Status of the Nuclear Powered Airplane

FRANK E. ROM*
NASA Lewis Research Center, Cleveland, Ohio

NASA has been carrying out a low-level effort to determine and solve the problems facing practical, safe and economical nuclear aircraft. The key problem is safety. The prevention of fission product release after a major accident on land is difficult. Studies indicate in principle that fission products can be contained; however, much work needs to be done to demonstrate the proposed techniques. Over-water flight minimizes the safety problem. This suggests the possibility of restricting early nuclear aircraft for over-water flights to gain experience and confidence. The use of thermal reactors appears to simplify the problem of containment because they make possible the avoidance of nuclear excursions in accidents by minimizing the fuel inventory. Low fuel inventory and the desirability of long reactor life requires reactor fuel with very high burnup capability. A fuel concept exists that has promise for meeting this requirement. Nuclear aircraft must weigh more than one million pounds in order that payloads of 15% of the gross weight or greater can be carried.

Introduction

IN theory, an ideal use for nuclear energy is to power aircraft. The airplane is a high-speed long-distance transportation system, but its range is limited even though it carries more fuel in terms of fraction of the gross weight than other vehicles. The fuel load is typically the major fraction of the vehicle weight. An airplane that could fly any distance on the globe without refueling would be a very important national asset. It would constitute a basic new capability that could find many applications.

If there is a chance that nuclear aircraft would be practical, they are worth investigating. We believe that there is a reasonable chance that such a potential exists. Studies[1,2] have shown that it may be possible to make nuclear aircraft safe and practical as long as the gross weight is higher than one million pounds. The high gross weights permit the use of complete shielding and the incorporation of safety provisions that could prevent the release of fission products even in the worst aircraft accidents. Therefore, a limited advanced technology effort is being carried out to evaluate the potential for a practical, safe and economical nuclear aircraft.

The objective of our study is to determine the major obstacles to practical, safe, and economical nuclear powerplants for aircraft and also to perform limited analytical and experimental efforts to assess the possibility of overcoming the major obstacles. This paper presents the highlights of our study to present concisely as possible, a general idea of the status and conclusions reached at this time.

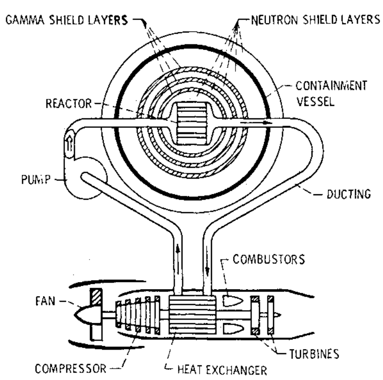


Fig. 1 Schematic drawing of a nuclear aircraft power plant.

Received May 19, 1969; revision received November 24, 1969.
* Branch Chief. Associate Fellow AIAA.

Description of Nuclear Aircraft Powerplants

The basic concept of a nuclear powerplant for aircraft use is shown in Fig. 1. The reactor is the source of heat energy. This heat can be picked up in a good heat-transfer fluid such as high-pressure helium or liquid metal. The heat-transfer fluid is pumped through a heat exchanger that heats the air flowing through a conventional turbofan engine. This heat exchanger is placed immediately in front of the normal combustor for the engine. The engine can then run either on conventional fuel or nuclear energy or both.

Shielding is provided so that the dose levels are reduced to that permitted for continuous exposure of the general population. Shielding against gamma radiation is provided by several layers of heavy metal material like tungsten, lead, or depleted uranium. Shielding against neutrons is provided by layers of hydrogen bearing materials that alternate with the gamma shielding layers. Water is used in our studies. Chemical fuel, other organic materials, or metallic hydrides can also be used if there is an advantage to doing so. A containment vessel is provided that is designed to prevent the release of fission products in the event of accidents. This feature was not considered in previous work on nuclear aircraft powerplants.

Typical weights of nuclear powerplants as a function of aircraft gross weight is presented in Fig. 2. The weights shown are those estimated for flight at 36,890 ft at a flight Mach number of 0.8. The weight of the shield is singled out since it is the largest single component. The important point to note is that the shield weight does not vary directly with the gross weight. This means that as the aircraft becomes larger, the shield weight becomes a smaller fraction of the gross weight. The payload fraction would, therefore, be expected to increase with increasing gross weight.

Requirements for Practical, Safe Nuclear Aircraft

To be practical, safe, and publicly acceptable, a nuclear aircraft must meet the following requirements:

1) It must have a unit shield, that is a shield that reduces dose levels to allowable values in all 4π directions around the reactor. This allows complete freedom of movement of flight crew, passengers, and ground crew in and around the aircraft in flight or on the ground without exceeding normally acceptable radiation doses.

2) There must be no release of radioactivity in normal operations.

3) The possibility of release of radioactivity in any accident situations must be reduced well within tolerable levels as approved by the National Radiation Council.

4) Reactor refueling must be infrequent because of the relatively complex operation that will probably be required. A suggested time between refuelings might be 5000–10,000 hr which is about the time between major overhauls of current chemical aircraft powerplants.

5) It must have good performance. The payload fraction should be of the order of 15% of the gross weight or better at speeds and altitudes of interest.

6) The over-all cost of operation must be at least comparable to conventional chemical airplanes.

Shielding

Unit or 4π shielding should enclose the reactor to reduce the dose levels to allowable levels in all directions. The allowable dose level for general population is 0.25 mrem/hr. In our studies we design for this dose rate at 30 ft from the reactor centerline. At further distances from the reactor the dose rate is reduced approximately as the square of the distance. When the reactor is shut down, the dose levels will, of course, be very much lower. There is, therefore, no restriction to the movement within or outside the aircraft either when the aircraft is flying or when it is on the ground.

