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Aircraft Nuclear Propulsion*

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(1) INTRODUCTION

A DISCUSSION OF THE INTERESTING SUBJECT of propulsion of aircraft by nuclear power is unfortunately considerably restricted by Security. My task in making this talk is, therefore, not an easy one, and if I omit to say exactly how some of the interesting problems that I shall tell you about may be solved, it will be understood that this is unwise at present. There is, of course, the chance that in following this line I shall be credited with knowing the answers to many more problems than actually have been solved, and I hope that, should you later discover that we who are working in this field have made more or less progress than you assume from my present remarks, you will not feel that I have intentionally misled you.

"In spite of the restrictions placed upon our discussion, we can discuss in fairly free fashion the principles underlying nuclear powered flight, some possible methods of achieving it, and some problems that are involved. Before starting this discussion, however, we should pause a moment to answer the question, 'Why do we want to fly an aircraft on nuclear power?'

"Many years ago, Breguet set down the formula that bears his name and which states that the range of an aircraft is proportional to its lift-to-drag ratio, to the efficiency with which its propulsive system works, and inversely proportional to the weight of fuel consumed per unit of work delivered to the propulsive system. Any decrease in the specific fuel consumption obviously leads to increased range. Because of the ingenuity of the designers of aircraft and engines, the Breguet formula is scarcely of more than academic interest in these days. Devices such as accomplishing most of a flight slowly and using high speed only at critical times, refueling in flight, and discarding not only the fuel tanks but also the lifting surfaces that support them as soon as they are empty—all have been seriously proposed or practiced and operate greatly to increase the range of modern aircraft. However, it is no deprecation of our heavy bombers, which are the best in the world, to say that even more range would be desirable, particularly if it can be coupled with high speed. This is the point at which the nuclear-propelled airplane comes into the picture. One pound of uranium-235 will liberate heat on undergoing fission equivalent to the energy liberated by burning 1,700,000 lbs. of gasoline. It is at once evident that, if a means can be found for converting the energy of nuclear fission into thrust, aircraft can fly for very long times on very small amounts of fuel. Indeed, fuel consumption would be measured not in thousands of pounds per hour, but in pounds per day. Because of the enormous amounts of energy available from a small amount of fuel, highly efficient utilization of this energy would no longer be crucially important. Thus, specific fuel consumption could be allowed to worsen somewhat if this were desirable in order to make some other feature of the power plant easier or better.

"Although the basic superiority of nuclear fuel over chemical fuel is thus superficially stated as a simple ratio of 1.7 million to 1, the implications and complications of this fact are extremely varied and far reaching. For example, some of the implications may be listed. A nuclear aircraft could encircle the globe many times without stopping, although this particular maneuver would be more dramatic than useful. It could fly entirely around the world at local midnight, accomplishing the entire circuit in darkness and with the lower vulnerability that night flying confers. Careful husbanding of fuel, programing of flight speed and altitude, and closely timed flight plans would become unnecessary in a nuclear-powered airplane. Such an airplane could fly at its maximum speed and at any altitude over its operating range for all or any part of its mission and still be perfectly sure of having enough fuel to return to its home base by any route whatever. A nuclear-powered aircraft could possibly stay aloft for many days. It would be limited only by the freedom

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of the aircraft and power plant from breakdown and by the ability of the crew to endure long hours of flight and exposure to nuclear radiation. It is clear that many missions that are impossible for chemical aircraft would be possible with nuclear-powered aircraft.

(2) PRINCIPLES AND SUGGESTED METHODS

"One of the basic principles of nuclear energy is that the energy of fission is manifested as heat. That is, a nuclear reactor is primarily a source of heat that must be converted into thrust or into mechanical work in more or less conventional ways. Hence, in any nuclear power plant, whether it is for an aircraft, a naval vessel, or for the generation of electricity on the ground, there will be a reactor and heat machinery. In the aircraft, the heat machinery is the propulsion system. Secondarily, and somewhat unpleasantly, the reactor is a source of radioactivity; hence, there will also be a shield of some type or other.

