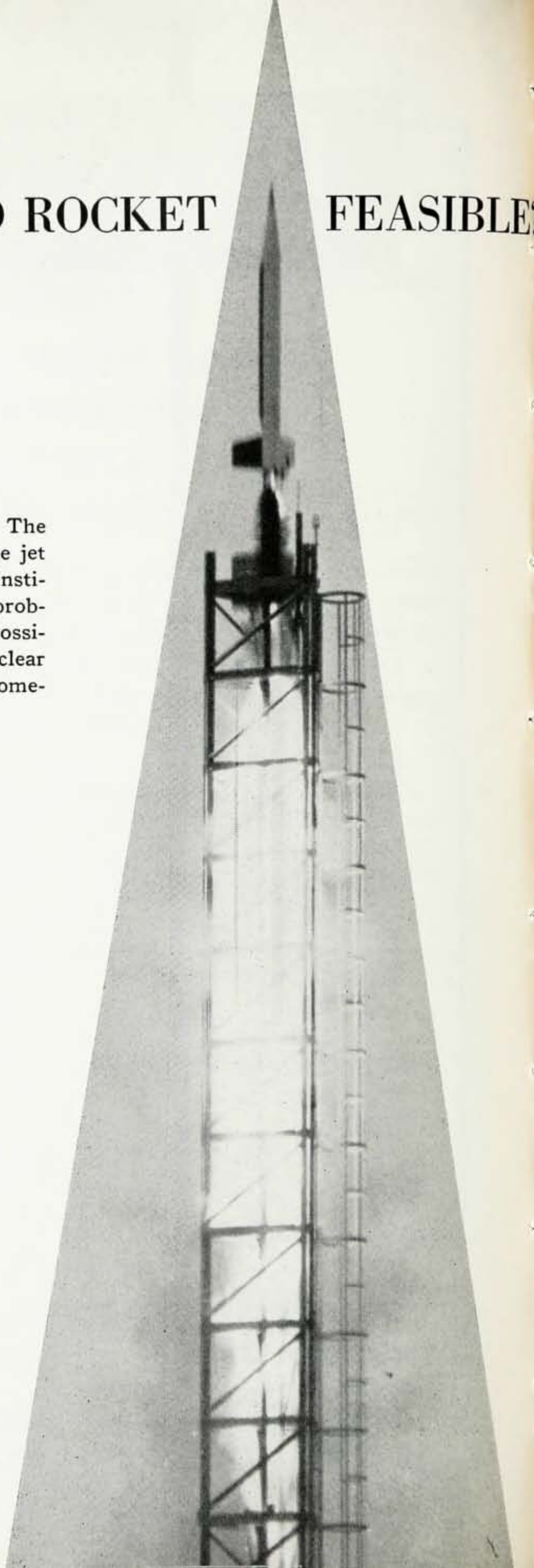
THE NUCLEAR-POWERED ROCKET FEASIBLE

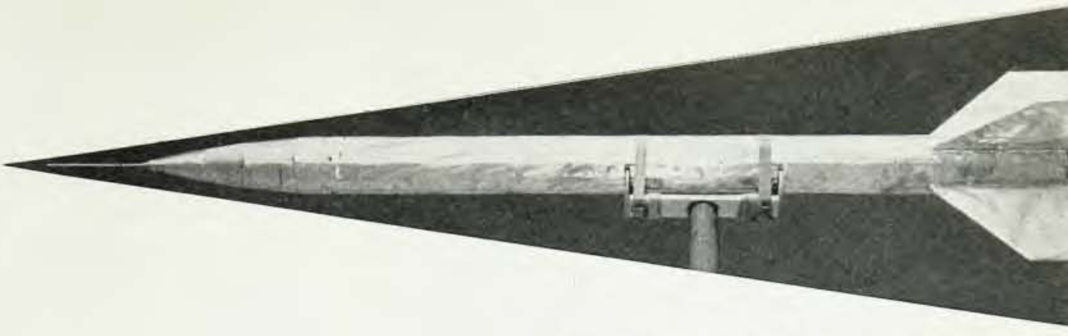
Space ships are not around the corner. The chief of the applied physics division of the jet propulsion laboratory at the California Institute of Technology treats here current problems in conventional rocketry and the possibilities of powering rockets with nuclear energy. The conclusions, he finds, are somewhat "melancholy."

by ***H. S. Seifert***



WAC-CORPORAL rocket emerging from launching tower.

All the photographs in this article were taken by George Emmerson of the Jet Propulsion Laboratory, California Institute of Technology.