How much does this low-dose rate cost in terms of shield weight? The curves for shield weight in Ref. 2 were computed for a dose rate of 2.5 mrem/hr at a distance of 130 ft. The dose rate we desire is much lower, that is, 0.25 mrem/hr at 30 ft. The weight of the shield must be increased by 30 to 50% to make up for the difference in dose rates. For this study we have used 30%. The resultant shield weight for uranium-water shields is shown in Fig. 3. The shield weight increases at a rate less than the square root of the reactor power. For reactors in the power range of 200 to 400 Mw the shield weights vary from about 250,000 to 350,000 lb. These are typical of the powers and shield weights for aircraft in the range of gross weights from one to two million pounds. Shield weights are thus of the order of 15 to 25% of the gross weight for this gross weight range.

Shielding weight appears to be acceptable as long as aircraft gross weights are greater than one million pounds. Of course, reducing shield weight will allow increases in payload weight, and is worth working for. But, a more important point is that the necessity for shielding does not prevent the nuclear aircraft from being feasible, as long as it is large enough.

Prevention of Radioactive Release in Normal Operation

To be practical and publicly acceptable, nuclear aircraft in normal operation should not release or produce radioactivity in the atmosphere. This is a ground rule that we have adopted in our studies. The main consequence of this rule is that the heat-transfer fluid that removes the heat from the reactor must be in a closed circuit. This excludes the possibility of passing engine air directly through the reactor. Another consequence of this rule is that the radiation dose rates outside the shield must be low enough to prevent activation of any material that might be near the shield. This is, of course, automatically taken care of when a unit shield is provided as discussed in the previous section.

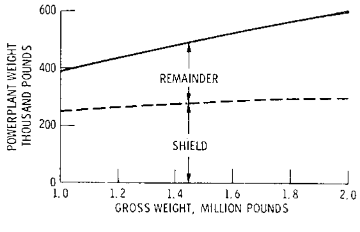


Fig. 2 Powerplant weight for nuclear aircraft flight altitude 36,089 ft; flight Mach number 0.8.

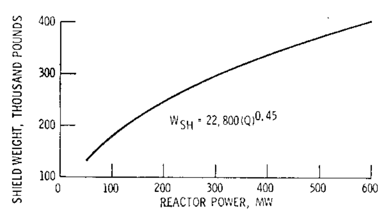


Fig. 3 Approximate weight of depleted uranium and water nuclear aircraft reactor shields. Reactor power density, 3.5 Mw/ft^3; dose rate, 0.25 mrem/hr at 30 ft from the reactor center.

Prevention of Radioactive Release in Accidents

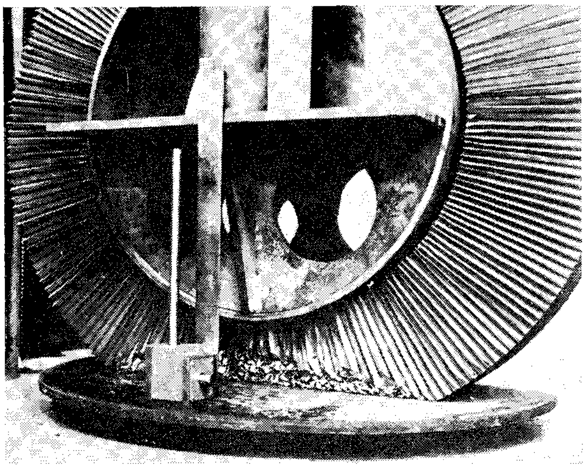
Accidental release of radioactivity due to an abnormal functioning of the reactor, powerplant, or aircraft must be made improbable by design and operating procedures. This probability should be low enough so that the potential advantages of the nuclear aircraft will outweigh the risk. As an illustration, the risk we are willing to take from the thousands of chemical aircraft that fly overhead everyday is worth the advantage that comes from their use. We accept this risk even though we know the consequences of a single accident, particularly a crash in a populated area, are severe and will become much worse as aircraft size increases. Yet, because the frequency of such accidents is so very low, we accept the risk in exchange for the benefits received.

In the case of nuclear aircraft, let us assume the worst accident we can. This would be a crash into a populated area followed by a sudden release of all the fission products in the reactor. A million pound nuclear aircraft operating for 10,000 hr would build up an inventory of about 200 lb of radioactive fission products. If this amount of fission products were suddenly released without warning in a populated area, it is conceivable that thousands of people would receive very serious doses of radiation. To be publicly acceptable for flight over populated areas, the simultaneous probability of a crash and the sudden release of all the fission products must be vanishingly small. The alternative is to restrict the flights to those over nonpopulated areas or over water.

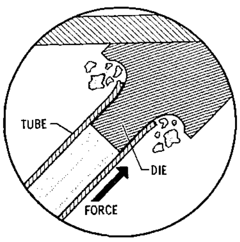
The prevention of the release of fission products in the event of a major aircraft accident is a difficult technical problem. We are first concerned with the prevention of rupture of the reactor containment vessel on impact, and secondly with the prevention of melt-through of the containment vessel due to the afterheat that is generated as the radioactive fission products decay. These are major areas that we have been investigating and are discussed in the following sections.

Choosing useful flight paths that avoid populated areas may not be so difficult. The flight paths could be mainly over water, for example. In this case, there is an additional feature that further reduces the hazard associated with a water crash even if the containment vessel is ruptured. Because of the scrubbing action of the water, only the fission gases that are inert such as xenon and krypton escape to the atmosphere. These gases constitute a much lesser hazard when compared to the total fission products.

