceleration of ionized gases can be accomplished by use of static electric fields or by moving magnetic fields. Here, as for the arc system, a nuclear-electric generator set can be used to drive the electrostatic or electromagnetic accelerator. Waste heat in the reactor circuit must be dumped to space by radiation. In principle, the propellant exhaust velocity from such a device is limited only by the velocity of light.

However, power requirements are proportional to the square of the exhaust velocity while thrust is only linearly proportional; thus the specific power (per unit thrust) increases linearly with increasing exhaust velocity. Since the weights of power handling components such as turbines, compressors, radiators, electrical generators, pumps, and other heat engine or electrical plant equipment are generally rather directly related to their power capacities, it is clear that increasing exhaust velocity results in roughly linearly decreasing thrust-to-weight ratio for any of the reactor-powered systems discussed earlier. For these or similar systems yielding super-performance from the propellant gas, it is easy to show that an optimum exhaust velocity exists for each specified vehicle burnout velocity.



Consider a vehicle of gross weight W_o, composed of fixed weight (payload, guidance, etc.) W_d, propellant weight W_p and propulsion system weight W_L. For a constant propellant weight flow rate the gross specific impulse of the complete vehicle is given by:

$$I_g = \frac{Ft_b}{W_0} = \frac{I_{sp} W_p}{W_d + W_p + W_t} \quad (2)$$

Figure 4 — Electric DC Arc System

A minimum weight system (arbitrarily chosen here as "optimum") results from operation at maximum I_g for any given value of W_d. This fixed load is related through the familiar mass-ratio equation to the gross weight and propellant weight by:

$$W_d = \frac{W_p (W_d / W_0) e^{\varepsilon}}{e^{\varepsilon} - 1} = W_p \left(\frac{W_d}{W_0} \right) \Phi_{\varepsilon} \quad (3)$$

The exponent ε is the ratio of vehicle burnout velocity in free space to propellant exhaust velocity, $\varepsilon = \Delta v / g_c I_{sp}$.

For no net energy losses in the equipment of the propellant exhaust circuit, the power required to produce the high temperature exhaust gas is given by:

$$P_s = 2.18x10^{-5} \frac{W_p I_{sp}^2}{t_b \eta_e} \quad (4)$$

where P_s is in MW, and η_e is the exhaust gas expansion efficiency, generally greater than 0.75 for large nozzles operating at low ambient pressure.

By definition, the weight of the complete propulsion system is simply related to the propellant exhaust circuit power requirements by:

$$W_t = \Phi_K P_s \quad (5)$$

where Φ_K is the propulsion system gross specific weight in lb/exhaust-circuit-MW. The detailed functional form of Φ_K depends upon the choice of system type, since different components may be used to make up each different system.

Combining Equations [2 through 5] to eliminate direct weight terms, the vehicle gross specific impulse becomes:

$$I_g = \left[\frac{2.18x10^{-5} I_{sp} \Phi_K}{\eta_e t_b} + \frac{\lambda}{I_{sp}} \right]^{-1} \quad (6)$$

where

$$\lambda = 1 + \frac{W_d}{W_0} \Phi_{\varepsilon}$$

The maximum value of I_g occurs when:

$$I_{sp} = 214 \sqrt{\frac{\lambda \eta_e t_b}{\Phi_K}} \quad (7)$$

Note that the optimum propellant specific impulse or exhaust velocity thus depends principally upon the operating time and the propulsion system gross specific weight. For this condition Equation [6] reduces to:

$$I_g = 10^7 \sqrt{\frac{\eta_e t_b}{\lambda \Phi_K}} \quad (8)$$

or

$$I_g = \frac{I_{sp}}{2} \lambda = 2.3x10^4 \frac{\eta_e t_b}{I_{sp} \Phi_K}$$

Now, the vehicle thrust-to-weight ratio is found from Equations [2 and 8] to be:

$$\frac{F}{W_0} = 2.3x10^4 \frac{\eta_e}{I_{sp} \Phi_K} \quad (9)$$

for the units given previously. Figure 5 shows this relation graphically for several arbitrary. values of Φ_K, for an expansion efficiency of $\eta_e = 0.8$. Note that one gravity acceleration (i.e., $F/W_o = 1$) requires a propulsion system specific weight of 18.4 lb/ exhaust-circuit-MW for a propellant specific impulse of 1,000 sec.