Propulsion Machinery

"There is scarcely a single type of aircraft propulsion machinery which has not been proposed for incorporation in a nuclear power plant for aircraft. One (1) obvious proposal is that propellers be used, driven by turbines that are in turn run by expanding through them vapor such as steam, heated in the reactor or air heated in the reactor. A variation of this scheme would (2) be to extract the heat from the reactor by some liquid coolant rather than vapor or air and transfer it to the vapor or air in an external heat exchanger or boiler. (3) Another fairly obvious proposal is that the reactor should directly or indirectly take the place of the combustion chambers of a conventional turbojet engine. Here again, the heat might be extracted from the reactor directly by the air or indirectly by other coolants, such as liquid metals, and transferred to the air outside the reactor. Ducted fans driven by turbines, operated in turn by vapor or air heated in the reactor, have been suggested. Obviously, the reactor might also take the place of the combustion apparatus in a ram-jet propulsion system. It has also been proposed that a compressor-jet type of propulsion system be used, with the compressor driven by vapor or hot air from the reactor and the heat supplied to the air by a heat exchanger through which the reactor coolant passes. In all cases, except that of the ram-jet and other direct air cycles, it is required that heat be transported in a recirculated coolant from the reactor to the propulsion machinery. In making a choice among the various types of propulsion machinery which have been suggested, the designer must perform detailed and careful analyses of many different possible combinations. Some of the problems that confront him are so obvious that they may be mentioned here. For example, if a propeller-type propulsion system is chosen, the hot fluid from the reactor must be piped to the turbines that drive the propellers; these in turn must be mounted on the wings. Thus, each propeller must be provided with its own reactor, or hot fluids must be piped around the airplane from a central reactor heat source. Any reactor coolant will undoubtedly become somewhat radioactive in passing through the reactor, and, hence, this alternative is not attractive. On the other hand, providing each propeller with its own reactor is not easy either, for two reasons. First, the weight of a reactor, with its shield, is extremely large; more than one reactor and shield therefore is highly undesirable from a weight standpoint. Second, two reactors per airplane would require more than twice the fuel investment of one reactor, and a low fuel investment per airplane is desirable, rather than a high one.

Reactor

"The design of the reactor will be greatly influenced by the coolant chosen. However, the basic principle upon which the reactor operates is the same regardless of the coolant. This principle is as follows: The reactor may be thought of as a more or less cylindrical body throughout which a fissionable material, such as uranium-235 or plutonium-239, is distributed. The reactor also contains passages for the flow of the coolant through it necessary for the removal of the heat and also usually contains a material that is called a *moderator*. The reaction starts with the capture of a neutron by a nucleus of, say, uranium-235. Since neutrons are present in small concentration in the atmosphere everywhere, this serves to start the reaction. Immediately after capture of the neutron, the U-235 nucleus disintegrates with the liberation of 2 to 3 neutrons and 2 atomic nuclei (fission fragments) both smaller than the original nucleus. Most of the energy of fission is carried off by the fission fragments; this energy is imparted to the material into which they are cast and appears as heat. Gamma rays and beta rays also are given off in the fission process.

"The 2 to 3 neutrons given off are ejected into the body of the reactor and may undergo one of three different fates. (1) They may escape from the reactor entirely and be captured outside it by some parasitic nucleus in the structure of the shield or its surroundings. (2) They may be captured by some of the nonfissionable materials in the reactor itself. (3) They may be captured in another U-235 nucleus, following which 2 to 3 additional neutrons will be given off. If we can design the reactor so that about 40 per cent of the neutrons given off in fission are captured in other fissionable nuclei in such a way as to cause fission there, the reaction will continue indefinitely until the fissionable nuclei are used up.

"The basic problem of reactor design is to reduce to acceptably low values the first two methods of loss of neutrons mentioned above—that is, leakage from, and parasitic capture in, the reactor. Leakage may be counteracted to some extent by surrounding the reactor with a neutron reflecting material that scatters but does not capture the neutrons. For example, graphite and beryllium oxide are known to be good reflectors.

