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ORNL 684
Reactors

AEC RESEARCH AND DEVELOPMENT REPORT

THE ATOMIC-POWERED AIRCRAFT

JANUARY, 1950

OAK RIDGE NATIONAL LABORATORY · U.S. ATOMIC ENERGY COMMISSION

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ORNL 684*
This document consists
of 36 pages. Copy 7
of 121, Series A.

Contract No. W-7405, eng 26

REACTOR TECHNOLOGY DIVISION

THE ATOMIC-POWERED AIRCRAFT
JANUARY, 1950

Cecil B. Ellis

Date Issued:

APR 26 1950

OAK RIDGE NATIONAL LABORATORY
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CARBIDE AND CARBON CHEMICALS DIVISION
Union Carbide and Carbon Corporation
Post Office Box P
Oak Ridge, Tennessee

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NOTE:

This status report was prepared in January, 1950, in answer to a specific list of questions submitted to the AEC by the Department of Defense. The present reprinting is being circulated with the hope that it may be of general interest to those engaged in reactor work. The views expressed within are those of the Oak Ridge National Laboratory only. They do not necessarily reflect the opinions of everyone associated with the Aircraft Nuclear Propulsion Program.

A. M. Weinberg
Research Director
April 17, 1950

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THE ATOMIC-POWERED AIRCRAFT

JANUARY, 1950

PART I. CONCLUSIONS

There are now moderately good grounds for believing that a supersonic airplane can be flown under uranium power. The most crucial questions outstanding today are those of the achievable aerodynamic lift-to-drag ratio for a large supersonic craft, and the attainment of reactor materials for high temperatures.

The nuclear power plant still poses many difficult unsolved problems. However, for each of these problems two or three promising approaches to a solution can now be sketched out. The number of possible alternatives in the design is great enough to suggest that feasible solutions will eventually be found, in one way or another.

It is still much too early for accurate prediction of the size and performance of the first nuclear airplane. However, the chief possibilities are discussed in the following sections, and some informed guesses can be made. It seems likely that a manned craft, built as a single unit, could be driven at Mach 1.0 at 60,000 feet altitude with a gross weight in the 350,000 - 450,000 pound range -- provided a lift-to-drag ratio of about 9.0 was available. The U^{235} content of the reactor might be in the neighborhood of 200 pounds. The allowable non-stop flight time at Mach 1.0 would be at least 100 hours. The continuous holdup of fissionable material in chemical and metallurgical reprocessing might be kept as low as 100 pounds per flying aircraft by special attention to the fuel element design. Of course the

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logistics of running a squadron of nuclear aircraft would lead to the tie-up of considerably more material than this in the complete operation. The outlook on other operating characteristics remains about the same as discussed in the Lexington Report.

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PART II. BASIC REACTOR DESIGN CRITERIA

The most important compromise to be adjusted in designing a nuclear aircraft is the balance between maximum reactor temperature and gross weight. Every possible effort must be made to relieve the materials problems by lowering the fuel temperature. Likewise, the gross weight must be kept as low as possible to reduce the difficulties of reaching supersonic speeds. These two factors usually oppose one another, since smaller shields mean smaller core volumes and thus higher power densities. The design balance should be struck at such a level that the materials difficulties are no worse than the aerodynamics difficulties.

If the desired flight conditions, and the best achievable L/D and machinery efficiency for those conditions, are fixed there still remain two possibilities for lowering the fuel temperature associated with any gross weight. These are (a) to improve the heat transfer rate within the core, so that the desired power density will not lead to such a high temperature, and (b) to improve the shielding art, so that the weight of the shield necessary for a given core size is decreased. It is for these reasons that the most intensive development work on the nuclear aircraft is now being applied toward better heat transfer systems, toward high temperature materials, and toward improved shields.

Heat Transfer Mechanisms:

The particular combination of fuel temperature and gross weight at which the problems on both sides seem most easily manageable will strongly depend on the heat transfer mechanism used, and will surely be different for different mechanisms.

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1. The first question affecting heat transfer is on the physical state of the material in which the heat is initially developed. If the uranium is dissolved in a liquid, this liquid can be circulated outside the restricted volume of the core and it will therefore not be necessary to accomplish the heat transfer within this small volume at all. There are of course a new group of difficulties brought into the picture by this device, some of which are discussed in the following sections. One of the important questions, for example, is the matter of the intermediate heat exchanger somewhere in the shield which would now be necessary. The primary circulating fluid will contain the intensely radioactive fission products and so cannot ever be allowed to circulate completely outside of the shield. If the heat exchanger between the primary circulating fuel and the secondary fluid, possibly another liquid metal, can be so designed that embedding it in the shield does not appreciably increase the shield weight, this system will doubtless have much merit.