It may be that the simplest way to gain early utilization of the potential of nuclear aircraft is to restrict it to overwater flight from airports with overwater landing and takeoff patterns. Coupling the fact that most of the Earth is water covered and that the range of nuclear aircraft is unlimited, it may not be difficult to find many useful applications. The experience gained in overwater flight operations will help solve the safety problems of overland accidents.



a) **Honeycomb**



b) **Frangible tube**

Fig. 4 Impact energy absorbers.

Impact Survival

In order to prevent the release of fission products in the event of a major aircraft accident, the reactor containment vessel must survive an impact without rupturing. In addition, provisions must be made to seal off all the coolant lines and other penetrations through this containment vessel. The sealing valves must remain intact during the impact.

The reactor vessel has a certain amount of kinetic energy depending on the velocity with which it impacts the Earth. If no special provisions are made, this kinetic energy is absorbed by deformation of the containment vessel or deformation of the Earth upon which it impacts. If the impact is on granite, however, most of the energy would have to be absorbed by deformation of the containment vessel and parts associated herewith. If this is the only technique used to absorb this kinetic energy, high impact velocities could not be tolerated with any assurance that the containment vessel would not be ruptured. For high impact velocities, means for absorbing the kinetic energy must be added. At the same time, the deceleration of the containment vessel must be kept within the tolerable limits.

We have examined the techniques that have been considered for impacting instrumented payloads on the moon and planets in our space program. The three most promising methods for absorbing kinetic energy are to utilize the crushing of balsa wood, the deformation of frangible tubes, and the crushing of honeycombs of metal or plastic. Figure 4 shows two of these techniques. For reference purposes balsa wood, which is not shown, can absorb approximately 20,000 ft/lb of energy per pound. Frangible tubes may be able to absorb about 80,000 ft/lb/lb. Honeycombs may be able to absorb over 100,000 ft/lb/lb.

To date, the only method that we have considered in some detail is the use of frangible tubes as an energy absorbing material. A schematic drawing of a system that uses frangible tubes is shown in Fig. 5. These frangible tubes would be placed in porcupine fashion all around the containment vessel. No matter from which direction impact occurred, there would be some of these frangible tubes available to absorb the energy. Unfortunately, frangible tubes will absorb a maximum amount of energy only when the impact occurs in a limited direction away from the axis of the tube. Beyond 15° from the axis the amount of energy that can be absorbed falls off rapidly. If this angle could be increased by proper bracing to 30°, the equivalent of about 15 energy absorbers each of which is capable of absorbing the entire kinetic energy of the containment vessel are required to provide protection for impact from any direction. For an impact velocity of 300 fps such a system would weigh about 35% of the mass to be stopped. In other words, a shield reactor package weighing 250,000 lb would need about 90,000 lb of energy absorber. If the effective angle were limited to 15°, the energy absorber would weigh 35% of the mass to be stopped only if the impact velocity were reduced to 150 ft/sec. If the effective angle could be increased to 45°, the weight penalty would be reduced to about 14%.

Preliminary estimates for honeycomb energy absorption systems indicate that the weight penalty might be reduced to 10% of the reactor-shield assembly weight if the effective absorption angle were 45°. For an impact velocity of 500 ft/sec, a honeycomb system would add about 36% to the shield weight. Although no data exist at present, it is expected that honeycombs will have a greater effective angle than frangible tubes. The weight of honeycomb systems presented previously are intended to show the best that probably could be done, and that energy absorption for impact above 500 fps is probably not possible for the techniques that have been considered thus far. A promising approach that is yet to be evaluated utilizes the deflection of the containment vessel and internal shield materials in addition to the external absorbers studied thus far. It may be possible to absorb the energy of impacts up to 1000 fps by this technique.

Reasonable external impact energy absorbing systems for impact velocities higher than 500 fps might be achieved by increasing the effective solid angle that a unit absorber can tolerate. This might be done through clever arrangement of the basic absorbing units so that they can transfer load to the absorbers that normally would not function because they are on sides away from the direction of impact.

Barring some major improvements through some technique as the aforementioned, it appears as if it will be very difficult to provide external impact energy absorption systems for impact velocities up to 500 fps without excessive weight penalty. At impact velocities of 300 fps, impact energy absorbing systems may be reasonable.

This leads us to the important conclusion that a nuclear aircraft system should have a collision avoidance system aboard because without them, speeds at impact could exceed 300 to 500 fps. This collision avoidance system must provide a continued monitoring of all possible trajectories that the aircraft could possibly attain caused by any accidental situation. It would then warn the pilot that he must take some corrective action. This corrective action could be a change in the flight speed of the aircraft, a change in its altitude or direction of flight, for example. If the pilot does not take these corrective actions, or if he does and the possibility of an accident is not reduced by any action he takes, then automatically the collision avoidance system would shut down the reactor and switch the engines over to chemical operation. At the same time the airplane velocity would be slowed down

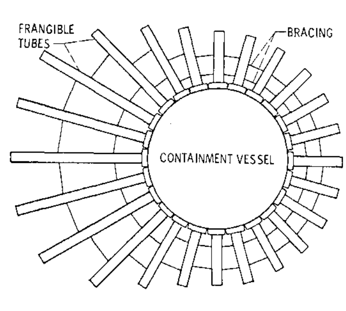


Fig. 5 Schematic of impact energy absorption system using frangible tubes.

by means such as aerodynamic braking. Its flight speed would be maintained less than a specified amount, probably in the range of 300 to 500 fps. If impact did occur, it would then be within the capability of the energy absorbing system to safely decelerate the containment vessel without a rupture. At the instant of impact, quick-acting valves in all the lines that pass through the containment vessel, which are designed to withstand the deceleration loads during the impact, are closed automatically. This action is taken only on impact and completely seals up the reactor and its fission products within the containment shell.

