SPACE PROPULSION SYSTEMS
material from
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presented by
6- by 6-Foot Supersonic Wind-Tunnel Branch

Studies of various space missions now being contemplated, have shown that one of the major requirements of the space vehicle is a suitable propulsion system of sufficient power, high efficiency, and good reliability. During this presentation, we shall describe three types of rocket propulsion systems which are now being investigated at the Lewis Laboratory of the NACA and elsewhere. We shall discuss the characteristics of these three types of systems and show how each may be used for various space missions. We shall discuss the problems associated with each type, and the research work now underway to improve their characteristics.

On the first slide we show the three types of rocket propulsion systems under which the principal motors now being considered can be classified, that is, chemical, nuclear, and nuclear electric. As you know, the chemical rocket obtains its thrust by burning a mixture of fuel and oxidant and ejecting the resulting hot gas rearward through a nozzle. In contrast, a nuclear rocket obtains heat energy from a nuclear reactor which heats to a high temperature a propellant that is then ejected rearward through a nozzle. Lastly, the nuclear electric rocket uses energy from some source such as a nuclear reactor, converts this energy to electricity, and then uses the electrical forces to push small ionized particles rearward.

Irrespective of the type of rocket motor being considered, two characteristics are important, specific impulse and thrust to weight ratio. These characteristics are shown in the second and third columns. Specific impulse is defined as the ratio of pounds of thrust to pounds per second of propellant flow. Let me define the term again since it will be used frequently during the remainder of the talk. Specific impulse is the pounds of thrust we obtain from each pound of propellant used per second. It is a measure of the efficiency of the system to produce thrust. Its significance lies in the fact that it indicates the weight of propellant necessary to perform a given mission. You can readily see that if the fuel is very heavy in relation to its thrust-producing capabilities, that is, has a low specific impulse, the total weight of fuel and tank volume for the mission are going to be very large.

The close relationship between specific impulse and the size of the vehicle for a given mission, and the importance of having a high specific impulse is emphasized by these two rocket models on your left. To indicate the size of the vehicles represented by these models, we have here a model of a six-foot man. The models, to the same scale as this man, represent vehicles capable of delivering a 20,000-pound payload in orbit. This payload might be carried in these tanks shown in the cut-away portion of the model. The larger vehicle uses fuel which might be used on the present-day Thor or Atlas. The smaller vehicle uses an advanced fuel having roughly twice the specific impulse. The reduction in size is quite impressive. The larger vehicle would have an initial weight of 1,500,000 pounds and the smaller would have an initial weight of 500,000 pounds. The advantages and necessity of high specific impulse is therefore obvious.

The next column considers the ratio of the thrust of the engine to its weight. To assess the requirements for the performance characteristic we must consider two types of missions. First consider a vehicle operating in a strong gravitational field such as taking off from the surface of the earth. If the vehicle can supply no aerodynamic lift by using wings or the like, the rocket must lift the pay load, structure, fuel weight, and its own weight. Hence the thrust must be considerably greater than the engine weight. A high ratio of thrust to engine weight is therefore a necessity. Now, let us consider a second type of mission. Here the vehicle is operating in a satellite orbit or traveling from one planet to another. In effect, the vehicle is floating in space due to the combination of gravitational and centrifugal forces acting on it. The rocket motor does not have to support or lift the vehicle weight so that the thrust can be small. Then thrust-to-weight ratio is of secondary importance. It is only indicative of the time of powered flight, that is, the smaller the thrust-to-weight ratio, the longer the time of powered flight. Of course, if the time of powered flight is long, the rocket must use fuel very sparingly.

Knowing the significance of these two performance characteristics, let us see how our rocket motors compare. We see that the performance characteristics of these three types of propulsion systems differ widely and none has both desirable characteristics, that is, high specific impulse and high thrust-to-weight ratio. The chemical rocket is a propellant hog and so may be undesirable for performing many space missions. It has, however, the high thrust-to-weight characteristics required for take-off and landings, earth satellites, moon flights, and reaction controls for directional guidance. In contrast, the nuclear-electric rocket uses propellant very sparingly so is suitable for distant space flights to Venus, Mars and beyond. Because of its low thrust-to-weight ratio, however, it can not lift its own weight from the earth's surface so that a vehicle using this motor would have to start its journey from a satellite orbit. The nuclear rocket lies between the chemical and nuclear-electric rocket and appears capable of performing most types of missions. It will probably be used generally for flights to nearby planets commencing from an earth satellite orbit.

