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SOME SCHEMES FOR NUCLEAR PROPULSION

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NUCLEAR ROCKET ENGINES

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By Marcia Ballegos 1-16-96

SOME SCHEMES FOR NUCLEAR PROPULSION

By

C. Longmire
F. Reines
S. Ulam

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INTRODUCTION

It is intended to present here a qualitative description of certain schemes for nuclearly propelled rockets. The ideas sketched in the sequel stem from the schemata proposed by some of us in the past. Various details and technical points were discussed in a Rocket Group which meets weekly in our Laboratory.

The scheme discussed in Part I might be considered as intermediate between the one outlined in LAMS-1955[1] and the ones where the idea is to propel a nuclear rocket by having a gaseous fission reactor operating inside the vehicle.[2] New ideas on isothermal gaseous reactors are discussed in Part II.

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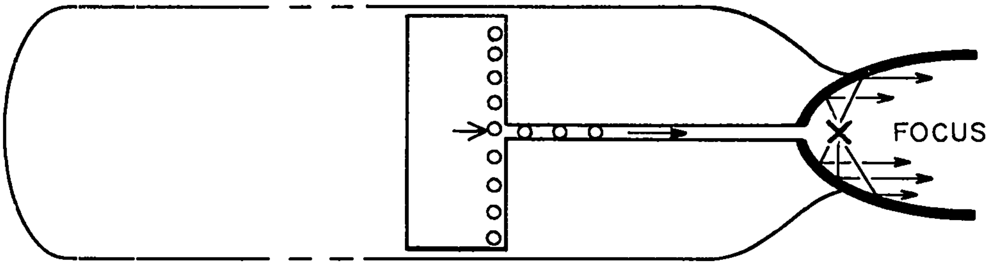
[1] On a Method of Propulsion of Projectiles by Means of External Nuclear Explosions, Part I, Everett and Ulam, September, 1955.

[2] T-821, Nuclear Chinese Rockets, C. Longmire, May, 1956.

[redacted]

PART I

C. Longmire and S. Ulam - Internal Explosions. Briefly speaking, we imagine a great number N of very mild explosions taking place in succession. These explosions involve bomb-like assemblies of either metal surrounded by a small amount of high explosive and essentially hydrogenous material or UD_k cores. Each of these explosions is supposed to heat the total mass involved only to very moderate temperatures. To fix the ideas we consider temperatures of the order of $\frac{3}{4}$ ev, i.e., 9,000°C, although temperatures up to a few ev may be useful. Each of these explosions will involve only several kilograms of active material and several tens of kilograms of hydrogenous material, and therefore the total yield of the order of a few hundreds of kilograms (sic!) of TNT equivalent. These explosions are, properly speaking, "fizzles" resembling burning rather than a true nuclear detonation. One imagines a large chamber with steel walls of roughly paraboloidal shape with the "explosions" taking place at its focus. The chamber may be considered, for the purpose of this discussion, as being evacuated except for the material to be exploded. The linear dimensions of the chamber are large compared to the assembly which is exploding. For orientation, we may assume the diameter of the chamber to be of the order of 4 meters, whereas the diameter of the bomb, together with the enclosing hydrogen, is say of the order of 40 cm. Each of our bombs should be thought of as being in a liquid or solid state before the explosion. This explosion will convert its whole mass into gas which will expand and fill the chamber with high velocity particles impinging on the walls and ultimately escaping from the chamber.



The "bombs" are brought in in rapid succession from a storage chamber and brought to the "nozzle" chamber where they are exploded. Compared to the proposals made in LAMS-1955, the present scheme differs in the following respects: The explosions are of smaller yield. Their number is greater by a factor of 10 or 20. They will be of longer duration and lesser violence, and therefore, by order of magnitude, the individual accelerations given to the body of the rocket in each push will be smaller. Secondly, they are made internally, which allows a greater fraction of mass to be used in imparting the momentum. This, of course, is more than counter-balanced by the greater number of supercritical assemblies that one has to employ. Let us say from the beginning that the total amount of fissionable material expended will be of the order of a few tons, at least for a first design. This makes it appear, offhand, that the primary use of such rocket motors would be to have large satellites and vehicles for interplanetary travel, rather than for stockpiling in large numbers.

