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Nuclear Rockets

Chemical rockets are already approaching their theoretical limits. Various ways of utilizing nuclear reactions for rocket propulsion have been suggested, some of which are in the experimental stage

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The rocket, after a remarkably brief period of intensive development, has broken the restraint of earth's gravity upon the aspiration and the deeds of man. But the roar and flames of chemical combustion that now propel the rocket may not carry man far into the realm of outer space where his imagination already soars. The most impatient astronaut must be given pause by the dimensions of the 3,000- to 7,500-ton vehicle that would be required to lift a modest space ship of 50 tons—the weight of a DC-6—from the earth. If the space ship had to depend upon chemical reactions to power its further travels, its fuel supply would leave little weight to spare for a payload of men and instruments. Plainly the rocket propelled by combustion must yield to the rocket that obtains its energy either directly or indirectly from nuclear reactions.

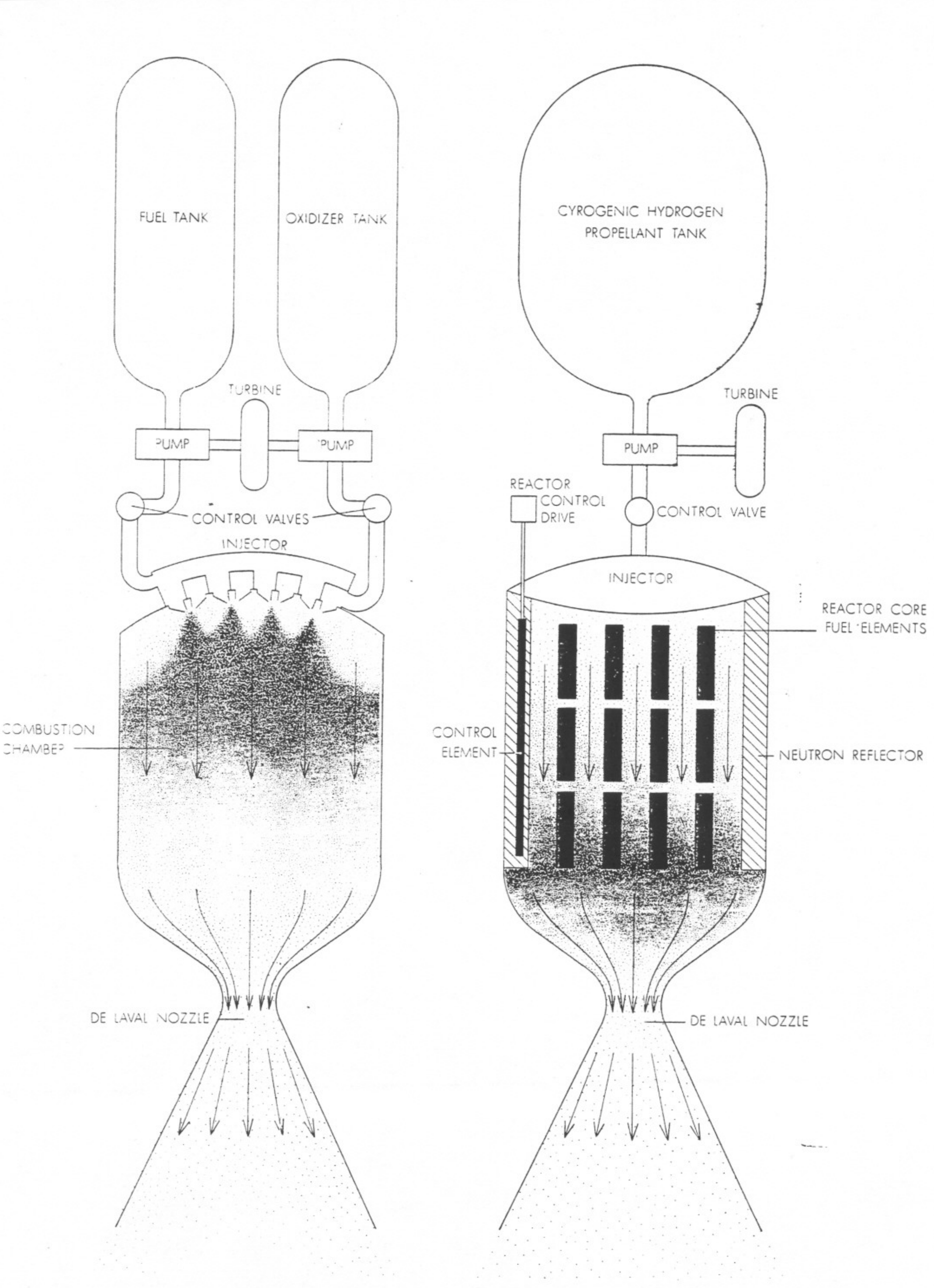
An exotic family of novel propulsion systems is coming into view, so diverse in concept that the name rocket seems in some cases almost misleading. For example, in the frictionless vacuum of space a flashlight or a plate coated with radium may constitute a perfectly good rocket engine, at least in theory. Given enough time, a comparatively feeble beam of light quanta, gamma rays or nuclear particles can accelerate a space ship to extreme velocities.