The reactor core itself is designed so that it cannot go critical during the impact process. The reactor may be designed strong enough so that it will not tear loose and breakup with a danger of a core compaction that could cause a nuclear excursion. We have been considering thermal reactors that use water as the moderator to make the possibility of a nuclear excursion extremely remote. The use of water allows sufficient moderator and shield water to be quickly removed by forced draining for all normal reactor shutdowns. In addition, whenever the collision avoidance system automatically shuts down the reactor, sufficient moderator and shield water is also drained as an operating procedure, just as for normal shutdowns.

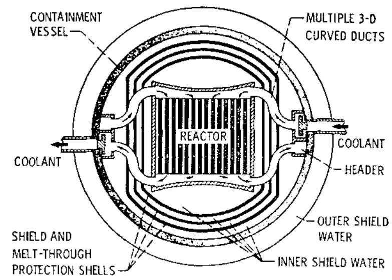
Afterheat Survival

A characteristic of a nuclear reactor is that the fission products that have been produced by fission are radioactive and emit energy as they decay. This process occurs even when the reactor is shut down. This energy is known as afterheat. It amounts to a few percent of the reactor power shortly after the reactor is shut down and decreases exponentially with time. At one minute after shut down, for example, the equivalent of about 2% of the reactor power continues to be generated by fission product decay. At one hour it amounts to about 1%; at one day about 0.5 of 1%; and at one week about 0.2 of 1% of the reactor power. For the first day, typical afterheat powers would be in the range of 1 to 5 Mw for aircraft in the range of 1 to 2 million pounds of gross weight.

In the event of a major aircraft accident it is assumed that all cooling systems would be destroyed. In addition, to prevent the release of fission products, the reactor is sealed off in the containment vessel. There is no way for the afterheat to be removed except by conduction, convection, or radiation from the outside of the containment vessel to whatever environment the containment vessel finds itself in. If it is in air, the containment vessel must be about 12 ft in diameter so that the afterheat can be removed from its surface without the surface exceeding a temperature of 1400°F.[2] In the case of a high-pressure helium system, the peak temperature occurs about one hour after shutdown. If the vessel is submerged in water following an accident during an overwater flight, the problem of afterheat removal is relatively simple. As long as the containment vessel is larger than 6 or 7 ft in diameter, the maximum surface temperature will not significantly exceed the boiling point of water.

The previous calculation considers that most of the water has been removed from inside the containment vessel prior to impact. This is done so that the possible pressure buildup inside the vessel is not too great. In addition, the calculation assumes that the heat flow from the surface of the containment vessel is everywhere the same. The implication of the latter assumption is that the heat generating fission products are distributed with approximate spherical symmetry within the core. This is to be contrasted to a more usual assumption of reactor safety analyses; that the molten reactor contains the fission products in a molten lump. The penalty that is paid in conventional power reactor practice for such an assumption has evidently not been sufficient to

Fig. 6 Schematic drawing of reactor-shield assembly.



warrant extensive studies of what actually happens when a reactor melts down in the absence of coolant.

Description of Reactor Meltdown

In the case of the aircraft reactor, if we are to provide containment after impact, we must consider carefully, in detail, the reactor melt-down process that may occur due to the loss of normal cooling. This is a very complicated undertaking because the fission products produce hundreds of various compounds with each other and with the materials of which the core is fabricated. Some of the fission products are gaseous, others are liquids and solids with whole ranges of vapor pressures depending on the chemical compositions and temperatures.

A general picture of what might happen in a reactor meltdown can be qualitatively described. Consider Fig. 6, which shows an illustrative drawing of a reactor shield assembly. The reactor is shown schematically by the central region. The uranium oxide fuel within the reactor is contained in fuel pins that are thick wall tubes about $\frac{1}{2}$ in. in diameter. In the case of the helium reactor they might be made of refractory materials like columbium or molybdenum. Clusters of these pins, perhaps 20 or 30, constitute fuel elements. The reactor core may contain a few hundred of these elements. Each of the elements is located in a tube that connects a top and bottom header plate. The space outside the tubes is filled with water-moderator. The helium flows downward in the spaces between fuel pins that are located in these tubes. The helium enters the containment vessel through the quick-acting seal valve referred to previously. It enters a circumferential header located on the inside surface of the containment vessel. From this header the helium is ducted to the reactor upper plenum by many curved ducts. The ducts are small and curved in three dimensions to prevent the streaming of neutron and gamma radiation from the core region. The hot helium is collected in the bottom plenum and ducted to a circumferential header in the same manner as for the inlet flow. The hot helium exits through a quick closing seal valve. Gamma shielding is provided by multiple layers of heavy material like uranium or tungsten. Neutron shielding is provided by layers of water that fill all the gaps between the reactor vessel, gamma shields and containment vessel. The gamma shield material is designed to provide reactor melt through protection as described below.