The circulating fuel arrangement has not yet been adequately explored, but it certainly represents another alternative to the solid fuel systems which have been more usually discussed so far. It has the immense advantage that radiation damage to the fuel elements is unimportant and that many of the questions of thermal stress within the core likewise vanish. It is to be noted that the really fundamental gain expected from the circulating fuel arrangement is in the increased size of the heat transfer surface available. Instead of having to transfer the heat from those surfaces which can be placed within the small core volume, one can now expose surfaces of the intermediate exchanger which is distributed throughout a presumably much larger volume within the core. However, it is not yet at all certain that

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there will be a net gain, since the maximum temperature allowable to the intermediate heat exchanger materials may not be very high.

2. If the fuel is to remain in the core, then heat transfer between some solid and the circulating working fluid will be necessary within the restricted core volume. It is this heat transfer process which then must be run at the greatest feasible number of KW/cm^2 or BTU/sq ft/hr. Of course the processes which will transfer the highest heat flux from a solid to a fluid are probably of the type which cannot be used in the reactor application. These would be such mechanisms as an explosive reaction occurring at the solid wall, or the use of chemical dissociation or ionization processes. Excluding such devices, the arrangement which would seem to permit the highest heat flux at temperatures suitable for aircraft work would appear to be convective heat transfer between the solid walls and a swiftly flowing liquid metal. It is true that the heat transfer properties of liquid metal systems at high temperatures have not yet been investigated; however, the measurements made so far, which have extended up to the neighborhood of 1200°F, all seem to justify a fairly simple heat transfer formula. When extrapolated to higher temperatures and flow velocities and larger film drops, it seems to be a reasonable expectation that heat fluxes of the order of 2 million BTU/sq ft/hr can be achieved with liquid metal working fluids. The liquid metal cooled system is the type of aircraft reactor now receiving the most intensive study by all laboratories interested in the ANP Program. The principal disadvantage is the probable difficulty of finding fuel wall and piping materials which will stand the corrosive action of liquid metals at the necessary temperature level. Some suggested sets of specifications for a liquid metal cooled aircraft are listed in Part V.

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The liquid metal cooled aircraft reactor system has been discussed in some detail on previous occasions where it was assumed that the system would represent a binary cycle, i.e., the liquid flowing through the reactor core would be led out through the shield to a radiator, where its heat would be transferred to air passing through a turbojet. It is now beginning to seem likely that no such binary system will prove feasible. There are at least three reasons for suspecting that the liquid metal cycle, just as the circulating fuel cycle, will require an intermediate heat exchanger located within the shield, and will therefore be a ternary system. Reasons which have been advanced for passing to ternary cycles are:

a. It is suggested that it will be impossible to prevent the occurrence of radioactive impurities from the tube walls getting into the primary coolant stream. Thus, the working fluid would carry radioactive material outside of the shield even though the working fluid itself was some relatively inert liquid such as bismuth.

b. The vulnerability of a binary liquid metal system to enemy attack might be too great to be tolerated. However, if the unique parts of the system -- the reactor core and its coolant -- were all kept within the massive shield where they are relatively safe from an enemy projectile, then it would be possible to have the several external turbojet engines served by several independent secondary fluid cycles, any one of which might be lost without jeopardizing the reactor as a whole.

c. If it proved desirable to use bismuth or lead-bismuth as the primary liquid metal coolant within the core, it would probably not be feasible to circulate this (even if inert) to possibly a dozen separate turbojets scattered around the plane. The volume of bismuth necessary would add too much weight to the system. It might, therefore, be desirable to transfer the heat within the shield to a lighter metal such as ordinary lithium, or perhaps to a molten salt such as NaOH.

However, it may be noted that none of these three points has yet been exhaustively explored, and the binary liquid metal cooled system is not yet completely excluded.

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3. Another system of possibly equal heat transfer capabilities to the liquid metal system is one using a boiling fluid within the reactor core. Such a system has always been considered impossible for use within a reactor. However, the question has never been settled experimentally and there are growing grounds for feeling that the subject should be re-opened. It is true that this system, being such a radical departure from previous reactor experience, will bring with it a number of problems on which there is yet extremely meager experience. One should therefore only turn to the boiling fluid systems if their capacity for coping with high heat flux seems to be markedly higher than that of flowing liquid metal, or if the liquid metal systems prove impossible to manage from a materials standpoint.