The first generation of nuclear rockets is in the preliminary stages of design and test. If the nuclear engines are intended to enable a vehicle to escape from the earth, they will still generate the pyrotechnics we associate with rocket launchings. It is the nuclear rocket that we shall discuss first, since of all the new systems it is perhaps the closest to realization.

In the U. S. work on the nuclear rocket has been conducted until recently under the auspices of the Air Force and the Atomic Energy Commission at installations such as the Los Alamos Scientific Laboratory. However, nuclear-rocket propulsion has now been set up as a joint venture of the A.E.C. and the National Aeronautics and Space Administration. The transfer is symbolic of a perhaps surprising aspect of this new technology: it has practically no application to military purposes. As far as weight and cost are concerned, the nuclear rocket is practically noncompetitive with long-range missiles already in existence or in prospect.

Chemical rockets intended for parochial missions inside the earth's gravitational field have begun to press hard on the limits of combustion. A rocket is a heat engine that employs the simple device of a nozzle to convert heat energy into the kinetic energy of a moving gas. The nozzle first converges and then diverges in the path of the outrushing gases; as the gases expand, their velocity increases sharply. The rocket's performance depends essentially upon the velocity of its propellant gases; the performance improves at higher exhaust velocities. The two most important factors determining gas velocity are the initial temperature and the molecular weight of the gases. The higher the temperature, the higher the ultimate velocity. The highest temperature to which the gases can be heated by combustion is 8,000 degrees Fahrenheit; chemical rockets operating at 5,000 degrees F. already approach this inherent ceiling. At a given temperature the velocity of the gases can be increased by lowering their average molecular weight. The unit of molecular weight is the weight of the hydrogen atom; the average molecular weight of the combustion gases of the best present fuels is 19, and the lowest weight attainable without too great a reduction in temperature appears to be about nine. At the optimum combination of temperature and molecular weight the highest exhaust-velocity that can be developed with chemical fuels is about 13,000 feet per second. This is an exhaust-velocity only a little higher than that which put *Lunik* and *Pioneer IV* into orbit around the sun.

Theoretically nuclear physics should free rocket propulsion from both of the limitations imposed by chemistry. Nuclear reactions can furnish heat at unlimited temperatures; either hydrogen or helium may be used as the propellant gas without regard to their chemical characteristics, simply because they are the lightest elements of all. Consider first the work-horse rocket which would be employed to carry a space ship clear of the earth's gravitational field. We may visualize it as a vehicle equipped with a conventional but compact solid-core nuclear reactor instead of a combustion chamber, and with a supply of hydrogen instead of fuel in its tanks. Stored in liquid form at minus 420 degrees F., the hydrogen



