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LEXINGTON PROJECT REPORT

No. 148

THE FEASIBILITY OF NUCLEAR-POWERED ROCKETS

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Jerry E. Keyes
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ABSTRACT

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Lexington Project Report # 148

Subject: The Feasibility of Nuclear-Powered Rockets
Author: E. M. Redding
Date: September 8, 1948
Place: Lexington

A. Summary

Nuclear-powered rockets appear to be useful only as extremely high-speed long-range guided missiles or as the only feasible single-step satellite or escape rocket vehicle. The tremendous development effort associated with the high reactor wall temperatures, the large gross weight and required long-range guidance system make the nuclear rocket of comparatively little interest at this time.

No design studies were made by the Lexington Project on nuclear rocket power plants, and it is recommended that development applicable only to nuclear rockets be delayed in favor of nuclear turbojet development.

B. History and Introduction

To date preliminary design studies on nuclear-powered rockets have been made by North American Aviation, Inc. (2), NEPA (3), and the Applied Physics Laboratory of Johns Hopkins University (1). Each agency reached the same conclusion, namely, that in principle a nuclear-powered rocket is feasible, but that several important engineering considerations must be solved before feasibility is a foregone conclusion.

The three studies were made early in 1947 and in none was consideration given to shielding the reactor to prevent radiation damage to the atomic bomb warhead, lubricants and electronic components and the guidance and control systems. Therefore, all conclusions reached by these agencies should be considered somewhat optimistic until such time as complete design studies are made using latest shielding and reactor information.

As will be shown below, the reactor wall temperatures required for nuclear-powered rockets are considerably higher than those required for turbojet use. In addition, the rocket is considered to be useful only as a guided missile for extremely long ranges at extremely high speeds. For these reasons alone the rocket quite definitely would require a much greater development effort than the turbojet airplane and, therefore, the Lexington Project made no further design studies on nuclear-powered rockets, concentrating instead on more feasible power plants.

C. General Discussion

By definition a rocket is a jet propulsion device whose working fluid is stored aboard the vehicle and pumped into the motor. Other jet devices use air drawn from the atmosphere as all or part of the working fluid.

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Therefore, a nuclear-powered rocket must carry a supply of such working fluid, and the time of operation of firing would be limited by the duration of supply of this fluid, called the "propellant". The advantages of a nuclear-powered rocket over the conventional chemically powered rocket would lie chiefly in the possibility of using a propellant of lower molecular weight, resulting in improved specific impulse and improved range for a given size vehicle.

D. Design Parameters

The liquid propellant is injected at fairly high pressures (say 20 to 50 atmospheres), into the reactor where it is vaporized and heated to a high temperature, and is in turn expanded through a suitable exhaust nozzle where it is accelerated to high velocities. Since the exhaust velocity is essentially a function of

$$\sqrt{\frac{T_c}{M}}$$

where T_c is gas temperature leaving the reactor and M is the molecular weight of the gas, the chief advantage of the use of a nuclear reactor instead of chemical reaction for gas heating is the possibility of using a propellant gas of lower molecular weight than is available with chemical rockets. High gas temperatures are made possible with chemical rockets by cooling of the rocket motor walls. This expedient is not possible in a reactor, as the maximum reactor wall temperature must be even higher than the maximum gas temperature. Therefore, the nuclear rocket does not offer any apparent advantages in the way of increased gas temperatures.

The lowest possible molecular weight propellant is hydrogen. All studies made to date have reached the conclusion that hydrogen would be the logical propellant to use, notwithstanding its low density in the liquid form which requires rather large tank volumes and weights.

Because of the limited "firing" time of a nuclear rocket having a finite amount of propellant, the rocket vehicle is not suitable for sustained level flight. By launching the rocket vertically and "firing" until high flight velocities are reached the vehicle can be made to traverse an elliptic-type orbit, returning to the earth's surface at high speeds. The range obtained is a function of the maximum velocity reached by the rocket, which in turn is a function of the rocket exhaust velocity and the ratio of propellant weight to gross weight (so-called "mass ratio").

Table 1 shows approximate values of maximum rocket velocities required for several ranges. It was obtained from Ref. (1).

Table 1

Range (miles)	1,000	5,000	10,000	escape
Velocity (ft./sec.)	12,300	22,300	25,600	36,700

The last column, "escape", refers to the condition where the rocket reaches sufficiently velocity to overcome the force of gravity and escape from the earth. The following simplified equation indicates the relation of specific impulse and mass ratio to maximum rocket velocity for a single-step rocket:

$$V = 32.2 \; I_{sp} \ln_e \left(\frac{1}{1 - \text{mass ratio}} \right)$$

where V = maximum velocity

I_{sp} = specific impulse

The sea level specific impulse of a nuclear hydrogen rocket is given below as a function of maximum gas temperature. Reactor outlet pressures of 50 atmospheres are assumed.

Table 2

Gas Temperature	Specific impulse lb. thrust / lb./sec. flow
5432°F	830
4040°F	730
3250°F	665
2472°F	590

Under the same conditions the maximum specific impulse of a hydrogen-oxygen chemical rocket is 395 with a chamber temperature of 4510°F.