We shall employ the following notations:

N = total number of exploding assemblies.

E_i $i = 1 \ldots N$ = the energy released in the i-th explosion.

M_i = the total amount of material exploded.

m_i = the mass of fissionable material in the i-th "bomb."

R = the diameter of the nozzle chamber.

P_i = the pressure on the wall of the nozzle.

d = the thickness of the wall.

v_e = the velocity of propellant mass escaping the chamber.

μ = mean molecular weight of the bomb material.

T_i = the temperature to which the mass M_i is brought as a result of the nuclear reaction.

W_w = weight of the walls of the paraboloid.

W_p = weight of the propellant.

W_a = weight of the structure of housing of the bombs, and injecting mechanisms, instruments and "payload".

$$W = W_w + W_p + W_w \text{ total weight}$$

We now give a tentative set of values in c.g.s. units for our quantities.

$$N = 10^3$$

$$m_i = m_1 = 5.10^4 \text{ gms}$$

$$R = 2.10^2 \text{ cm}$$

$$T = \frac{3}{4} \text{ ev}$$

$$d = 3 \text{ cm}$$

$$\mu = 3$$

The effective volume V of our paraboloid with a length of 300 cm would be $V \sim \pi R^2 \ell = 3.14 \times (2.10^2)^2 \cdot 3.10^2 \sim 4.10^7$ cc.

$$W_w \sim 2\pi R d \ell \rho \cong 6.3 \times 2.10^2 \cdot 3.10^2 \times 3 \times 8 \cong 10 \text{ tons}$$

$$W_p \sim 10^3 \times 5.10^4 \sim 50 \text{ tons}$$

$$W_a \sim 10 \text{ tons}$$

$$W \sim 70 \text{ tons}$$

The exit velocity v_e of the propellant will be sensibly higher than the thermal velocity of our material at the temperature obtained in the nuclear explosion. This is so because of the effects of the recombination of the molecules and ions. If $T = \frac{3}{4}$ ev, $\mu = 3$, the thermal velocity v is about 6 Km/sec., and the final v_e about 10 Km/sec. The energy E_i of each explosion is then given by $E \sim \frac{1}{2} m v_e^2 = \frac{1}{2} \times 5 \times 10^4 . 10^{12} = 2.5 \times 10^{16}$ ergs, about 500 kgs of TNT equivalent. The pressure on the walls will be of the order of $P \sim (\gamma - 1)\frac{E}{V} = \frac{.4 \times 2.5 \times 10^{16}}{4 \times 10^7} \sim 2.5 \times 10^8$

~ 250 atmospheres ~ 4000 lbs/sq.in.

In the first discussion we shall assume that the quantities are independent of i, that is to say, each assembly and explosion have constant characteristics.

The numerical data above represent merely an order of magnitude orientation about the scheme and are, of course, in no way optimal. There are many degrees of freedom in this scheme. Obviously, most of the fissionable material is "wasted" and we could choose our yields E_i within a very wide range of values - also the composition of the hydrogenous material surrounding the bomb and its mass in proportion to the mass of U^{235} is at our disposal, in a large measure. The geometries of the chamber, etc., seem not to be limited from above by the numbers adopted here.

Speaking qualitatively, the possible advantages of our scheme are as follows:

1. If we admit that the temperature of the material heated by the nuclear explosion is of the order of $1/2 \sim 1$ ev, the expansion of this material in the vacuum of the nozzle chamber will convert most of the energy released and initially present in the form of thermal energy to kinetic energy of the particles with the corresponding cooling of the gas. The velocity of the escape of the propellant will be therefore of the order of 10 kilometers per second, that is to say, the velocity of a satellite. For the velocity of the final "payload" to be of this order, one needs only a ratio $\underline{e}$ between the mass of the propellant

and the mass of the installation and instruments, etc.