CHEMICAL AND NUCLEAR ROCKET-MOTORS are contrasted in these schematic diagrams. Chemical motor (*left*) burns fuel with an oxidizer to produce a jet of hot combustion gases which propels the rocket. Nuclear motor (*right*) "burns" fissionable uranium or plutonium in a lattice of fuel elements. These heat hydrogen gas which serves as the propelling fluid. The nuclear motor can exert more thrust than the chemical motor because the low molecular weight of hydrogen makes possible higher nozzle velocities.

would be pumped to the high pressure of 1,000 pounds per square inch, forced between the fuel elements of the reactor, heated there to as high a temperature as the reactor could stand and then ejected through the rocket nozzle [*see illustration on preceding page*]. The choice of propellant gas alone would give such a system an immediate advantage over the most advanced chemical rocket. At a temperature of only 4,000 degrees F. the hydrogen would attain a velocity of 25,000 feet per second. This constitutes a 100-per-cent improvement on the theoretical maximum velocity of the chemical rocket.

On the other hand, as we approach the design of the first nuclear rocket-engine, the temperature of 4,000 degrees F. looms as a formidable objective. A chemical combustion-chamber can be made to contain even higher temperatures because the heat can be confined to the combustion gases, the shell of the chamber being cooled on its outer surface by the inflowing fuel, which acts as a heat-exchange medium. We face a very different situation in adapting the nuclear reactor to serve as a rocket engine. The reactor generates its heat in the solid structure of its core by the fissioning of the uranium incorporated into its fuel plates. Since heat must always flow from a higher to a lower temperature-potential, the fuel plates will be at a considerably higher temperature than the gas. Moreover, the transfer of heat to the gas is hampered by the "boundary layer" of stagnant hydrogen which clings to the surface of the fuel plates. To achieve a gas temperature of 4,000 degrees F., the temperature in the central plane of the fuel plate must be 4,800 degrees F. Few materials that are usable in a reactor can withstand such temperatures. Consequently the choice of materials sets a limit on the gas temperatures we can hope to attain. A promising material is graphite impregnated with uranium. But even though graphite retains its strength at 4,800 degrees F., this strength is rather low. Erosion and corrosion by the flowing hydrogen promise to create additional problems.

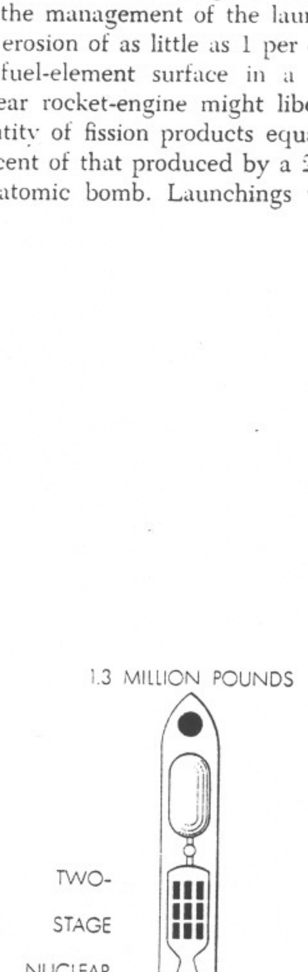
The design of this relatively feasible rocket engine confronts the designer with a host of additional stringent requirements. In the first place, the size and weight of the reactor must be held to a minimum. Calculation shows that a reactor of compact size must generate as much as 10 kilowatts of power per cubic centimeter of uranium-bearing graphite. This is about 10,000 times the equivalent output of the British power reactor at Calder Hall, the first gas-cooled graphite-moderated power reactor. Fortunately the fuel elements may need to remain integral for only a few minutes, since this kind of engine may be jettisoned when its work is done.

The transfer of such huge quantities of heat to the propellant gas requires a relatively large number of thin fuel-plates. The greater surface area between the fuel plate and the gas reduces the amount of heat that must pass through a unit of area in a given time. As a result the peak temperature at the central plane of the plates and the stresses created by thermal gradients within the plates may be kept within permissible bounds. But the solution of the heat problem creates some new ones. The greater surface area causes a larger drop in the pressure of the propellant gas as it flows between the plates. In a typical design, with 1,000 pounds of gas per second flowing through a 10,000-pound core, the frictional drag of the gas on the plates adds up to a total force on the reactor of as much as 300,000 pounds! Since useful thrusts in nuclear-booster rockets require high propellant flow-rates, this drag is not easily reduced. Fewer and thicker plates would crack or warp.