Excessive capture of neutrons in nonfissioning nuclei in the reactor may be avoided by eliminating from the reactor atomic species that have a strong tendency to capture neutrons or, in the language of the nuclear physicist, have a high neutron capture cross section. Unfortunately, it is not always easy to do this because some of the materials that are most suitable for use as reactor structure, and without which the reactor will not support itself, have rather high capture cross sections. These are thus poisons for the nuclear chain reaction although essential for the mechanical stability of the reactor. Obviously, we may increase the fraction of the neutrons that are absorbed in U-235 or Pu-239 nuclei by increasing the proportion of U-235 or Pu-239 present in the reactor. Unfortunately, this increases the amount of fissionable material invested in the reactor, and, since fissionable material is extremely precious, it is desirable to keep its investment to a low value. We usually, therefore, resort to the device of introducing into the reactor a *moderator*. A *moderator* is an element of low atomic weight and low capture cross section for neutrons. Because of its low atomic weight, a neutron striking it loses a relatively large fraction of its energy in each such collision. Because of its low capture cross section, it does not capture many of the neutrons that strike it. After the neutrons are thus slowed down or moderated, their capture by the fissionable material in the reactor becomes much more probable since the cross section for capture of low energy neutrons is higher than that for high energy neutrons. Typical moderators are graphite, ordinary water, heavy water, beryllium, and beryllium oxide.

"The control of the chain reaction is, in principle, exceedingly simple. One of the most direct means of control is to arrange an absorbing rod so that it can be inserted into the reactor or withdrawn from it. If the rod is withdrawn from the reactor, it will absorb a smaller number of neutrons than before. If, in its original position, the rod was absorbing that number of neutrons which made the reactor just critical (that is, neither rising nor falling in power), then withdrawal of the rods will create a slight excess of neutrons in the reactor and the power will begin to increase. If, for example, we withdraw the rod so that the fraction of the neutrons absorbed in fission is 0.1 per cent greater than before, then the number of neutrons in the reactor will increase by 0.1 per cent in each neutron generation. Since the neutron generation time is extremely short, the reactor will build up fairly rapidly in power in an exponential manner. When it is desired to stop this build-up, all that is necessary is to insert the control rod to its original position. This will deprive the neutron cycle of its 0.1 per cent excess, and the power of the reactor will stay steady at the new level thus reached. Similarly, if it is desired to decrease the power of the reactor, inserting the rod more deeply than its original position will enable it to absorb more neutrons than before, and the chain reaction will gradually die. Other methods of control have been proposed also. For example, in a reactor which has a reflector, removal of part of the reflector will allow the leakage of more neutrons than before. This will decrease the reactivity and constitutes a method of control. Also, removal of part of the moderator or of some of the fuel itself from the reactor will decrease the reactivity, and these expedients may also be used as control mechanisms.

"It is evident that the control of the reactor is an important matter; not so much because of the very remote possibility that the reactor might turn itself into a low-grade atomic bomb, but because, if the power of the reactor fluctuates without a corresponding fluctuation in the heat removal capacity of the heat-transfer system, the reactor inevitably will heat up. Overheating, if sufficiently severe, can cause accelerated corrosion, warping, or even melting of parts of the reactor. Evidently, too, it is important that the reactor not be operated without a flow of coolant through it, since this certainly will result in serious damage if not destruction of the reactor.

Shield

"Although most of the energy of nuclear fission appears as kinetic energy of the two fission fragments mentioned above and this kinetic energy in turn appears as heat in the fuel elements, a substantial portion of the energy of a reactor appears as kinetic energy of the neutrons and as ionizing radiation, such as gamma rays and beta rays. The neutrons and gamma rays, if allowed to escape with complete freedom from the reactor, would make it necessary for human beings to stay at a distance of more than a mile from a high-powered reactor while in operation. Moreover, since the fission products themselves are radioactive and continue to emit gamma rays even after the chain reaction has been stopped, it would not be possible to approach the reactor much closer than this even after it had been shut down. It is clear that a *shield* must be provided.

"The basic requirements of the shield are dictated by the two basic types of radiation which it is desired to stop. The neutrons are slowed down most effectively by light atoms such as hydrogen and, moreover, are more easily captured after being slowed down. For this reason, an effective shield will contain light atoms such as hydrogen, which also is a good slow neutron absorber. Gamma rays, on the other hand, are degraded in energy and stopped best by heavy elements, such as lead. Hence, the shield normally will contain heavy elements also. It is clear that a mixture of light and heavy elements arranged in the most strategic fashion will be desired. The details of this arrangement are not particularly important for a large stationary reactor such as those that have been built on the ground in the past. However, for a reactor that is to be mobile, it is important that the shield weight and dimensions be kept small. Hence, the materials put into the shield must be the best possible and must be arranged in the best possible fashion. The detailed solution of this problem is extremely complicated.