When the coolant flow ceases, the reactor fuel elements rise in temperature due to the heat generation by the fission products. About one fourth of this energy is in the form of gamma radiation that is absorbed in surrounding materials, the remainder is generated in place. As the temperature rises, heat is removed from the fuel elements by radiation and conduction to the surrounding core structural material. The fuel pins become weaker and burst due to the pressure of the fission gases within them. The fission gases, which amount to about $\frac{1}{4}$ to $\frac{1}{3}$ of the fission products, diffuse uniformly throughout the void spaces in the containment shell. Some fission product compounds that were vapor condense on cooler surfaces within the shell. The fuel pins continue to rise in temperature, and as more and more fission products become vapor, they leave the pins and condense on the nearest cooler

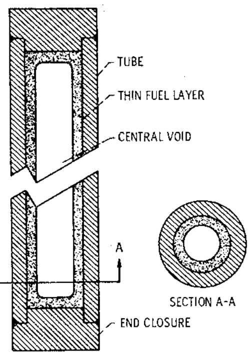


Fig. 7 Schematic drawing of very-high-burnup vapor-transport fuel-pin concept.

surfaces. In this stage some UO_2 would also vaporize and condense. As the temperature continues to rise, portions of some of the fuel pins will melt. The drippings will fall down to colder surfaces where they condense and solidify. As more of these drippings collect, the heat generation again becomes significant and the drippings remelt and form pools. If shells are provided to hold these pools as long as possible, more and more volatile fission product compounds leave the pool and recondense on cooler surfaces.

The surfaces that were once cool begin to increase in temperature due to the heat generation of the condensed fission products. Condensation of volatile fission products will then tend to take place further toward the outer regions within the containment vessel. In the meantime, the molten pool of drippings receives more and more molten fuel pin materials. The shell that was holding this pool now also heats up and fails, allowing the molten pool to dribble through to the next shell. The volumetric heat-generation rate of the molten pool at this time is less than it was in the beginning. This is because the decay heat is reduced with time and because many of the more volatile fission product compounds have evaporated and recondensed elsewhere. This process continues, and if the design is correct, the fission products should end up in a near symmetrical uniform distribution.

We have just begun the task of finding and assimilating all the data pertinent to this problem. There are interesting fuel meltdown experiments sponsored by the AEC now going on which should give insight into the details of fission production vaporization and condensation. Because of the complex nature of this problem, analysis with a high degree of confidence will probably not be possible. Carefully thought out experiments will be needed to provide the necessary insight to formulate analytical models and procedures for predicting performance of real systems. As yet we have not done much work in this area, although our designs incorporate features that are our best guesses as to how to prevent melt-through of the containment vessel.

Accidental Criticality

Another consideration for meltdown after impact is accidental criticality caused by potential critical masses that could be formed in pools in various voids within the containment vessel. We have made a study of this problem for a thermal reactor system similar to that shown in Fig. 6. If the total uranium investment is kept under 1000 lb and if sufficient reactor moderator and shield water are removed, it is not possible to achieve critical geometries for all the cases of molten pools we could envision. Further study is required to try to accomplish the same goal for fast reactors.

An interesting observation occurs as a result of limiting the total uranium in the core to 1000 lb for safety reasons. Inasmuch as 200 lb of uranium are consumed in 10,000 hr of operation, the average fuel burnup capability must be 20%. This means peak burnups of the order of 30% of the initial fissionable atoms. Considering the fact that the highest burnups for commercial reactors are in the range of 1 to 3%, we are asking for an order of magnitude increase. References 3–5 present and discuss a fuel pin concept which can provide such high burnups. This concept is discussed later in the following section on long life. The important point is that high-burnup fuel is required for prevention of accidental criticality of aircraft reactors.

Long-Life Reactor System

Because of the relatively complex operation required to refuel a nuclear reactor, the time between refueling should be as long as possible. Conventional chemical engines require a major overhaul about every 5000 to 10,000 hr. A reasonable goal might be that the time between reactor refuelings should be in the same range. In addition, all other powerplant components such as heat exchangers, pumps, piping, valves, and auxiliary systems should have lives comparable with chemical engines. The problems of long life and a discussion of the current status in several of the most important areas is presented in the following sections.

Reactor

The two major problems in long-life reactors are high-burnup fuel and reactor core design with adequate control margin for the high burnup required. There are two reasons for requiring high-burnup fuel. The first reason mentioned earlier is for safety. High burnup means lower initial fuel inventory which is inherently safer. The second is to minimize reactor size. The less fuel, the less the core volume required. This is of importance in minimizing shield weight.

High-Burnup Fuel

The Lewis Research Center has proposed the use of a fuel pin concept that can achieve 20% burnup or higher. It is a relatively simple approach that accepts in a conservative way well-known facts about fuel behavior. Figure 7 shows a schematic drawing of this fuel-pin concept. As described in Ref. 3, it does not use any new physical principles or ideas that have not previously been thought of. The pin consists of a tube that is designed as a pressure vessel. Fuel is contained within the pin in a thin layer relative to the thickness of the tubular pressure vessel. The objective is to assure that the fuel material is weak compared to the clad so that when the fuel swells or expands due to the buildup of fission products within it, the fuel will flow plasticly into the central void without introducing a major stress in the strong clad material. The void also provides room for the gaseous fission products to expand. The void is designed large enough so that at the desired burnup level the fission gas pressure can be held by the strong clad tube wall material. We are currently carrying out in-pile experiments in the Plum Brook Reactor to verify the concept for aircraft use. The experiments are being conducted at the pressure levels, temperatures, power densities, heat fluxes and neutron fluxes that would be characteristic of aircraft reactors. We expect the pins to perform as predicted, because they use ordinary design principles and conservative assumptions. Blake in England[4,5] has tested fuel pins of this type which verified the basic principles.