To aggravate the problem, the rocket may have an acceleration of 10 g—that is, an acceleration 10 times that of a body falling at the surface of the earth—by the time it nears the end of its powered flight. This means that in effect the reactor will be 10 times heavier than when it started; the 10,000-pound engine will "weigh" 100,000 pounds. With the increased weight added to the frictional drag, the reactor will exert a total force of 400,000 pounds or more on the rocket structure. Yet the support members that bear this load must occupy a minimum of space, stand up under a temperature of 4,000 degrees F. and contain little or no metal. Since metals that are resistant to high temperatures interfere with the nuclear reaction, graphite again may have to be used for the structural beams or columns. But graphite is difficult to join together; the cabinetmaker's slots and dovetails may have to be employed.

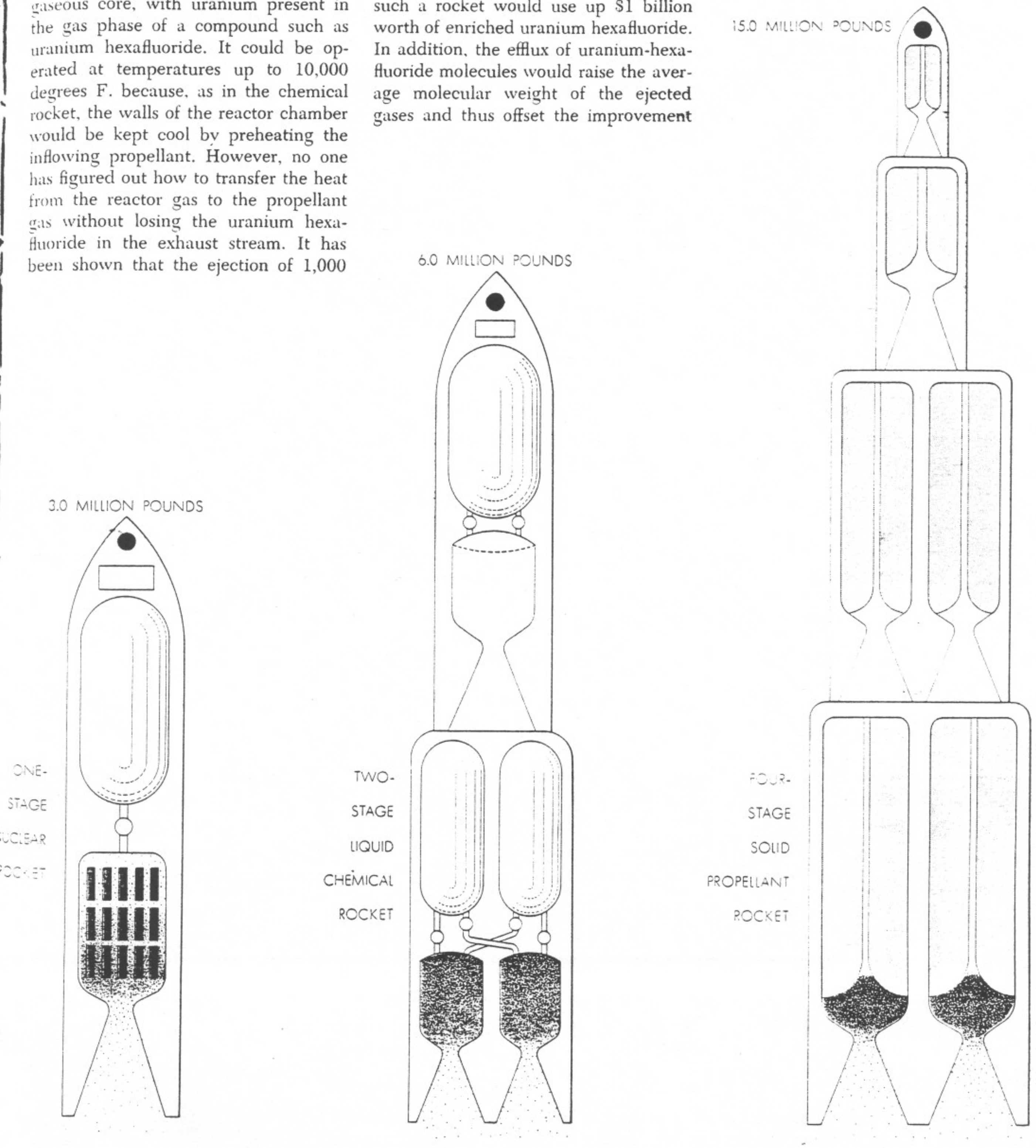
The start-up and control of the nuclear-rocket reactor present another whole family of problems. To avoid a tremendous loss of hydrogen, the reactor must heat up rapidly to operating temperature. But rapid heating creates heavy thermal and mechanical stresses in both the fuel elements and structure of the reactor. Though the danger of a "runaway" that would melt the system is slight, it cannot be ignored. For example, a large increase in hydrogen density arising from accidental blockage of the flow channels could result in melting. We cannot foresee all of the difficulties; they must be uncovered by operating experience with prototype reactors in ground test-beds.