Let us now discuss in greater detail the characteristics of these motors and the problems associated with each type to indicate some of the research now underway in an effort to improve their performance. I would like to introduce Mr. ____________ who will discuss the chemical rocket.

As the previous speaker has said, the chemical rocket burns a mixture of fuel and oxidant and ejects the resulting hot gas rearward to obtain thrust. Let us examine some of the features of a liquid propellant rocket on this schematic diagram. Fuel and oxidizer from the tanks enter these centrifugal pumps which are powered by this gas turbine. The turbine is driven by high-pressure gas resulting from the combustion of small quantities of fuel and oxidant in this tank. The pumps raise the pressure and pump the propellants through control valves to the engine. The fuel from the upper pump is used as a coolant by circulating it through a jacket surrounding the combustion chamber and nozzle. It is then sprayed into the combustion chamber through this injector. Meanwhile the oxidant comes directly to the injector from the lower pump and is also sprayed into the chamber. Fuel and oxidant mix, burn, and the hot gases expand and accelerate through the nozzle to produce the thrust reaction.

We see that the chamical rocket is a relatively simple motor and can be made very light in weight. We thus have the favorable performance characteristic previously mentioned, that is, high thrust to engine weight. On the other hand we must supply both fuel and an oxidant to have combustion. The oxidant can be very heavy, so that the weight of fuel and oxidant to produce the required thrust can be very large. We thus have the undesirable characteristic of chemical rockets, low specific impulse.

Let us discuss some of the problems relating to chemical rockets. A typical problem in determining chemical rocket performance arising from the gas expansion process in the exit nozzle is shown by this slide. For the high energy combination of fluorine and hydrogen, we show theoretical values of specific impulse as a function of the percent of hydrogen weight to total propellant weight. The results are shown for a ratio of chamber pressure to exhaust pressure of 600 as used at high altitudes, and for two types of expansion in the nozzle, equilibrium and frozen. Let me digress to explain these terms. In the combustion process of hydrogen and fluorine, the gas temperature may be so high that the gas molecules break down and become atoms. If, as the gas cools in passing through the nozzle, these atoms re-combine just as if they had never been at the high temperature, we have equilibrium flow. However, if no re-combination occurs in the expansion process, we have frozen flow. Now frozen flow merely means no change in the type of gas particles as they expand through the nozzle. It has nothing to do with the temperature of the gas, which is at incandescent temperatures. Returning to the slide, it is seen that there can be large differences in the specific impulse depending upon whether the process is an equilibrium or a frozen expansion. Experimental research must be conducted, therefore, to determine which type of expansion exists and how it is affected by the fuel used. A further major advantage is at stake for the fluorine-hydrogen combination. To obtain the maximum specific impulse, we would like to operate near the top of the curve. If we have equilibrium expansion, we require only a small percentage of hydrogen. However, if frozen expansion exists, the percentage of hydrogen must be large. Now hydrogen is a very light weight fluid, so that large tanks are required to contain a given weight. The increase in hydrogen will therefore necessitate a large increase in the weight of the tanks containing it, thus reducing the attractiveness of hydrogen-fluorine as a fuel.

Another problem in liquid propellant rockets is the proper injection of the reactants into the combustion chamber to get smooth, efficient, combustion. You'll recall that this is the injector. The Lewis Laboratory is doing considerable research on this problem, some results of which are shown on the next slide. Here we show three types of injectors for a propellant combination where the fuel requires appreciable heat for vaporization and the reaction begins in the vapor phase. F is the fuel and O is the oxidant. We see that injection through straight holes to give parallel, separate, jets called Showerhead injection gives a relatively low performance. If the oxidant impinges against the injector, as here, or the fuel impinges against itself, as here, so that the separate jet streams fan out to form continuous sheets, a considerably higher performance is obtained. Similarly, a high performance is obtained when both fuel and oxidant impinge on each other as for the triplet injector. Fuels with different physical and chemical properties would respond differently. Thus the search proceeds for the injection method that is best from considerations of performance, cooling, weight, combustion stability, and ease of fabrication.