Mock-up of sounding rocket, covered with copper foil, and mounted on pole for antenna pattern tests.

It seems but natural for physicists to ponder on the dramatic possibilities of using nuclear power to operate a rocket propulsion plant. It is possible, without trespassing on classified information in any way, to reach some interesting and perhaps melancholy conclusions, merely by the use of elementary and well-disseminated ideas.

In medieval times, the Chinese made crude "fire-arrows" (circa 1232); Italian books have been found, dated 1400, containing sketches of rockets. The nineteenth century opened with the siege of Cologne, successfully prosecuted by the British in 1807 with rockets developed by Sir William Congreve. After 1900 the Russian, K. Ziolkowsky, wrote a rather complete mathematical analysis of the problems of space travel, and the German, H. Oberth, attempted both analysis and experiment with rocket projectiles.

The pioneers of the twentieth century were Eugen Sanger in Germany and the late Robert Goddard (a professor of physics) in the United States. Both these men did successful experimental and analytical work and served their governments during World War II. But during much of the second quarter of this century rocket experimentation was in the hands of visionaries, crack-pots, lone frustrated inventors, and small bands of zealots such as the American Rocket Society, the British Interplanetary Society, and the Verein für Raumschiffahrt. Among professional engineers rocketry was considered scarcely reputable.

However, with the advent of World War II, the study of liquid rockets, stimulated by the need for guided missiles, has burgeoned into a full-scale research with status on a par, for example, with radar. Solid propellant weapon rocket investigations enjoyed similar prosperity, but the detailed history of this effort is too long to be included here. Two of the leading figures of this period in liquid propellant rocket research were Werner Von Braun, who supervised the German rocket work at Peenemunde, and F. J. Malina, who directed the Jet Propulsion Laboratory of the California Institute of Technology. Today, in the field of jet propulsion and rockets, there are texts written, courses offered, fundamental problems pursued, hardware built, and withal, a substantial increase in the national debt.

Some of the fruits of this large effort have been spectacular. The German V-2, using liquid oxygen and alcohol, was one of a series of missiles with intended ranges up to two thousand five hundred miles. The "Wasserfall" was a guided anti-aircraft missile using nitric acid which ignited spontaneously with a hydrocarbon fuel. The German ME-163 airplane consumed concentrated hydrogen peroxide as oxidizer. The fabulous "Natter" was a rocket interceptor plane which was launched *vertically* from a pole. After striking at its objective it disintegrated, leaving the pilot to return earthward by parachute. In the United States, the XS-1 rocket airplane has achieved supersonic speeds, and the WAC-Corporal sounding rocket carried aloft by a V-2 has risen two hundred and fifty miles! Indeed, the respectability of rocketry has grown to the point where a national pictorial weekly recently offered seriously a detailed four-page spread of a moon rocket. It must be admitted, however, that professional rocket engineers have many questions concerning this proposed space vehicle which they would like answered.

Problems Today

A fundamentally novel prime mover, such as the rocket, will give rise to many wholly new fields of

Howard S. Seifert, chief of the applied physics division of California Institute of Technology's Jet Propulsion Laboratory, has had seven years experience with jet propulsion problems. His main concern in rocket research has been with the developing of propellant-cooled motors and with heat transfer problems. The ideas expressed here (and more) have been stated more quantitatively in the series "The Physics of Rockets" which appeared in the American Journal of Physics in January, March, and May, 1947.

Looking into the throat of a V-2 motor and showing paper collars used to prevent incorrect oxygen impingement at start of flow.

technology, in a manner analogous to the creation of the present aeronautical sciences by the airplane. As usual, the number of new problems to be solved has far outrun the number of problems successfully completed. These problems may be classified into those relating to the propulsion power plant, and those relating to the vehicle in which this propulsor is applied.

Concerning rocket motors, one may ask the following important questions: How can a container be built to withstand heat flow rates exceeding those of any known thermal device, and simultaneously resist the erosive and corrosive effects of gases flowing at sonic and supersonic speeds? What are the mechanisms of high temperature, non-equilibrium combustion, and how are they affected by the manner of introducing the reactants into the combustion chamber? How rapidly do liquid streams atomize and vaporize, and how may the reaction between oxidizer and fuel be most rapidly initiated? What happens, exactly, at the surface of a burning solid propellant? What chemical substances provide maximum *momentum* release when burned in a rocket motor? Evidently much fundamental new knowledge is needed.