Radiation is another hazard that calls for ingenuity in the design of the rocket and the management of the launching. The erosion of as little as 1 per cent of the fuel-element surface in a typical nuclear rocket-engine might liberate a quantity of fission products equal to 3 per cent of that produced by a 20-kiloton atomic bomb. Launchings will of



FOUR ROCKETS of different types are compared in these drawings. Each represents the estimated weight of a rocket powcourse have to be conducted at remote sites.

The temperature limitation inherent in the solid-core nuclear reactor has inspired a number of alternative systems. One of these is the gas-phase nuclear reactor. Such a reactor would have a gaseous core, with uranium present in the gas phase of a compound such as uranium hexafluoride. It could be operated at temperatures up to 10,000 degrees F. because, as in the chemical rocket, the walls of the reactor chamber would be kept cool by preheating the inflowing propellant. However, no one has figured out how to transfer the heat from the reactor gas to the propellant gas without losing the uranium hexafluoride in the exhaust stream. It has been shown that the ejection of 1,000 pounds of hydrogen per second would sweep out at least 350 pounds of uranium hexafluoride per second. In the three to five minutes it would take the rocket to escape from the earth, as much as 100,000 pounds of uranium hexafluoride would be lost. At the present cost of $10,000 per pound, the launching of such a rocket would use up $1 billion worth of enriched uranium hexafluoride. In addition, the efflux of uranium-hexafluoride molecules would raise the average molecular weight of the ejected gases and thus offset the improvement in rocket performance that the higher gas-temperature was supposed to give. It has been proposed that the heavier uranium gas might be retained in the outer periphery of the chamber by a kind of centrifuging arrangement, with the lighter propellant rushing through the



erful enough to launch a 100,000-pound payload (*symbolized by black spheres*) into space; the drawings do not attempt to show sizes in accurate proportion. The two-stage nuclear-chemical rocket at far left appears more efficient than the single-stage nuclear vehicle next to it. However, the problem of separating the two stages in flight would probably make the single-stage rocket more reliable.