Many other problems are being investigated concerning chemical rockets. We would like to make the motor lighter. We would like to find new materials capable of withstanding the very hot temperature in the nozzle without the requirement of large cooling. We must find ways to store and handle the high energy fuel easily and safely.

The first speaker mentioned several rocket motors with which you may be unfamiliar, the nuclear and nuclear electric rockets. The next speaker, Mr. ___________ will discuss these newer types.

We have here a schematic cut-away of a nuclear rocket. This rocket differs from the chemical rocket in that the propellant does not supply the heat energy, but rather is heated by a reactor, as shown here. The reactor is composed of plates containing the fissioning material and moderators which slow down the neutrons generated in the fission process to speeds required by the chain reaction. A reflector indicated here minimizes the loss of neutrons from the reactor core. Shielding is provided here to reduce gamma and neutron radiation on the propellant in this tank and the crew housed as far away as the vehicle size would permit.

The propellant, in this case hydrogen, is stored in liquid form under pressure in this tank. It is forced through these passages and cools the nozzle shell, reactor internal shield, and reflector. The hydrogen is now a gas. It is heated to high temperature in passing through the fuel elements and expands through the nozzle.

It is obvious from this description that the weight of a nuclear rocket will be large due to the amount of shielding required. We thus obtain the moderate thrust-to-weight ratio mentioned by the first speaker.

On the other hand, the propellant we use is light, hydrogen, and we need no oxidizer for the combustion process. It is thus possible to obtain a good specific impulse.

One of the major problems in obtaining a high specific impulse is associated with the type of materials which can be used in the reactor. We must operate the reactor at the highest possible temperature to obtain high specific impulse as shown on the next slide. Here we show specific impulse as a function of propellant temperature using hydrogen as a propellant. A number of materials now being considered for nuclear rockets are located along the curve at these maximum safe operating temperatures. Beryllium and graphite are moderating materials. The remaining materials are typical of those used for fuel elements and internal structure.

Beryllium is a much better moderator than graphite and so its use would result in a much lighter reactor. However, if the reactor temperature were limited to the low operating temperature of beryllium, the resulting specific impulse would be only slightly better than the best chemical rockets. If we wish to increase the operating temperature of the reactor so as to improve the specific impulse, it will be necessary either to cool the beryllium moderator or use a moderator material which can operate at higher temperatures. Of course in such cases, the fuel element must be constructed of materials which can operate at these higher temperatures also, as for example tungsten-base alloys or carbides rather than the nickel-base alloys.

There are, of course, many other problems to be solved before we can achieve a satisfactory nuclear rocket propulsion system. They are, for example, the effect of propellant dissociation on nozzle design, selection of materials and designs to minimize weight, particularly shielding weight, and the establishing of reliability. Intensive research is required to find solutions to such problems.

In contrast to the chemical and nuclear rockets which impart velocity to their propellants by converting thermal energy to kinetic energy, electric propulsion systems accelerate the propellant by means of electrostatic or electromagnetic forces. There are several types of mechanisms now being proposed which used electrical forces to obtain thrust. We are going to demonstrate a simplified working model of one type and therefore will concentrate on the description of this type. Almost all types have the same problems, however.

The next slide is a schematic diagram of our model. It is called a plasma accelerator because the material being ejected rearward to produce the thrust is a mixture of electrons and ions, called plasma. The model has two parallel electrodes which are oriented with their plane at right angles to this magnetic field generated by permanent magnets in this case. Current from a high voltage DC power supply is discharged across the electrodes at this end. Current continues to flow through the plasma of the arc as the plasma is accelerated by the same type of electromagnetic force as acts on an armature wire in an electric motor. In our model the plasma consists of air molecules in the partial vacuum in which it is operating. In actual practice, the electrodes will supply the plasma material, or a separate propellant could be used by feeding it through this tube. On our model we have an indicator attached to this target which will deflect when the ejected plasma jet strikes it. I shall now demonstrate the model.

Here you see the arc strike, the plasma travels along the magnet and strikes the target. The indicator then moves. I shall demonstrate the model again.