"Another point of importance is that not only must the shield prevent escape of radiation from the reactor to the desired degree but also it must be capable of admitting and emitting the coolant that carries the heat away from the reactor. This means that the ducts must pierce the shield, and we are then confronted with the problem of leakage of radiation through these ducts. Generally speaking, gamma rays and neutrons travel in straight lines. However, under certain conditions, they can be scattered or reflected around corners or curves. This confronts us with another difficult but interesting problem in the shield.

(3) Some Problems of Nuclear-Powered Aircraft

"It may be interesting to pose some difficult problems, in addition to those mentioned above, which confront the designer of a nuclear-powered aircraft.

Shield Weight

"The shield will be the heaviest single object aboard the aircraft. Early published estimates of shield weight placed the minimum shield at 50 to 100 tons, without any provisions for removal of heat. From this it is evident that a large aircraft will be required to carry a weight of this magnitude even though the aircraft need carry little or no chemical fuel. To a first approximation, one may balance off the weight of the shield against the weight of the fuel load that would be carried in a large modern aircraft, since the shield and the reactor that it contains essentially replace the fuel load. The fuel loads of modern aircraft range up to the neighborhood of 75 tons or more. If the early estimates of shield weight referred to above are anywhere near correct, it is evident that the weight of the shield plus the reactor is not grossly different than that of the fuel that can be carried in a large conventional aircraft. However, every effort must be made to keep down the weight of the shield and the reactor. One obvious way to do this is to make the reactor small so that the shielded volume is kept small. This in turn restricts the amount of cross-sectional free flow area through which the coolant may pass through the reactor and increases the pressure drop. Moreover, as the reactor diameter decreases, it usually is found that more fissionable material is required. This is undesirable. There is therefore a balance to be struck between the benefits of small shield weights resulting from decreased reactor size on the one hand and the disadvantages resulting therefrom in smaller free flow area for coolant flow and larger fissionable material investment required.

Balance and Structure

"The existence of a larger concentrated weight, such as the shield and the reactor at one point in an aircraft, makes it necessary to redesign the structure of the aircraft to accommodate this weight. Although large aircraft are designed for very large gross weights, this weight is usually distributed over the wing and throughout the fuselage. Concentrating the weight in the fuselage greatly increases wing bending moments and necessitates structural redesign in many cases.

Large Landing Weight

"The very fact that only a small amount of the fuel is consumed in flight means that the gross weight of a nuclear aircraft will be approximately the same on landing as on take-off. This gives rise to a possibly serious set of new problems. First the landing gear must be made strong enough to take the higher gross landing weight. Second, the landing speed is increased, and there may be a change in landing attitude which possibly could require changes in the landing gear or in tail clearance angle requirements.

Heat Transfer

"The very essence of a nuclear power plant is the transfer of heat from the reactor to the propulsion machinery. The requirements for small size and high-power density placed upon the aircraft reactor push the heat-transfer designer to the limit of his knowledge. He must avoid hot spots in the flow system, he must have good flow distribution, and he must know exactly how the power is distributed in the reactor so that he can supply the right amount of coolant to each part of it. Solution of these problems requires a great deal of detailed analysis and experiment. For example, consider the cooling of a surface beneath which nuclear fuel is located in a reactor. The rate of heat generation is independent of the local temperature; thus, if the surface be deprived of its coolant, it will at once rise in temperature until it melts or disintegrates. The reactor is like a heat exchanger to which heat is constantly supplied whether it is taken away or not; only by maintaining the flow of coolant can trouble be avoided. Reactors in which the fuel is in solution in the coolant have been suggested for avoiding such problems.