Turning attention to the vehicle, the following problems press for solution: What are the properties of the upper atmosphere through which the vehicle moves, especially its composition, density, and transparency to radiations? What are the aerodynamic laws of a medium so rarefied that the mean distance between molecules is comparable with the size of the vehicle, and to which the concept of a continuous fluid no longer applies? How can one build a rocket structure even lighter and stronger than conventional aircraft? Is it possible to guide a vehicle moving at thousands of feet per second so that it deviates from a desired direction less than a thousand feet in a thousand miles? What is the smallest number of pounds of electronic gear which suffices to communicate with and control a vehicle hundreds of miles away? And finally, a philosophical question which cannot be evaded—are these vehicles worth their enormous cost?

The foregoing remarks suffice to show the breadth of the difficulties involved in developing even a conventional chemical rocket, and should in some degree furnish an antidote for the popular conviction, promoted by such popular media as the comic cartoons, that space ships may all but be taken for granted. Let us now look at the physical essentials of the rocket, and endeavor to state some of the realities of the problem of supplying it with nuclear power.

Idiosyncrasies of Rocket Mechanics

We begin by noting that a rocket propels itself along by expending its substance, much as does the toy balloon which slips out of your hand while you are inflating it. One measure of the excellence of a rocket is the fraction of its avoirdupois which it can lose in flight. The less of it remaining after all the fuel has burned, the faster and farther this remnant will go. In this respect, there is a subtle difference between a rocket and other more common devices for producing a force, for example, an automobile engine. The automobile can carry its energy packaged in a small tank, and use it so efficiently that little weight is lost en route. The rocket, on the other hand, must jettison large quantities of matter merely to stay aloft.

It is momentum rather than energy which is important to a rocket. This means that a large amount of matter must be ejected every second by the rocket, and at the highest possible velocity, to produce the maximum thrust. Since the rocket wishes to "push" for as long as possible, the most favorable plan of operation is to ration its expenditure of mass and eject that mass with the maximum attainable speed. It can be shown, with a little algebra, that this process is entravagant of energy. Production of a given amount of momentum is achieved by a small mass moving with high velocity (as in the case of a bullet) at a much greater expense of energy than

by a large mass flow moving with low velocity (as in the case of a river). The principle can be illustrated conversely. If the same energy (i.e., powder charge) which in a rifle bullet produces a tolerable recoil impulse against your shoulder were used to propel a projectile as heavy as a brick, a broken shoulder would be probable.

Light Weight Important

A rocket must spend mass. It can do this most frugally if it has a wealth of energy to squander. For this reason, of course, nuclear energy, provided it be concentrated in a very small mass, can be important to the science of rocketry. It is even more necessary for a rocket than for an airplane to have the lightest possible weight. Consider the influence of payload on the range of a rocket. By payload factor is meant here the useful fraction of the initial weight left when the propellant is exhausted. With fifty percent payload factor, and using known propellants, it might be possible for the rocket to go fifty miles; with ten percent payload, the same rocket will go five hundred miles. This extremely rapid increase in range as dry weight decreases is characteristic of all rockets. Thus great attention must be paid to reduction of weight. A rocket with ten percent payload, for example, has the same ratio of liquid propellant weight to solid skin as has an egg to its shell. This eggshell fragility is of course the source of many problems, and further desirable reduction in payload factor (with a corresponding increase in range) will await fundamentally stronger materials of construction applied to new designs.

Propellant Limitations

In order that the rocket with fifty percent payload mentioned above be able to travel five hundred

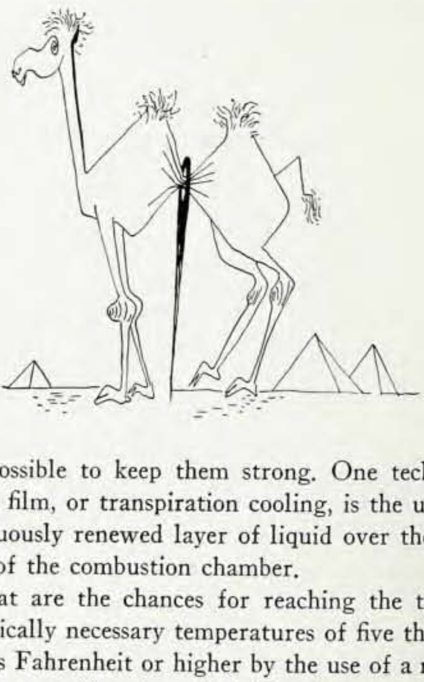
A V-2 just after take-off at White Sands Proving Grounds, New Mexico.
Courtesy American Journal of Physics.