Although this model is a relatively crude example of the plasma accelerator for use in a space ship, it illustrates several of the primary problems associated with this type of rocket. For one, the motor will be extremely heavy in comparison to its low thrust. Secondly, tremendous amounts of energy are required so that a fission reactor or solar radiation must be used. We have already seen that the fission reactor is heavy. Also the equipment to convert this thermal energy into electrical energy must be light weight and thus considerably more advanced than anything in use today. Lastly, large amounts of cooling will be required for the magnetic field, electrodes, and energy source, a further item of weight. With such problems as these, it is no wonder that the thrust-to-weight ratio of this motor is very poor. The ejected plasma is light, however, and is accelerated to extreme velocities as much as 200,000 miles per hour. We then have the desirable characteristic mentioned by the first speaker, that is high specific impulse.

In conclusion, we have seen the need for high specific impulse and the advantages of small engine weight for propulsion systems to be used on space missions. None of the three types of propulsion systems has both desirable characteristics, that is, high specific impulse and high thrust-to-weight ratio. In fact, our present knowledge seems to indicate that high specific impulse goes hand in hand with low thrust-to-weight ratio and vice versa. Only through intensive research can this situation be improved.

This concludes our presentation discussing some aspects of space propulsion systems. Will you kindly follow your guide out through the door at the far corner of the room.

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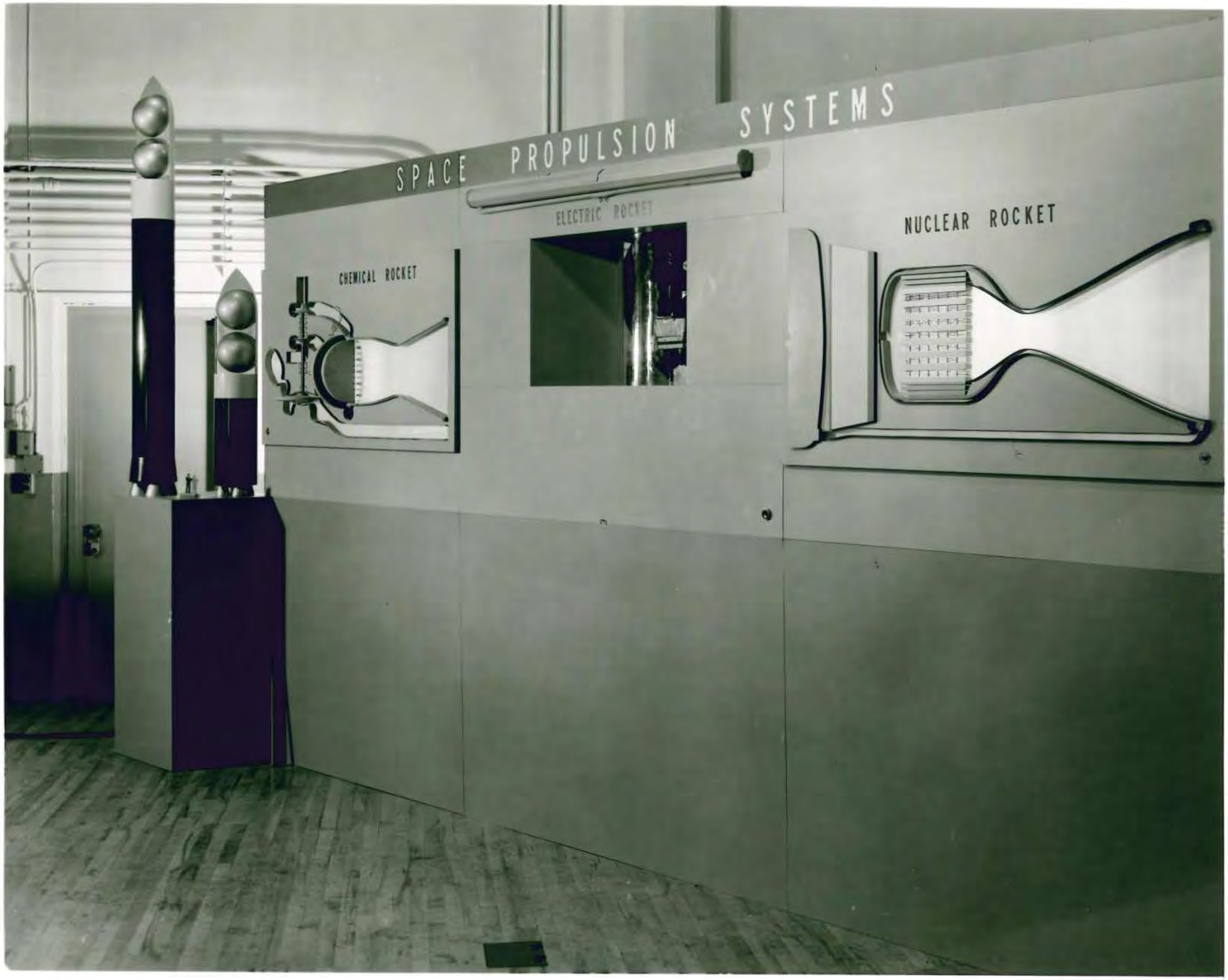