2. We mentioned a ratio of about 10 between the linear dimensions of the nozzle chamber and those of the exploding assembly. The density of the gas which will fill the chamber before impinging on the walls will be therefore 1/1000 of the original density. This means that the pressure on the wall will be moderate. The tensile strength of the wall of a fixed thickness depends, adversely, linearly on the inner diameter. If we assume that the pressure on the wall is given by the Bernoulli formula $P = \frac{1}{2}\rho(v^2)$ -- since ρ depends inversely on the cube of the linear expansion there is obviously a gain by having the walls of given tensile strength far apart. This gain obtains as long as the total weight of the propellant, auxiliary equipment and the "payload" exceeds sensibly the weight of the walls of the chamber where the explosions take place. Heating by neutrons and gammas becomes even less of a problem - when, with the weight of the payload and equipment essentially constant, the chamber is large.

Considerable computational and experimental work seems necessary to provide a design of the above sort. First of all one should try to calculate individual explosions which are to heat the material to be reproduceable and as precise as possible. This should be done with the greatest possible economy of the fissionable material. Probably experiments have to be made with actually exploding such assemblies in order to learn about their characteristics. The action of the expanding gas on steel or tungsten covered structures has to be studied in order to understand the erosion of the material by successive explosions of this sort. The velocity of the propellant leaving the chamber has to be calculated - possible benefits from shaping the exit of the nozzle should be studied. One should discuss the possibilities of cooling of the walls by "sweating" if that should be necessary. We have not discussed the problem of "pumping" individual assemblies at a sufficiently fast rate and the concommitant engineering difficulties. At any rate, the problem here involves a shoving in of masses of the order of 50 kilograms each in intervals of about 1/10 sec. The problem of neutron heating should be calculated in detail, also the problem of the residual gas remaining after the i - 1-st explosion at the time when the i-th explosion is to take place, etc.

It seems likely that a shock absorber between the thrust chamber and the remainder of the missile is desirable, to spread the sharp impulses out over time as well as possible. The number of g's that the main structure has to stand can thus be reduced to a small number.

It appears that steel of average 3 cm thickness will, for our choice of the radius of the wall, contain 4000 lbs/sq.in.

The wall can be coated with tungsten to resist the temperature of the gas accumulating on its surface. The contact of the gas with the wall is of extremely short duration - in a case like the one illustrated above about 1 millisecond for each explosion, so that heating by conduction is seemingly negligible.

Materials other than steel could be considered for confining the exploding gas, with greater strength for weights than steel.

The main problem is the construction of "economic" bombs giving yields of $\sim$ 1 ton of TNT equivalent.

We had the benefit of conversation with George Bell on this problem and C. B. Mills is in the process of calculating critical masses and "alphas" for such UD_k assemblies.

PART II

F. Reines - A gaseous Fission Reactor Rocket Motor.*

1. Introduction

The idea of using a gaseous fission reactor for rocket propulsion, where the reacting materials are ejected, has the attractive feature that heat transfer from heat source to working fluid, or propellant, is extremely rapid and efficient.[1,2] Difficulties with such a scheme center on the relatively large amounts of fissile materials which are thrown out the nozzle. The point of view adopted here is that it is worth many tons of fissile material to propel a manned ship into interplanetary space, allowing for a landing on Mars, for example, and returning to

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*This chapter is, with minor modifications, contained in a memo, T-2-50, dated January 17, 1958.

I should like to acknowledge helpful discussions of these ideas with many people at Los Alamos among whom were: Aamodt, Bell, Cranberg, Leland, McInteer, and Taschek. I especially wish to thank S. Ulam for his interest and stimulation.

[1] Steady State Fizzlers, R. W. Bussard, memorandum N-3-134 (1956). In this memo references are given to considerations of H. T. Gittings (1954) and D. S. Young and G. A. Jarvis (1955).

[2] It should perhaps be added that static tests of such motors would not be wasteful of fissile material because the exhaust could be caught and reused.

earth. Nevertheless it is recognized that some limit on the expenditure of fissile material exists and that any design must keep this cardinal fact in mind. The limitations characteristic of other schemes arise from the temperatures and pressures at which materials can be used. It is conceivable that thermal gaseous reactors are much less limited because of the possibility of generating heat directly in the working fluid while converting the energy into ordered motion. In principle, this could be accomplished in stages by first passing a uranium-hydrogen gas into a region surrounded by a neutron reflector so that it becomes supercritical and heats up, then allowing it to expand through a nozzle ordering its random energy, repeating the process until the desired propellant velocity is attained. The materials limitation in such a scheme is the local heating in the vicinity of the walls caused by the friction of the very high velocity propellant-reactor gases. In addition, we must consider the heating of the container walls by the neutrons and gamma rays from fission and neutron capture. These limitations are much less severe than those imposed in the more conventional schemes in which fission energy generated in a solid must be transferred out of the reactor and into the propellant. The hope is that sufficiently high propellant velocities can be attained so that the payload per pound of fissile material ejected will become attractive.