Long-Life Reactors

Fuel pins that operate with 20% average burnup have been discussed. At the end of life only 80% of the fuel is left. In addition, there has been a buildup of poison fission products. Control systems that allow continuous and adequate control of the reactor for large burnups of this nature, and that allow for xenon override so that we can start the reactor at any time after shutdown, are problems we are not investigating. The solution involves new control concepts, not only because of the large reactivity that must be controlled, but because conventional rod control systems tend to require large volumes. The reactor should be compact in order to minimize the shielding. Therefore, reactor control systems that are quite different from the ordinary systems are being considered.

A feature of one of the control systems that is being investigated capitalizes on the properties of the fuel pins that have been described. If the fuel pin is designed so that the inside surface of the fuel (uranium dioxide) operates at a temperature of 4000° to 5000° F, a very interesting and important phenomenon occurs. At these temperatures, the UO_2 has a relatively high vapor pressure. If for any reason the fuel surface temperature in one area is higher than in another area, the fuel will vaporize from this hot zone and recondense on the cold region. For example, if there should be a hot spot on the pin because of poor local heat transfer, the fuel would tend to operate at a higher temperature in this region. It would tend to vaporize and condense in the remaining cooler zones of the pin. The hot spot would thus tend to be relieved.

In most reactors, the highest rate of fuel burnup occurs in the center of the core because the neutron flux is the highest here. This means that uranium is being depleted at a greater rate in the center than at the ends of the core. If this occurs, the heat-generation rate tends to be reduced in the center of the core. If the heat-generation rate is reduced, the surface temperature of the fuel will be reduced. This means that fuel will be transferred by the vapor transport phenomenon from the cool ends of the pin toward the center where the fuel burnup is most rapid. Fortunately, there is an important benefit that arises from this phenomenon because the fuel is worth more in terms of reactivity in the center of the core than at the ends. The core life will, therefore, be increased because we are taking fuel from the region where it is not worth as much and allowing it to be automatically transported to those portions of the reactor where it is worth more in reactivity. The over-all change in reactivity during the life time of the reactor is thus reduced.

It is possible to take further advantage of fuel vapor transport and use it for reactor control. We could, for example, blanket off one end of the core by means of neutron absorbing regions This would produce a large cold no-power zone at the end of each pin. This is illustrated in Fig. 8. The reactor fuel would tend to condense and form a solid mass of UO_2 in this end of the pin. As fuel is burned up in the remainder of the reactor, the poison could be gradually withdrawn to expose some of the fresh uranium to the neutron flux. This fresh uranium would then redistribute in the remainder of the pin that is generating heat. The reactor in effect would have a reservoir of unused uranium that can be called into play as the rest of the fuel is used. The vapor transport feature of this fuel-pin concept allows reactor control with less control system movement for any given reactor life.

Other Components

Long-Life Heat Exchangers

In aircraft nuclear systems, the heat from the reactor is transferred by means of a heat-transfer fluid to a heat exchanger that transfers the heat to the air of a jet engine. In the case of a high-pressure helium system, the high-pressure helium gas transfers heat to the air of the turbofan engine. The heat exchanger material limits the turbine inlet temperature that can be achieved in a nuclear powerplant that operates on nuclear power alone. The heat exchanger material must be an oxidation resistant and strong high-temperature material. In the case of liquid metal systems, the heat exchanger material must also be compatible with the liquid metal used.

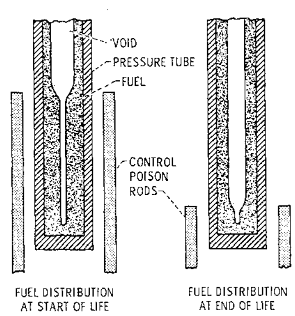


Fig. 8 Schematic drawing of a long-life reactor control concept using vapor-transport fuel pins.

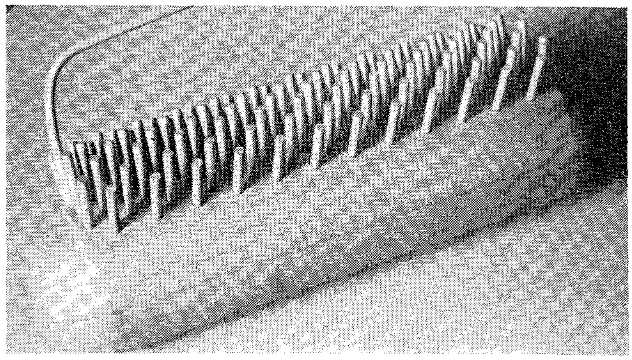


Fig. 9 Header for high-pressure helium-to-air heat exchanger.

We have carried out an experimental program aimed at determining the capability of helium-to-air heat exchanger materials. We have been performing two kinds of tests. One kind of test involves determination of the creep properties of tube material made of high-temperature oxidation resistant materials. Many high-temperature oxidation resistant materials have been tested. The most suitable available material we have found so far is N-155 alloy.[6] It is a ductile material that can be welded, worked and machined readily. It allows operation of high-pressure helium-to-air heat exchanger tubes at temperatures in the order of 1500° to 1600°F.

We have also done experiments on header configurations. The high-pressure gas heat exchangers we envision would be composed of high-pressure helium headers that have closely spaced heat exchanger tubes welded into them. A picture of one header design for which we made a representative section for tests is shown in Fig. 9. This header and tube section was designed to operate for 1500 hr at a pressure of 1000 psi and temperature of 1550°F. It actually ran for more than 5000 hr before it failed. The limited amount of heat exchanger work we have done has been adequate to determine design stresses and verify header design techniques. It remains to be shown, however, that whole heat exchangers or representative sections of a heat exchanger will perform reliably for the life time we predict when exposed to the complete environmental conditions that would exist in an airplane. This involves investigation of thermal cycling, vibration, and thermal expansion problems.