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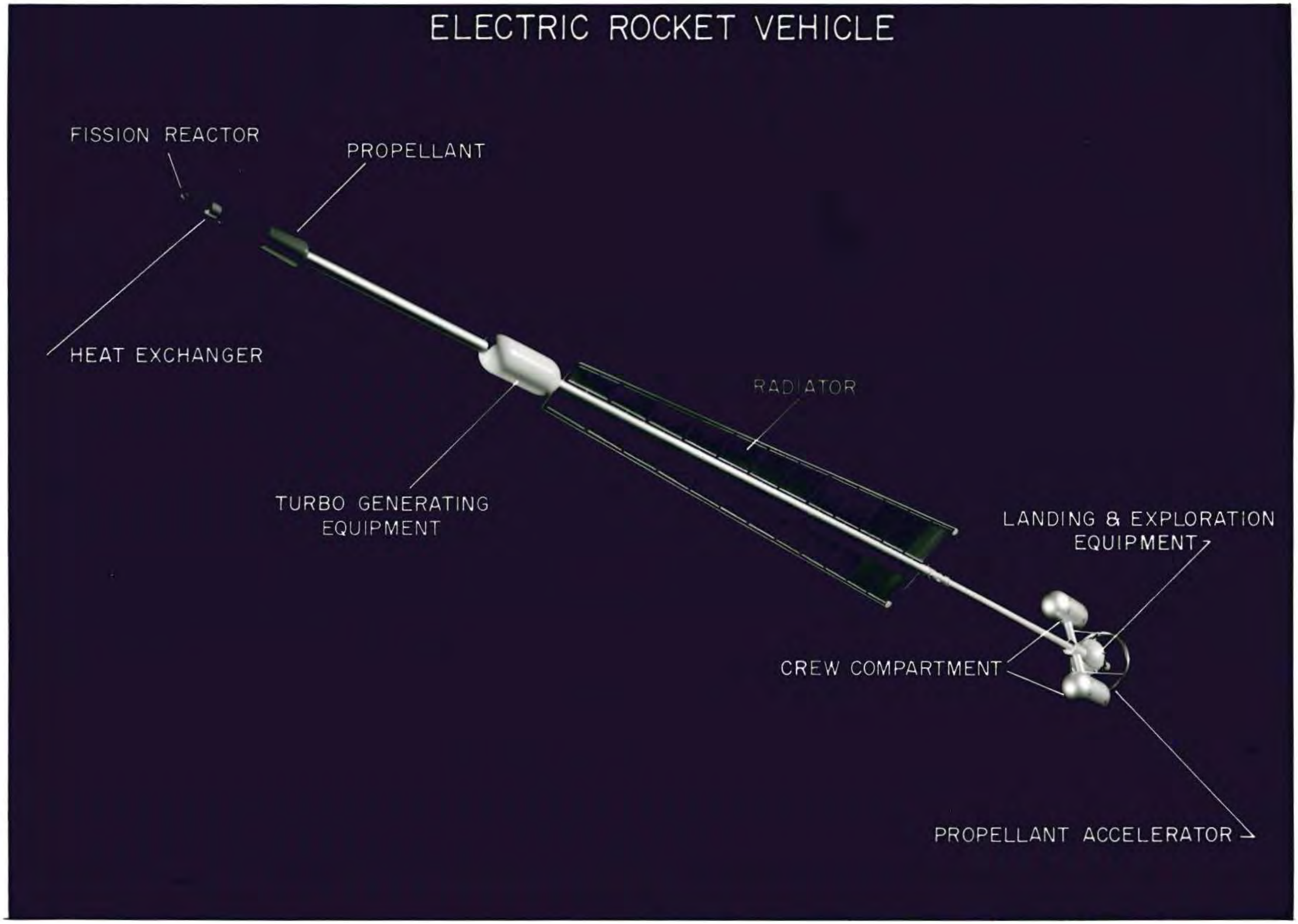