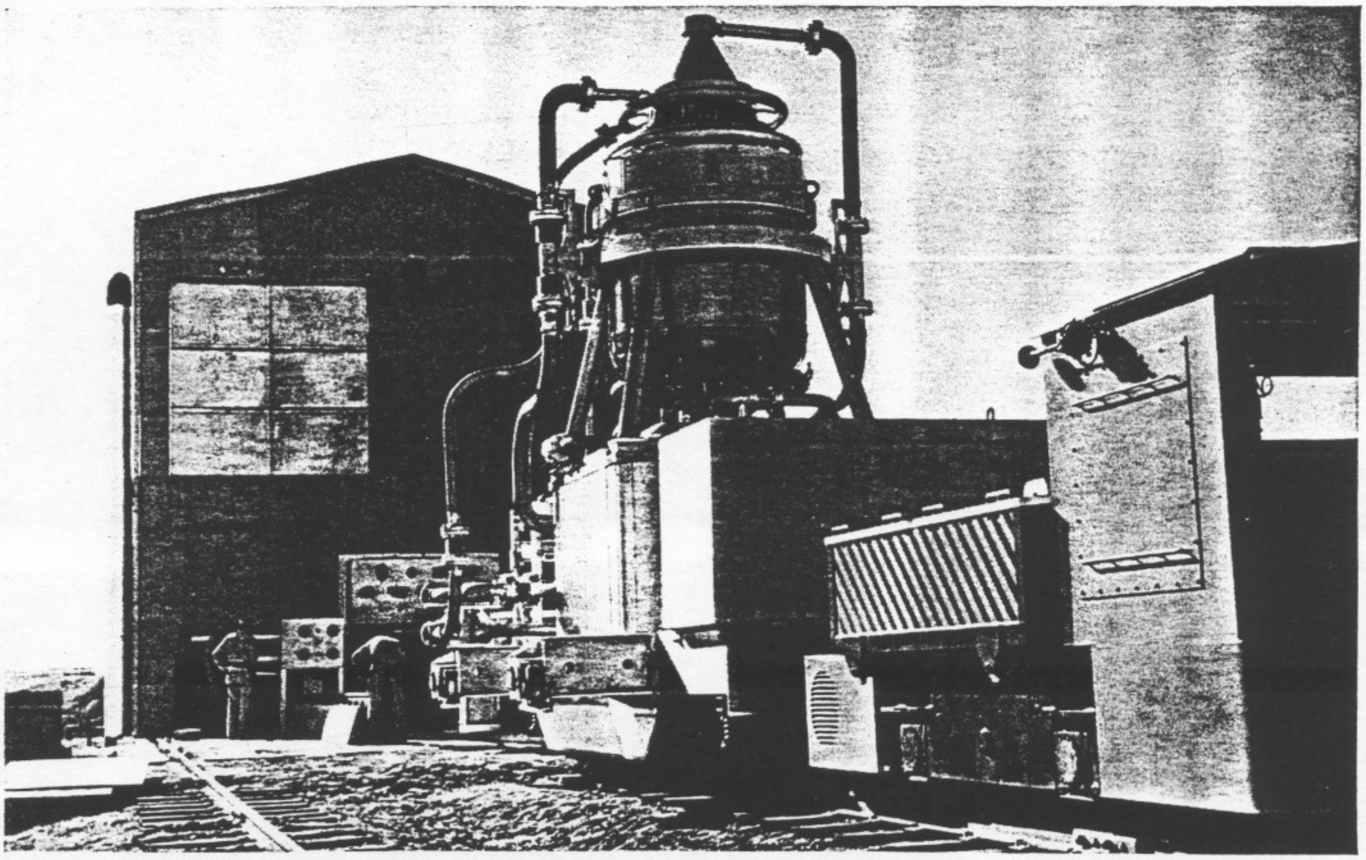
center. Alternatively, porous barriers might be used to "strain" the larger uranium-hexafluoride molecules out of the exhaust stream. Each such suggestion, however, raises more problems than it solves.

Yet temperature limitation is so critical that the gas-phase reactor is receiving further attention, along with other equally radical ideas. According to a recent announcement by the A.E.C., an even more radical idea is being studied. In essence this scheme would utilize sequenced and controlled nuclear explosions to propel a rocket into space. Here again the cost of a single mission might be very high; the technical problems are also formidable.