miles instead of fifty miles, the energy imparted to its exhaust gases would need to be multiplied ten times. It can thus be seen that the creation of a truly economical rocket, able to carry a large payload for a long range, will depend upon the availability of a concentrated supply of energy. It is at this point that the value of a source giving vast quantities of energy with very little loss of weight becomes evident. Present rocket propellants have definite limitations. Most of them consist of various combinations of the four atoms: carbon, nitrogen, oxygen, and hydrogen. No matter how these atoms join hands or change partners, marry or divorce, they cannot achieve a frenzy great enough to eject themselves from a rocket nozzle with more than a certain limited ultimate speed. This speed is determined by their mutual potential energy and is of the order of seven thousand feet per second. This may seem to be an enormous velocity, but it is actually quite a commonplace one for heated gas molecules. In order to achieve these speeds, the four types of atoms mentioned above must, to begin with, be joined together into very disagreeable compounds which may be toxic, corrosive, or explosive, or a combination of all three. The prospects for greatly increasing the ultimate speed of exhaust are not bright, for even though one selects the most energetic combinations of atoms afforded by the ninety-two natural chemical elements—for example, hydrogen and fluorine—and allows these unpleasant substances to react in the most ingenious manner, not more than fifteen thousand feet per second is likely to be achieved.

A fundamental limitation on all rockets using chemical reactions is that the propellant is used both as a source of energy and as the mass or working fluid to be ejected in obtaining thrust. A suitable nuclear reactor would allow the power consumption and the working fluid mass flow rate to be independent of each other. The ultimate exhaust velocity would then at least not be limited by the chemical ceiling on energy per unit mass.

Rocket Temperatures

There is no furnace hotter than the combustion chamber of a rocket. This fact poses a difficult question to the rocket designer, whether he uses nuclear energy or ordinary chemical reaction energy. The temperature of the gases inside a rocket, although not so high as the sun's temperature, is still much higher than the melting point of the walls containing them. How, then, are these gases to be corralled, collimated, and guided through the exhaust nozzle without stampeding through the surrounding solid barrier? One might as well ask a snowman to swallow a cup of hot coffee. A great deal of ingenuity (and perspiration) has been devoted to schemes for keeping the hot gases confined to a pathway through the throat of the rocket nozzle, a task comparable in difficulty with passing a camel through a needle's eye. Fortunately it is not necessary for the melting temperature of the rocket walls to be above the temperature of the enclosed gases. By continually removing heat from the walls into a cooling fluid,



it is possible to keep them strong. One technique, named film, or transpiration cooling, is the use of a continuously renewed layer of liquid over the inner walls of the combustion chamber.

What are the chances for reaching the thermodynamically necessary temperatures of five thousand degrees Fahrenheit or higher by the use of a nuclear reactor or radioactive pile? Uranium metal melts somewhere below three thousand four hundred degrees Fahrenheit. Evidently extensive research will be needed to build a reactor capable of operating at elevated temperatures.

Nuclear Energy with a Working Fluid

If a reactor could be arranged whose materials were highly reflecting to the radiations and particles involved in the nuclear reaction, and the process so ordered that the locus of the release of heat energy was in the working fluid itself, it might then be

Loading WAC–CORPORAL sounding rocket into launching tower.

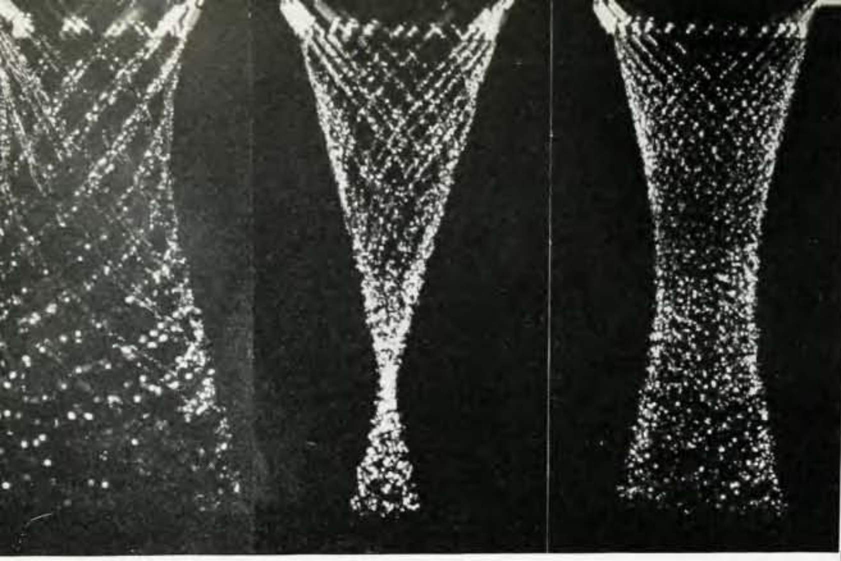
possible to reach adequately high temperatures in the fluid without melting its surrounding chamber. To operate a rocket of one thousand-pound thrust, a suitable reactor would have to supply fifty thousand horsepower or more for a period of many minutes.