Other Long Life Components

Because of our limited effort we have not been able to do much work in many areas that would require attention if nuclear airplanes were considered for development. These areas involve pumping systems for high-pressure inert gases, seals for these systems, valves, piping required to duct high-pressure, high-temperature gases from the reactor to and from the engines, and auxiliary systems such as for afterheat cooling. The air breathing portion of the system requires studies of the problems involved in extending the shaft lengths of the turbofan engines so that the heat exchanger can be incorporated. An experimental program is required to determine the feasibility of fast acting valves that are necessary to seal off coolant lines and other penetrations into the containment

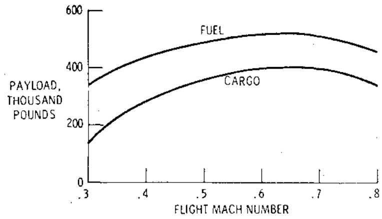


Fig. 10 Typical variation of payload of nuclear powered aircraft with flight Mach number. Gross weight, 1.75 × 10⁶ lb; flight altitude, 36,089 ft.

vessel during a major aircraft accident. Detailed over-all powerplant conceptual designs are required to arrive at realistic weight estimates of the entire system. They would also provide base points for realistic parametric and optimization studies that are required for mission analyses.

Performance of Nuclear Aircraft

Calculations have been made to illustrate typical performance that can be anticipated for nuclear aircraft. Figure 10 shows the payload anticipated for nuclear aircraft with a gross weight of 1.75 million pounds. The payload is plotted as a function of flight Mach number for an altitude of 36,089 ft. The payload is composed of cargo and fuel. Fuel has been provided in this case for takeoff and landing and for one hour flying time at design flight conditions. The payload is in the vicinity of 500,000 lb for design flight Mach numbers of 0.5 to 0.75. The fuel load is about 120,000 lb, so that the cargo capacity is about 400,000 lb. This amounts to better than 20% of the gross weight. Similar calculations for a one million pound aircraft indicates payloads of about 10 to 15% of the gross weight.

Figure 11 shows the corresponding weight breakdown as a function of flight Mach number. The major weight components shown are total structure weight, engine weight, shield weight, fuel weight, and payload. The largest single block of weight is the structure that is in the range of 0.42 to 0.45 of the gross weight for Mach numbers of 0.5 to 0.8. The calculations took into account landing gear weights that allow landing at takeoff weight. In chemical aircraft, the landing weight is considerably less than the takeoff weight because fuel is used or can be dumped if it is not. Also an important penalty was that the cargo space was provided with a flat floor that is supported only at the sides. Depending on the applications, optimization and improvements in large aircraft structures, the structure weight could be appreciably reduced. If the structure could be reduced to 30% of the gross weight, for example, the payload could be increased by more than 200,000 lb.

The shield constitutes only 15% of the gross weight. The shield and fuel together would constitute about 20%. Another 7% or so can be attributed to items of weight that would not be present on a chemical aircraft. Thus, if this were a chemical aircraft it would have a fuel capacity of about 27%. The ultimate range for such an aircraft would be about 6000 miles. In terms of equal cargo carrying capacity this would be the break-even range. For greater flight distance, the nuclear aircraft would carry more payload.

Concluding Remarks

The potential of the nuclear aircraft is sufficiently attractive so that it continues to be worth considering. NASA has been carrying out a low-level effort to determine the problems facing the possibility of a practical, safe, and economical nuclear aircraft and to access the potential for solving them. The key problems are safety and long life. Safety is concerned with provisions that assure that no person whether on board or on the ground can receive doses greater than generally accepted safe limits. In the case of a major aircraft accident, the prevention of the release of fission products either due to the impact or subsequent reactor meltdown is a major problem area. The prevention of the release of fission products in water due to accidents resulting from overwater flight is considered to be a minor problem when compared to that of a land accident. Limiting initial nuclear aircraft flight to overwater routes seems worth considering as a first application of nuclear aircraft.

The following are some specific conclusions that can be made, based on our studies up-to-date:

1) Shielding that is sufficient to reduce dose levels in and around the aircraft to the very low values that are generally acceptable for general population exposure does not stand in the way of feasibility of nuclear aircraft if the gross weight is over one million pounds.

2) Nuclear aircraft powerplants can be designed to prevent the release of radioactivity in normal operation by the use of closed reactor heat-transfer loops.

3) The prevention of the release of radioactivity that could occur in a major aircraft accident on land is a major problem area. It appears feasible, at least in principle, to design a reactor shield assembly that is housed in a containment vessel that will not rupture for impact velocities up to 300 fps Following impact, it appears feasible to provide means for preventing the reactor from melting through the containment vessel assuming all normal cooling systems are destroyed.

4) The nuclear aircraft probably must have a collision avoidance type system that continually computes all possible trajectories that could result from any normal or abnormal situation. The system warns the pilot to take evasive measures. If this fails, the system automatically takes all the corrective action necessary to assure that if one of the possible accident situations did occur, the reactor system would be ready for impact. It takes the necessary actions to assure that impact could not occur at a speed greater than that for which the energy absorbing system is designed.

5) Accidents that occur in water are easier to handle than land accidents. The consequences, even if all the fission products should be released, are much less serious than for a land release.

6) The use of thermal reactors can assure that nuclear excursions during and after impact on land can be avoided. The requirement is that sufficient moderator and shield water be removed (as in the case of a normal shutdown) by the collision avoidance system. Also the fuel inventory should not exceed about 1000 lb of uranium.