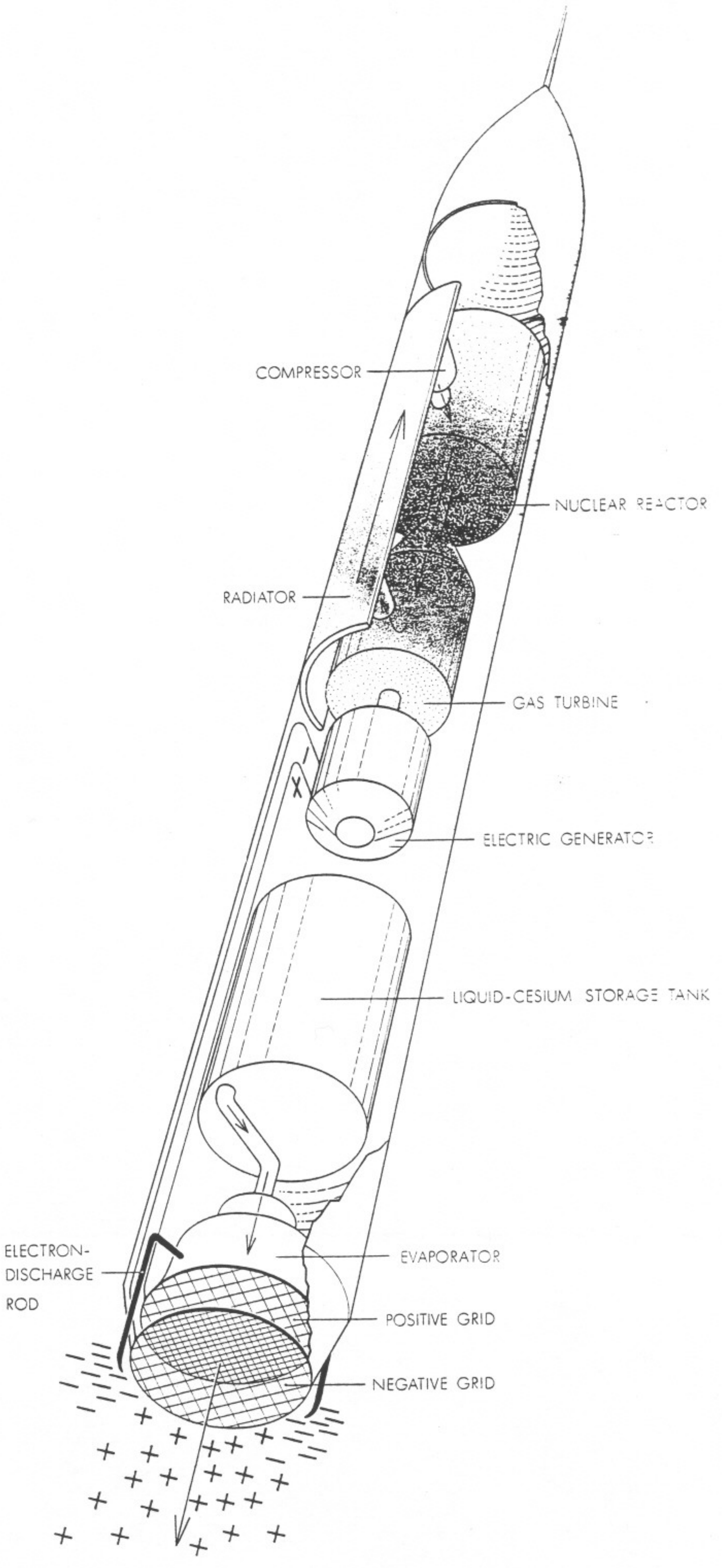
In view of all this, the solid fuel-element system represents the most probable first-generation nuclear rocket. Judging from the literature, effort along these lines is being pursued in the U.S.S.R. as well as in the U. S. The solid-core nuclear rocket clearly excels the standard chemical systems when the payload of the rocket becomes high or when the mission requires escape from the earth's gravitational field. For launching huge satellites or space craft, of say 50 tons as compared to the 2,000- to 3,000-pound weight of the Sputniks or the 40-pound weight of the Explorers, the nuclear rocket comes into its own. Chemical rockets would require many stages and enormous take-off weights to achieve such launchings. The nuclear vehicle can do it with a single stage, a lower total weight and much higher reliability. If we want to reckon with the possibility of space vehicles designed for voyages of long duration, then we must provide them with nuclear boosters to carry them free of the earth's gravitational pull.