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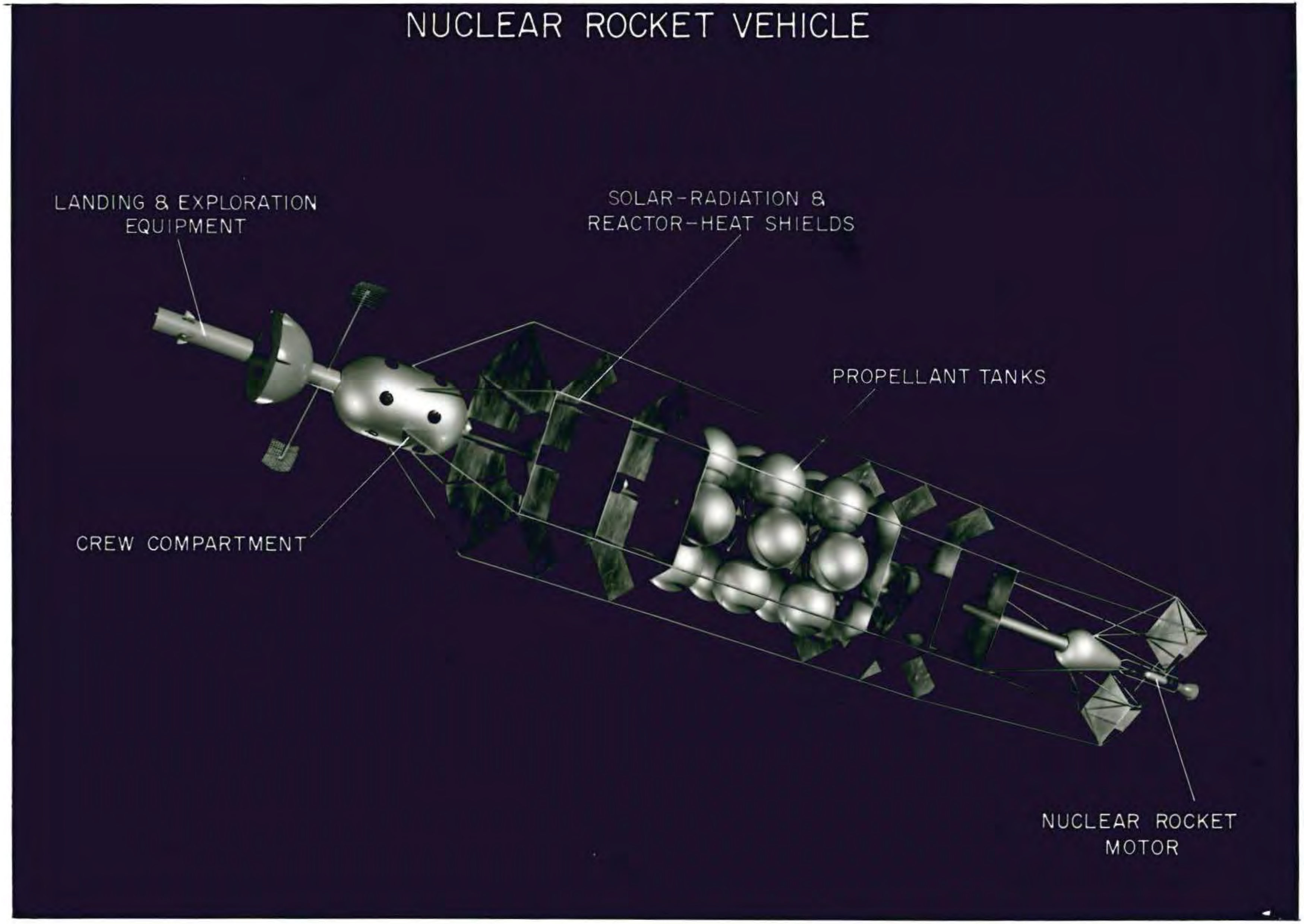

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