Fissionable Material Investment

"The desirability of keeping the quantity of fissionable material in the reactor small has been mentioned previously. It is obvious that this is desirable. However, the chain reaction will go in the reactor only so long as there is present a certain minimum quantity of fissionable material called the *critical mass.* As soon as the reaction has consumed so much fissionable material that the mass drops very slightly below the critical mass, the chain reaction dies and cannot be started again without adding more fissionable material. Moreover, the products of fission remain in place in the fuel elements and eventually must be removed. This makes it necessary to remove the remaining fuel from the reactor, purify it, and prepare it for reuse. The amount of uranium which may be tied up in the reprocessing activities may easily exceed that which is tied up in the reactor proper. Thus, the uranium investment is not simply the amount of uranium carried aboard the aircraft but also that which is on the ground in various stages of preparation for use. The question of recovery and reprocessing of the fissionable material is a matter for the chemist and chemical engineer and is a whole new subject on which I shall not touch further here.

Radiation Damage

"Internuclear collision between neutrons and the nuclei of materials used as structures or as moderators in the reactor or between fission fragments and other nuclei results in dislocation of the nuclei with which collision occurs. While it is not definitely known how great an effect these dislocations have, it is known that the properties of the materials in which they have occurred undergo a change. Usually this change is in a detrimental direction. For example, a decrease in thermal conductivity may occur, thus making the heat removal problem even harder. Or, other equally critical properties may deteriorate.

"Some liquids or gases that might be proposed as reactor coolants are decomposed by radiation and are, hence, not usable. Organic compounds are particularly susceptible, and, even outside the zone of most intense radiation in the reactor, ordinary lubricants turn tarry or even solidify. Lubricated machinery hence may not be used in such locations. Electrical insulation, on prolonged exposure to radiation, breaks down and disintegrates or loses its effectiveness.

"There is here a large field of investigation, particularly in the physics of solids, where much work must be done in order to elucidate the effects of radiation damage, as this phenomenon is called, on the materials that might be used in an aircraft reactor or in radiation-exposed locations in the shield.

Escape of Radioactivity

"It is evidently necessary to confine substantially all the radioactivity of the reactor within it. This imposes on the designer of the reactor another restriction. It is occasionally suggested that a nuclear aircraft will create a hazard to population in its vicinity. Inasmuch as the aircraft itself will carry a crew which must be protected adequately, persons at a distance will not be affected in any way.

Materials

"One of the most important problems in reactor technology today is the finding and development of materials adequate for use in reactors that are proposed for production of power in one form or another. The combined effects of high temperature, corrosion by various coolants, radiation damage, thermal stresses, and mechanical stresses can be extremely serious in some cases. The aircraft reactor presents these problems to an unusual and critical degree. For example, a difference of 100°F. in permissible maximum reactor temperature can easily produce a significant difference in thrust output of the power plant. High-temperature materials are therefore a prime necessity. A corrosion-resistant coating on the reactor heat-transfer surfaces a few thousandths of an inch thick may double the critical mass. A brazing alloy containing a few per cent boron (a strong neutron absorber) may put so much boron into the reactor that it cannot be made to go critical, and this particular alloy may therefore be entirely unusable. An alloy high in nickel may have good corrosion and high-temperature strength properties for use as reactor structure but be so strong a neutron absorber as to be substituted by another alloy of lower nickel content and poorer corrosion and strength properties. The finding of materials adequate to withstand these conditions is a challenge worthy of the best metallurgist, ceramist, or chemist.

(4) Outlook

"In many respects, the propulsion of aircraft is an ideal use for nuclear energy. Here, to a higher extent than in any other application, the advantages of a highly concentrated source of heat can be used to good result. Although the goal of producing a nuclear-powered aircraft is an admittedly ambitious one, it is only such high-performance, premium uses of energy which can today justify the consumption of as rare a resource as uranium-235 or plutonium-239. Moreover, it is inescapable that a development of this type has great military significance.

"In recent months, the Government has announced that the nuclear aircraft program is entering a new phase. In this new phase, the Aircraft Gas Turbine Department of the General Electric Company has been given the responsibility for the propulsion system, and the Consolidated Vultee Aircraft Corporation is to supply an air frame.

"My belief is that our efforts to fly an aircraft on nuclear power will be successful. The difficulty of the task and the value of the result combine to form a challenge that is, in my opinion, unmatched."