2. The working fluid, critical masses

The working fluid, i.e., the reactor-propellant, we propose is a mixture of U^{235} and deuterium (D_2) intimately mixed.[3] Hydrogen (H_2) is preferable as a propellant because of its lighter mass but the neutron capture cross section (0.33 barns at 1/40 ev) is so large that the number of hydrogens per uranium atom must be kept low if a chain reaction is to be sustained. Under these conditions the propellant is mostly uranium and hence is extremely inefficient. If, on the other hand, we choose a deuterium-uranium mixture, then because of the low neutron capture cross section in deuterium (0.0057 barns at 1/40 ev) reacting mixtures of UD_n with $n \sim 10^5$ can be imagined. The critical mass of U^{235} in an infinite D_2O reflector at normal temperature and pressure has been calculated by Bell[4] to be 900 grams. It seems reasonable on the basis of calculations given in the AEC Reactor Handbook RH-1 for D_2O moderated reactors to believe that the gaseous critical mass, though insensitive to n, should drop to ~ 300 gms for $n = 2000$. In a finite reflector, say 50 cm thick, the critical mass might rise to ~ 600 gms. The radius of the gaseous sphere would then be ~ 35 cm, and the pressure 310 atmospheres. Since we wish to operate at a maximum temperature in the range 2000-3000°K the pressure would, for this size sphere, be 2300-3400 atmospheres. Such a pressure would dictate

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[3] The U^{235} might be contained in the gas UF_6, the D_2 stored as liquid.

[4] G. I. Bell, LA-1874 (1955).

an excessively heavy container and consequently an increase in volume is indicated so as to reduce it to a more reasonable ~500 atmospheres. Because the neutron moderation occurs primarily in the D_2O walls an increase in container volume by a factor of 4.6 to 6.7 (or to a radius of 60-70 cm) should not increase the critical mass of U^{235} very much. One final adjustment in these numbers is required because of the elevated temperature at which the system operates. The fission cross section of U^{235} drops by about a factor of three when the temperature rises from 273°K to 3000°K, thus raising the critical mass by this factor. Summarizing our numbers we have for an initial gaseous reactor stage:

Sphere: $R_c = 60\text{-}70$ cm
Reactant: $U^{235}D_{2000}$; 1.8 kgms U^{235}, 31 kgms D_2
Reflector: D_2O, 50 cm thick
Pressure: 500 atmospheres
Temperature: 3000°K

3. Thrust, fuel consumption from initial stage motor

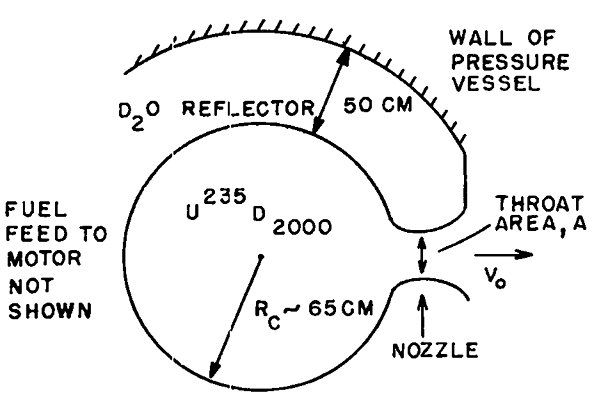

Fig. 1 Schematic of Initial Stage

Assume D_2, disassociated into 2D, but do not count on extra thrust due to recombination in the nozzle (conservative). The velocity of sound in D at 3000°K is

$$V_s = \sqrt{\gamma RT}$$
$$= \sqrt{1.4 \times 41.25 \times 10^6 \times 3 \times 10^3}$$
$$V_s = 4.2 \times 10^5 \text{ cm/sec.}$$

The ordered maximum velocity V_{out} of the D leaving the nozzle is given by

$$V_{out} = \sqrt{\frac{3KT}{m}} = \sqrt{\frac{3 \times 1.38 \times 10^{-16} \times 3 \times 10^{3}}{3.35 \times 10^{-24}}}$$

$$V_{out} = 6.1 \times 10^{5} \text{ cm/sec.}$$

This corresponds to a specific thrust of 630 seconds.