D. General Characteristics

1. Effect of gas temperature and maximum reactor wall temperature. No systematic study was made to determine a practical lower limit to maximum gas temperatures. North American (2), assumed a design gas temperature of 5432°F. NEPA (3) assumed a design gas temperature of 3000°F. APL (1) made a rough study of the effect of gas temperature on overall size of rocket required for a range of 5000 miles. It was concluded that the overall size of the rocket increased very rapidly as the gas temperature decreased below 3250°F. The maximum reactor wall temperature assumed for a gas temperature of 3250°F was 4040°F. It may be tentatively concluded from the data so far accumulated that reactor wall temperatures of at least 4000°F are required for rocket use. This temperature is well above the temperatures required for turbojet use, which may go as low as 1200°F.

The thrust of a nuclear rocket increases with increasing altitude because of the reduction in nozzle backpressure. The thrust increase is negligible above 100,000 feet altitude. The thrust at 100,000 feet is approximately 20% greater than the sea-level thrust and depends slightly on chamber pressure.

In addition to the high required maximum reactor wall temperature one of the most critical factors in the design of a successful nuclear rocket is the attainable mass ratio. The low density of liquid hydrogen requires that the volume and weight of propellant tanks be quite large, greatly complicating the problem of reducing the structural weight of the rocket. The weight requirements are so stringent that no thermal insulation for the tanks can be considered.

Comparisons have been made between nuclear rockets and chemical rockets (1), (2). Table 3 below presents such a comparison between a hydrogen nuclear single-step rocket and two chemical rockets, the first being a 3-step hydrogen-oxygen rocket, and the second being a 4-step alcohol-oxygen device (2).

Table 3

	Nuclear	Chemical	
Weight, lb.		Hydrogen-Oxygen 3-step	Alcohol-oxygen 4-step
Payload	8,000	8,000	8,000
Structure	29,500	51,000	100,200
Propellant	55,500	193,000	571,800
Total	93,000	252,000	680,000
Cost, dollars			
Structure	1,475,000	2,550,000	5,010,000
Propellant	56,000	39,000	57,000
Total	1,531,000	2,589,000	5,067,000

The costs presented for the nuclear rocket do not include the weight of uranium. If uranium cost is considered it is likely that the nuclear rocket could not be justified from a cost standpoint if the above analysis is nearly correct. If nuclear rockets costs are nearly equal to that of the hydrogen-oxygen 3-step rocket, for instance, the greater complexity and gross weight of the chemical rocket probably would influence the choice in favor of the nuclear rocket.

The high-velocity trajectory required for a long-range rocket introduces a very troublesome matter, that of re-entry into the atmosphere at high Mach number. For ranges of 5000 miles and above it is quite certain that the rocket would burn up due to the high boundary layer temperatures at these conditions. Special skin cooling or thermal insulation of the warhead have been suggested to counteract this trouble. The chances of success are not known.

The question of reactor shielding has not been considered in the three rocket studies quoted above. The most recent information indicates that approximately 2 feet of shield, density 6, would be required to prevent jamming of the electronic equipment by radiation, as well as to protect the atomic bomb warhead. The weight of this shield would be on the order of the total weight of the rocket vehicles considered in these studies. The inclusion of the shield, therefore, would tremendously increase the gross weight of the rockets. Complete design studies are required to determine the extent of this gross weight increase.

E. Components

The pumps required for feeding liquid hydrogen to the reactor must be carefully designed to prevent cavitation from the low-boiling fluid, but apparently no great development problems are anticipated. The pumps can be driven by a turbine powered by hot hydrogen gas bled from the reactor at a suitable point. Small liquid-hydrogen pumps already have been developed by such agencies as Aerojet Engineering Corporation, and the development of a suitable feed system for a large rocket should not be a bottleneck in the overall development program.

The development of an exhaust nozzle would not be too easy. The pressure ratio across the nozzle changes radically over the period of powered flight, and ideally a nozzle with an adjustable expansion ratio would be needed to maintain a reasonable nozzle efficiency. However, several schemes have been proposed which would have the same effect. One scheme (2) consists of a series of baffles in the expanding portion of the nozzle which are released in sequence or burn away to gradually increase the expansion ratio of the nozzle without reducing the throat area.

F. Power Plant Aspects of Reactor

The very high reactor wall temperatures required for rocket application limit the choice of moderator and structure to graphite. Because of the slow but appreciable reaction of hydrogen with carbon at temperatures of about 4000°F, the graphite would have to be coated with some substance such as tantalum carbide (2). If no shielding is required, reactors of 7 feet diameter can be incorporated into any rocket so far considered. A requirement of appreciable shield thickness would cause a reduction in allowable reactor diameter for a given gross weight.

The propellant would have a pressure drop through the reactor on the order of 150 psi (2). The reactor must have sufficient mechanical strength to withstand the forces associated with this pressure drop as well as the inertia forces corresponding to accelerations up to 8 g's.

Thermal stress problems do not appear to be excessive with such large reactors with graphite structure.

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3. "NEPA Technical Report No. 4", May 15, 1947.