7) Reactor fuel that has the capability of providing more than 20% burnup of the heavy atoms is required to meet the safety requirement of limiting the fuel inventory to 1000 lb, while also maintaining the requirement that the reactor operate for 5000 to 10,000 hr between refueling.

8) A fuel concept that shows the possibility of burnup in excess of 20% is available. The validity of the basic principles of this concept have been experimentally demon-

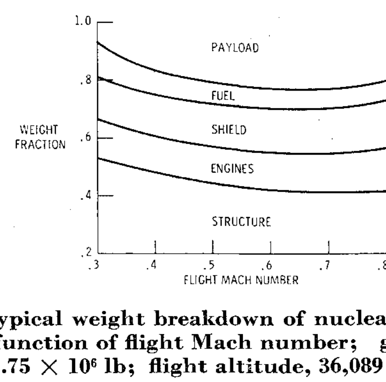


Fig. 11 Typical weight breakdown of nuclear power aircraft as a function of flight Mach number; gross weight, 1.75 × 10⁶ lb; flight altitude, 36,089 ft.

strated for lower burnups. Tests are being conducted to demonstrate full burnup at operating temperatures.

9) The aforementioned fuel concept when it incorporates the feature of vapor transport within the pin may provide for a simpler high-burnup reactor control.

10) Nuclear aircraft with gross weights in the range of 1 to 2 million pounds may be capable of payload capacities in the range of 10 to 25% of the gross weight for altitudes up to 36,000 ft and Mach numbers of 0.8.

References

[1] Wild, J. M., "Nuclear Propulsion for Aircraft," *Astronautics and Aeronautics*, Vol. 6, No. 3, March 1968, pp. 24–30.

[2] Rom, F. E. and Finnegan, P. M., "Will the Nuclear-Powered Aircraft be Safe?" *Astronautics and Aeronautics*, Vol. 6, No. 3, March 1968, pp. 32–40.

[3] Rom, F. E., Finnegan, P. M., and McDonald, G. E., "Very-High-Burnup Vapor-Transport Fuel-Pin Concept for Long-Life Nuclear Reactors," TN D-4860, 1968, NASA.

[4] Blake, L. R., "Achieving High Burn-up in Fast Reactors," *Journal of Nuclear Energy, Part A and B, Reactor Science Technology*, Vol. 14, April 1961, pp. 31–48.

[5] Blake, L. R., "Irradiation of Uranium-Metal and Uranium-Oxide Fuel Pins to High Burn-up at High Temperature," *Journal of Nuclear Energy, Part A and B, Reactor Science Technology*, Vol. 15, 1961, pp. 140–159.

[6] Morris, R. E., "Creep-Rupture Data for Welded N-155 Tubes," TN D-5195, 1969, NASA.

JANUARY 1971 J. AIRCRAFT VOL. 8, NO. 1

Evaluation of Heat Transfer for Film-Cooled Turbine Components

DARRYL E. METZGER*

Arizona State University, Tempe, Ariz.

AND

DARRELL D. FLETCHER†

AiResearch Manufacturing Company, Phoenix, Ariz.

Film cooling has been shown to be an effective method for the cooling of a variety of gas turbine engine components. In many of these applications, the region of primary interest, as far as calculation of heat-transfer rates is concerned, is the region immediately downstream of the injection location. Conventional methods for predicting heat-transfer rates, based on adiabatic wall temperature data alone, are generally inadequate in these regions. An experimental apparatus that can be used to readily obtain the comparative film cooling performance of different injection configurations, with surface heat transfer, is described. A convenient means of presenting comparative performance is used to present the results of an extensive series of tests with film injection through flush two-dimensional slots and through single spanwise lines of flush circular holes. Injection angles of 20° and 60° are covered for both injection types over a range of injection rates and downstream distances of interest in turbine cooling applications. In all cases the cooling protection provided by injection through holes is much less than that available with spanwise continuous slot injection. The results should provide the designer with a measure of the coolant penalty accrued when structural or other constraints preclude continuous injection slots.

Nomenclature

A = heat-transfer area
c_n = center-to-center distance between adjacent holes (Fig. 5)
C = surface block thermal capacity
d_n = hole diameter (Fig. 5)
G = mass flow rate per unit area
G^* = mass velocity ratio [Eq. (4)]
h = heat-transfer coefficient
l = cooled surface length
t = temperature
$\dot{q}$ = heat-transfer rate
s = actual or equivalent slot width
x = distance along the surface downstream from the injection opening (Fig. 2)
β = injection angle (Fig. 2)
θ^* = temperature difference ratio [Eq. (5)]
θ^*_{ad} = adiabatic temperature difference ratio [Eq. (6)]
μ = viscosity
τ = time
Φ = normalized average surface heat transfer [Eq. (3)]
Φ_0 = normalized average surface heat transfer at $t_f = t_m$

Subscripts

aw = adiabatic wall
f = film flow, identifies quantities evaluated at the injection nozzle exit
m = main flow, identifies quantities evaluated upstream of injection
w = wall, identifies quantities evaluated at the cooled surface

Presented as Paper 69-523 at the AIAA 5th Propulsion Joint Specialist Conference, Colorado Springs, Colo., June 9–13, 1969; submitted June 19, 1969; revision received March 11, 1970. At the Conference, E. R. G. Eckert, R. J. Goldstein, and D. R. Pedersen presented a written comment on this paper; it also is published in this issue of *Journal of Aircraft*.

* Associate Professor, Mechanical Engineering Department; also Consultant to AiResearch Manufacturing Company, Member AIAA.

† Engineer, Preliminary Design Section.