Suppose we ask for a final rocket velocity $V_f = 6$ km/sec then, neglecting gravity, a mass ratio

$$\frac{M_{initial}}{M_{final}} = e^{1} = 2.7$$

is required.

For $V_f = 11$ km/sec, $\frac{M_{initial}}{M_{final}} = e^{11/6} = 6.2$ is required. The acceleration, a, we choose then determines the mean rate of propellant ejection. Suppose $a = 15$ g and $V_f = 11$ km/sec, then the time of ejection $t_{15} = \frac{11 \times 10^5}{15 \times 10^3} = 73$ sec; for $a = 100$ g, $t_{100} = 11$ sec. These numbers, together with the $\frac{M_i}{M_f}$ determine the nozzle dimensions required. At this point it is instructive to calculate the number of tons of payload plus vehicle per ton of U^{235} ejected which achieves $V_f = 6$, 11 Km/sec.

$$\frac{M_i}{M_f} = \frac{M_{propell.} + M_f}{M_f} = 1 + \frac{M_{propell.}}{M_f}$$

but $M_{propell.} = M_D + M_U = M_U(1 + M_D/M_U)$ so that

$$\frac{M_f}{M_U} = \frac{\frac{M_D}{M_U} + 1}{\frac{M_i}{M_f} - 1}$$

and hence

V_f km/sec	$\frac{M_i}{M_f}$	$\frac{M_f}{M_U}$
6	2.7	10
11	6.2	3.3

where $\frac{M_D}{M_U} = \frac{31}{1.8} = 17.$

Elementary structural considerations suggest that a ratio of 3.3 is incompatible with a pressure vessel weight plus tanks for the propellant but that 10 is quite reasonable.*

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*The mass, M, of a pressure vessel is estimated from the consideration of hoop stresses which yields the equation

$$M = 2\pi R_o^3 \frac{p\rho}{S_t} \times 10^{-6} \text{ (metric tons)}$$

where R_o = container radius (cm) + 65 (reactor chamber radius) + 50 (reflector thickness)

p = internal pressure (psi) = 7500 psi

S_t = permissible tensile stress (psi)

ρ = density of container material (gm/cm^3).

For steel container (allowing no safety factor)

$$M = 2\pi(115)^3 \times 7500 \times \frac{7.85}{4 \times 10^5} \times 10^{-6}$$
$$= 1.4 \text{ metric tons.}$$

A more reasonable figure on the tank weight, allowing for a small safety factor, would be two tons.

It is of course possible to imagine schemes which might improve the performance of this single stage motor such as having "sweat cooling" of the container walls so allowing higher propellant temperatures. In addition, recovery of the U^{235} might be considered.[5] Though worth pursuing, these suggestions will not be discussed further here. Instead we will outline the multiple heating proposal mentioned in the introduction.