Reactors for use at turbine temperatures have been proposed, but these are of course much lower than occur in a rocket. The problem of building structures to contain higher and higher temperatures is one of such difficulty that it may determine the practical limits of performance of nuclear propellants.

How may nuclear energy be used in a rocket to increase the velocity of the ejected gases? Two schemes come to mind at once. In the first and more obvious one a modified radioactive pile, which itself does not lose weight appreciably, is used as a boiler in which a working fluid is heated and then allowed to expand and escape through a nozzle in the usual way. In the second and much more speculative system, the nuclear reactions themselves might be so controlled that particles, or radiation, or both would be ejected in a preferred direction, without an intermediate thermal process. Pending the ultimate dissemination of more information, one can only conjecture about the actual embodiments of nuclear processes into jet propulsion devices.

In spite of our ignorance where nuclear engineering is concerned, certain conclusions may be drawn about the boiler process mentioned above. They are the following: a working fluid must be expended; second, the laws of thermodynamics require that for efficient production of momentum in this fluid it must be heated to very high temperatures, the higher the better; and third, the complete rocket must weigh less than the thrust it can produce, i.e., it must be able to lift itself. Existing chemical sources of energy can produce temperatures of five thousand degrees Fahrenheit in a gas

Rockets which stray among the peaks of the 7000-ft. Organ Mountains, seen from White Sands Proving Ground, are difficult to recover. The photograph at the right shows instruments in nose of rocket lowered by parachute.



Small scale rocket flame us
to study spacing of lumino
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Studies of a rotating jet of fluid showing droplet paths.

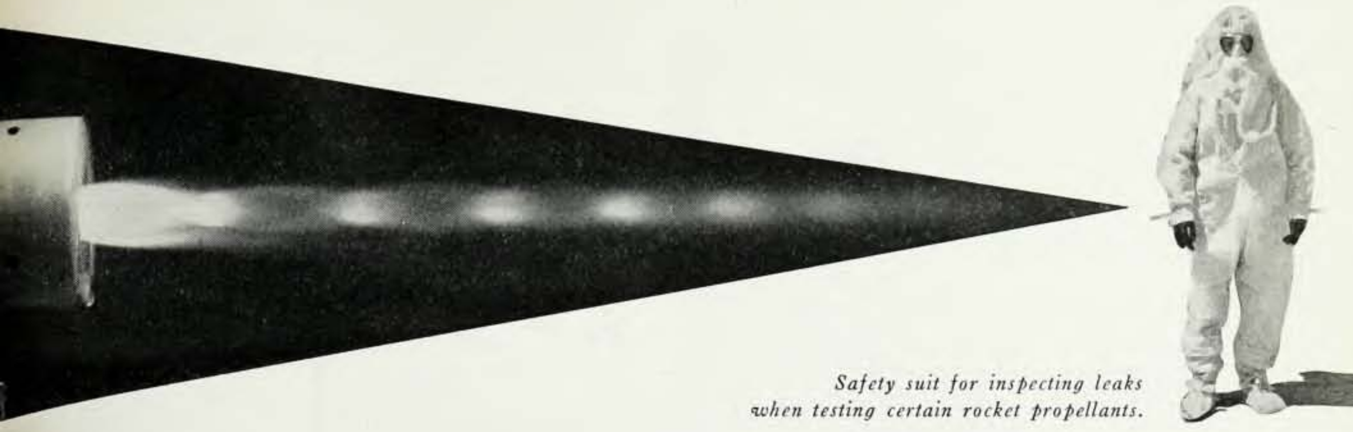
Water test showing manner in which fuel and oxidizer impinge in a liquid propellant rocket.

whose molecules weigh about twenty-four times as much as hydrogen atoms do. In order to improve on this situation, a new source of energy would have to produce the same or higher temperatures in molecules no heavier than twenty-four times the hydrogen atom. The reason for this emphasis on molecular weight is the following: The energy equipartition law of the kinetic theory of gases requires that a pound of light molecules contain much more kinetic energy than a pound of heavy molecules at the same temperature. One consequence of this is that light molecules are able to contribute more momentum and hence thrust per pound when allowed to expand through a rocket nozzle, than are heavy molecules, assuming that both species are at the same initial temperature. Thus a working fluid of the lowest possible molecular weight is desirable, however contrary this may seem to intuition.