For the thermo-mechanical gas compression system previously discussed, the gross specific weight is made up of terms describing the turbine-compressor set, reactor, radiator, and the secondary (exhaust) circuit gas compressors. A "reasonable" estimate of a minimum value of Φ_K can be made for this system, assuming operation at a radiator temperature of 3,000 R, reactor exit gas temperature of 4,000 R, and the use of very lightweight rotating machinery. Similar estimates can be made for the d-c arc and ion accelerator electrical systems, using data on presently available lightweight electrical generators.

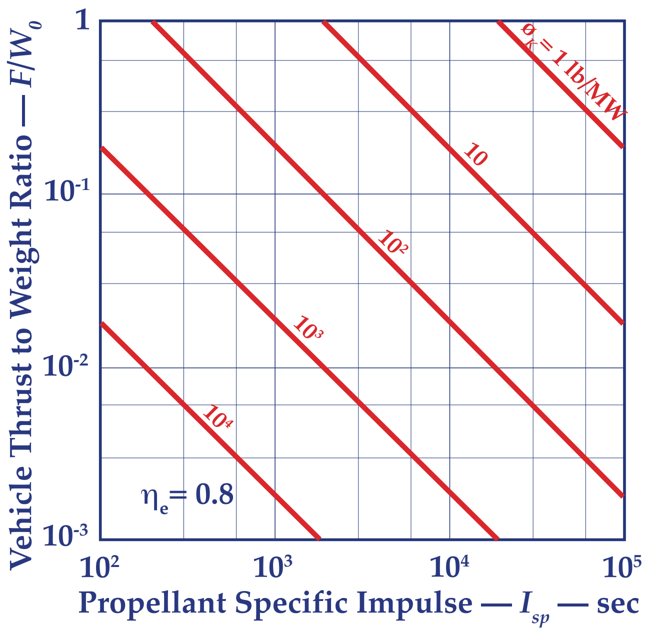


Figure 5 — Generalized Performance of Reactor System Powered Vehicles

Typical estimated minimum values for the principal components of each system are shown in Table 2, assuming operation at the conditions given above. In general it appears that the minimum system specific weight attainable with present-day equipment is the order of 1,000 lb / exhaust-circuit-MW. For this value, Figure 5 shows that the vehicle thrust-to-weight ratio will be less than 0.07 for propellant specific impulse greater than 250 sec. Such systems thus appear to be of potential use only in free-fall conditions where no artificial acceleration requirements (such as overcoming the earth's field) exist.

Table 2a — Estimated Minimum Specific Weights for Thermo-mechanical Gas Compression System

Component	Specific Weight per Unit Power Handled	Specific Weight per Unit Power in Exhaust Circuit
Turbine-compressor	300 lb/MW	300 lb/MW
Radiator	50 lb/MW	200 lb/MW
Reactor	5 lb/MW	25 lb/MW
Gas compressors	100 lb/MW	500 lb/MW
Total	Φ_K	1025 lb/MW

Table 2b — Estimated Minimum Specific Weights for Electric DC Arc or Ion Acceleration System

Component	Specific Weight per Unit Power Handled	Specific Weight per Unit Power in Exhaust Circuit
Reactor circuit	(see above)	525 lb/MW
Electrical generator	1000 lb/MW	1000 lb/MW
Arc electrodes and container	25 lb/MW	25 lb/MW
Total	Φ_K	1550 lb/MW

A reduction in system specific weight of about a factor of 100 seems necessary in order to permit operation with high specific impulse and high thrust-to-weight ratio. Unfortunately the outlook is not bright for order of magnitude reductions in the specific weight of heat engine rotating machinery. Great decreases in weight require corresponding increases in the strength of materials used in construction. These do not appear on the research horizon at present. Significant reduction in the weight of electrical generators may possibly be made if electrostatic fields can be used as the basis for generator design[14], rather than electromagnetic fields with their attendant massive magnetic flux guides. However, reduction of the generator weight in electrical cycle systems simply reasserts the problem of reducing the turbine-compressor-radiator weight in the reactor circuit. What is really needed here is a conceptually new, and lightweight, method of producing shaft power or electrical power from fission. The efficient production of electricity directly from nuclear processes[15] (10) would at last provide the key to space travel and the practical exploration of our solar system.

History

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Footnotes

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