4. Multiple reheat motor (MRM)

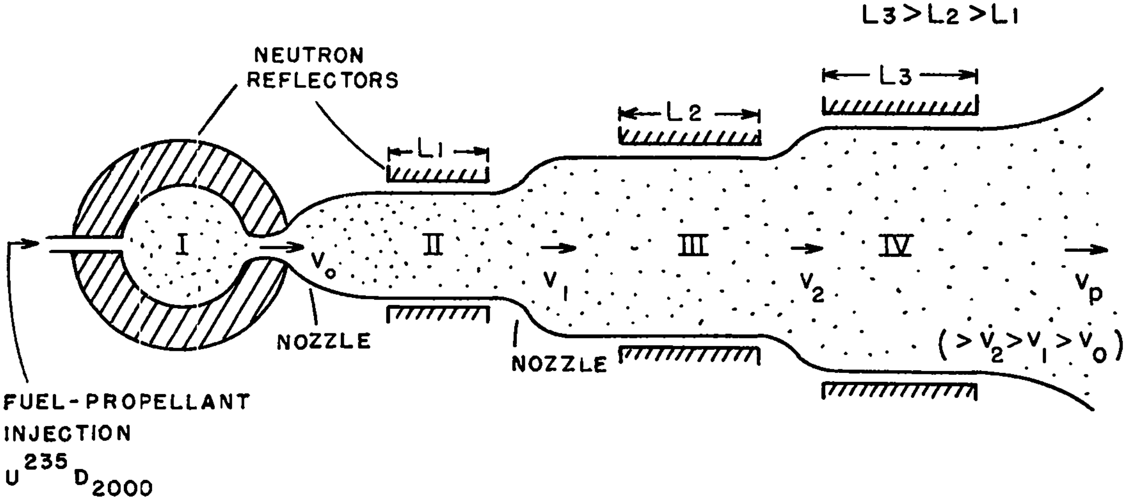

Fig. 2 Crude Schematic of Multiple Reheat Motor. (Not to scale)

In this motor the fuel-propellant mixture is injected into the reactant chamber I where it is heated and expelled into chamber II through the nozzle which serves to order the thermal energy somewhat. The mixture is now cooled and at a lower pressure passes into the part

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[5] R. W. Bussard and G. M. Grover, N-3-270 (1957).

of region II which is surrounded by a neutron reflector making it react and heat up again. It then is nozzled out into the non-reacting section of III again cooling down as its velocity increases. The procedure is repeated until the desired exit velocity is achieved.

We have in this brief description indicated the basic idea of the multiple reheat motor. The scheme bears a kinship with the more desirable isothermal nozzle which would result if the number of stages were increased without limit and were made continuous in space. However, for simplicity in explanation, let us consider at this time the discrete situation outlined above.

The essential features of MRM have to do with the unconventional fission reactors involved. As the fuel-propellant achieves higher velocities, fission cross sections drop so that the material becomes less reactive. This means that more excess reactivity has to be included initially in the form of more U^{235} in the fuel-propellant and the reflector must be progressively enhanced (thickened) for successive stages.[6] In addition, since the time spent in a given region varies inversely with the ordered fuel-propellant velocity the length of each section must be increased accordingly for a given heat input. In addition we must also consider the effects on criticality of neutrons being

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[6] The fission cross section drops by a factor of ~ 3 as the energy rises from 1/3 ev to 2 ev. Other fissile materials should perhaps be considered since their cross sections behave rather differently. U^{233}, for example, has a broad high (average ~ 500 barn) resonance in the 2 ev region. This means that U^{233} is about 10 times better than U^{235}, i.e., that an order of magnitude less U^{233} would be required!

swept along by the rapidly moving gases.

If this system is to represent an improvement over the single heating arrangement it should give a greater thrust per unit weight of fissile material employed. In rough terms we can say that an m stage MRM will weigh more than m times that of the one stage motor which is practically completely surrounded with moderator and that further, because of the increased fuel-propellant speeds approximately twice the U^{235} will be required. Suppose we achieve a $V_{propell.}$ of 2 ev (= 16.5 kilom/sec), then for V_f = 11 kiloms/sec,

$$\frac{M_i}{M_f} = e^{11/16.5} = e^{0.66} = 1.95$$

or

$$\frac{M_f}{M_U} = \frac{18}{0.95} = 19$$

This fine ratio is, however, achieved at the cost of a much heavier rocket motor, more than ten times as heavy, cancelling out the gain over the single stage motor.

These numbers are at best crude, but they indicate the need for an improvement over MRM. The direction in which to go is toward the continuous or isothermal case, and possibly the use of U^{233}. The continuous isothermal nozzle reactor has only one "open" end, i.e., end without neutron moderator, and so should be much more economical of fissile material. It seems clear that the optimal isothermal system

[redacted]

from the points of view of the minimal length and mass of fissile material required is one in which many smaller parallel pipes constitute the motor.

At present a group in the Theoretical Division is considering the hydrodynamics of the isothermal nozzle and is looking into the energy generation characteristics of such novel flowing reactors.

It should perhaps be added that static tests of such motors would not be wasteful of fissile material because the exhaust could be caught and reused.

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