Let us consider the scheme most feasible for immediate development. Assuming that a nuclear energy source could be built to operate at temperatures of five thousand degrees Fahrenheit and that one used the lightest and most favorable working fluid—liquid hydrogen—the momentum supplied to the rocket per pound of hydrogen expended would even so be only about four times that of a good chemical propellant. One would have to contend with the difficulty of keeping the hydrogen liquid; it boils at about minus four hundred and twenty-two degrees Fahrenheit, only thirty-eight degrees Fahrenheit above absolute zero, and is a very evanescent liquid. Added to this is the fact that liquid hydrogen has a very low density; a pound of it fills a two gallon container. This increases the difficulty of building a light rocket by imposing the requirement of very large tanks. The weight of the reactor must be added to that of the working fluid, thus increasing the dead load and decreasing the range.

The weight of the pile or energy source is difficult to estimate. One criterion must inevitably be satisfied by the rocket energy source. It must weigh substantially less than the thrust it can produce, preferably less than one-fourth of this amount; otherwise it will never rise from the ground. Thus in a rocket of reasonable size—say, a German V-2 with twenty-five ton thrust—the energy source, which must produce two million horsepower, should not weigh more than six tons.

On the other hand, a nuclear chain reaction will not sustain itself unless at least a certain critical minimum quantity of fissionable material is brought together in a specific geometrical configuration. In the absence of proof to the contrary, there is no



Safety suit for inspecting leaks when testing certain rocket propellants.

a priori reason for believing that an energy source of the proper weight is impossible. There is, however, room for doubt whether the first nuclear rocket built on the boiler principle will be much of an improvement over its chemical predecessors, although there is also hope that subsequent models may be much better.

Nuclear Energy Without a Working Fluid

An entertaining subject for speculation—and speculation only—is the possibility of a thrust-producing system in which the fissionable materials themselves might be expended in such a manner as to produce momentum in a specified direction, without the use of a separate working fluid. This process, while conceptually possible, has no more status at the moment than that of a mere wishful hypothesis. The ultimate efficiency in producing momentum from a given amount of mass would be achieved by converting that mass entirely into unidirectional radiation. One gram of matter is the equivalent of nine hundred billion billion metric units of radiant energy. It is a familiar fact that radiation exerts pressure. For example, sunlight falling squarely on the wall of an average house exerts a total force of about one thousandth ounce, or the weight of a postage stamp. This is certainly not enough load to worry the architect designing the house. However, the radiation achieved by the complete annihilation of matter is inconceivably stronger than sunlight, and significant pressures result from it.

One might imagine a rocket, then, in which matter was completely converted to energy ("pure photon" propellant), and this energy flow directed out the rear of the rocket. The reaction of the radiation pressure against the solid matter from which it emanated would then propel the rocket. A propellant of this type would have a momentum-producing efficiency one hundred thousand times greater than the best chemical propellant. For instance one quarter pound of matter would yield a radiation thrust of two pounds for a period of almost one hundred hours before it was exhausted. A rocket propelled in vacuo by such a source could achieve a velocity one-tenth the velocity of light. It would be inadvisable for an observer to stray into the energy beam issuing from the rear of this rocket, since he would intercept several hundred million kilowatts—a death ray in the best comic cartoon tradition!

Specific questions about the actual details of this "photon" rocket would of course prove embarrassing, and it is not intended that the idea be taken too seriously. Also, the economics of any nuclear device which is subject to high probability of permanent loss are discouraging. Nevertheless, it is entirely appropriate to give some thought to the application of nuclear physics to rockets, even though decades may pass before a nuclear-powered rocket is successfully launched.

In summary one may say that the nuclear rocket seems to be one of the less practical applications of nuclear energy. Its problems are even more numerous and more stubborn than those of the nuclear electric power plant, nuclear ship, and similar bulky devices. This does not, of course, mean that they cannot be solved. It is entirely possible that the nuclear rocket will be the only device which can achieve certain objectives, and that the time may arrive when humanity will be willing to make the necessary effort to reach these difficult goals.