The space vehicle, on the other hand, has quite different energy requirements. Since it is essentially weightless, quite small forces can be utilized to propel it, and it may call upon a wide selection of new and strange propulsion techniques. It might again use a nuclear reactor, but a reactor with low gas-flow and low thrust. However, for space missions of long duration (on the order of a year) a nuclear reactor that directly heats the propellant is not so effective as some of the more exotic systems. One of the more feasible of these systems, first proposed by the Austrian rocket pioneer Hermann Oberth, is ion propulsion. The nuclear reactor that powers an ion-propelled space ship will be markedly different from the engine that gets it off the ground. This reactor will not heat up and accelerate the propellant ions directly but must generate electrical energy for that purpose and others over a long period of time. It will, therefore, more closely resemble an earth-bound nuclear-power plant. Electrical energy from the reactor will first of all vaporize liquid cesium and ionize the free atoms. An electrostatic field of several thousand volts will then accelerate the positive cesium ions to high velocity, while an auxiliary electrostatic accelerator (or perhaps simply a pointed rod in the stream of ejected ions) will bleed the orphaned electrons off into space [*see illustration on opposite page*]. Such an arrangement can impart an exhaust velocity to the ions as high as 200,000 feet per second. The thrust of the ion beam is low; it is on the order of .1 to 10 pounds, or a ten thousandth the weight of the rocket, as compared to the high ratio of thrust to weight required in the launching vehicle. Yet the small thrust is sufficient to propel the space vehicle and, given sufficient time, to accelerate it to extremely high velocities. Since many space missions may take more than a year, the time needed for acceleration is not of great consequence.

It is the intrinsically large mass of the ion-propulsion system that dictates the 50-ton weight of the space vehicle that has been projected in this discussion. The nuclear reactor would be coupled, by means of a helium working-fluid, with



FIRST EXPERIMENTAL ROCKET REACTOR will shortly be ground-tested at Jackass Flats in Nevada. The device, named *Kiwi-A* after the flightless bird of New Zealand, is a gas-cooled solid-fuel reactor that resembles the one diagrammed on page 47.



ION ROCKET shown at right is a still-hypothetical device for space travel. Helium (*colored area at top*) heated in a reactor drives a gas turbo-generator; exhaust helium is cooled in a radiator and returned to the reactor. Current from the generator vaporizes liquid cesium, ionizes it and ejects the ions (*plus signs*) at velocities up to 200,000 feet per second. Electrons (*minus signs*) stripped from cesium atoms are bled into space from discharge rods. Ion rockets would exert a weak thrust for long periods, and would require the help of more conventional booster rockets to escape from earth.

a turbine. The turbine would drive an electrical generator, and the spent helium would be compressed and sent back through the reactor. All of these machines contribute to the weight of the rocket. In addition, the low-temperature waste heat of the reactor must be radiated away from the rocket; the size and weight of the required radiator are considerable. As a result of its great weight of equipment, the rocket accelerates slowly and cannot escape from strong gravitational fields without the help of its complementary twin: the high-thrust nuclear booster.

Still another possible means of nuclear-rocket propulsion is the fusion rocket. As regular readers of this magazine are well aware, several laboratories are at work on ways to contain a plasma of electrically charged particles in a magnetic field and to raise the temperatures of the plasma to the point at which its nuclei enter into a fusion reaction. If such a thermonuclear reactor can be made, it should be possible to adapt it to the purposes of a rocket engine. This would be done by ejecting the plasma from the reactor, thus providing thrust.

The prospects of space propulsion abound in such strange systems of energy transformation. The direct conversion of nuclear-fission, or thermonuclear-fusion, heat to electricity would reduce the weight of auxiliary equipment in the ion rocket and lead to improved performance. Propulsion by the ejection of plasmas via internally generated electrostatic and electromagnetic fields and by the ejection of photons are presently under study. Providing man succeeds in surmounting his own menace to his continued existence on earth, he may soon be venturing into space, not unlike the first prehistoric fish that flopped awkwardly out of the sea into thin air on dry land.