The heat fluxes which can be achieved between a solid wall and a boiling fluid in high speed forced convection have never been adequately explored in the laboratory. It is known that the nature of the solid surface exercises a profound effect upon the boiling phenomena, and it would probably be difficult to maintain constant surface conditions. The only really extensive experience is on water ranging from normal boiling under atmospheric pressure to boiling at pressures as high as 1400 psi or more. With water at atmospheric pressure, the highest heat fluxes obtained are in the neighborhood of 1/2 million BTU/sq ft/hr. This figure really applies to natural convection; doubtless a high speed flow of the water would produce much greater heat transfer rates than this. At rather high pressures, heat fluxes of 2 million BTU/sq ft/hr have been achieved already. These fluxes are comparable to the fluxes attainable with liquid metals at atmospheric pressure. If, now, one changed from water to a suitable high boiling fluid, it appears very likely that the heat transfer rate of liquid metals could be matched without going to very great pressures in the system.

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The disadvantages of such a cycle are obvious. The material used would be new and the boiling phenomenon is difficult to maintain in a smooth steady state. The problem of controlling a nuclear reactor with even minute fluctuations in the average core density has been discussed many times.

4. From the purely heat transfer standpoint, there seems little reason to consider other liquid arrangements than the circulating fuel, the liquid metal, or the boiling liquid systems. All other flowing liquids would yield lower heat transfer coefficients. However, there is some possibility of making use of molten NaOH as primary coolant for the purpose of decreasing uranium investment by the addition of hydrogen as a moderator. This would be at the expense of increased gross weight because of the lower heat transfer, and thus larger core volume and shield weight.

5. Another liquid system which has hardly been explored at all is to use a fluid within the reactor core which may be vaporized outside by reducing the pressure and allowing it to run a vapor turbine. Such an arrangement offers no improvement of the heat transfer properties of the core volume, but it permits operation of the turbine at considerably lower fluid temperatures and so permits lowering the temperature of the reactor materials even without improving the heat transfer. So far, it has not appeared to be wise to put much time on this cycle since the difficulties of devising efficient turbine machinery for such an arrangement would be expected to outweigh the gain from the reduced material temperatures. It is expected that such vapor cycles will be explored only if the problem of reactor material temperatures eventually turns out to be even more acute than it seems now.

6. Continuing in the direction of decreasing heat transfer coefficient, the next step is to a compressed gas. Here, helium at some 2000 psi should

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be most suitable for aircraft work. This cycle has so far received insufficient attention. The survey in the Lexington Report suggested that even with the decreased heat transfer rate of the gas as compared with liquid metal, the resulting airplane still had a chance of matching the liquid metal gross weight with no more than about 100°F increase in fuel temperature. Such a premium would be quite reasonable to pay for relief from materials corrosion troubles.

7. The system of lowest heat transfer coefficient is the open-cycle air cooled reactor. Here, air is taken into the machine at ambient pressure and compressed to possibly 20 times this pressure before being sent into the reactor core. Although this heat transfer mechanism will lead to a rather large core volume, and so to considerably higher reactor temperatures for a given gross weight, it has to recommend it the great merit of simplicity as regards handling the working fluid. Whether this asset is counter-balanced by the added materials difficulties arising from high temperature oxidation and by the heavy machinery weight at highest altitudes, still remains to be settled. Both the NEPA Project and the Lexington Project have explored the air cycle in considerable detail.

Surface to Volume Ratio:

The preceding remarks on heat transfer have stressed the choice of the best heat transfer mechanism. There is of course the companion aspect of the problem -- in order to get the greatest number of KW/cm^3 from the core, one should also have the largest possible amount of cooling surface area per cubic centimeter. The geometry of the core material should be arranged to give maximum surface to volume ratio practicable in view of the requirements of structural rigidity, resistance to thermal stress, resistance to radiation

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damage, etc. In general, of course, one would achieve higher surface to volume ratios by going to smaller coolant passage diameters. The limit in this direction is the use of porous materials. This has not been explored adequately because of the difficulty of coating inside the pores to prevent escape of fission products. If this problem could be solved, it is certain that very large heat fluxes could be handled by passing gaseous or liquid coolants through porous materials.

High Temperature Materials:

If the liquid metal cycle is used, structural and fuel elements must be sought which are resistant to corrosion at high temperatures. Work in this field is now off to a vigorous start with exploration of various solid metals against liquid Bi, Pb and Li. It is also possible that the fuel elements could be ceramics with metal cladding. The possibilities for the use of ceramets also remain to be explored. The materials problem of the circulating fuel cycle would appear roughly the same as for the liquid metal cycle, with the exception of the greatly decreased surface area to be protected. Possibilities of materials with the boiling fluid or vapor cycle have not yet been thought out. With the helium cycle, the material difficulties should be greatly relaxed since the corrosion worries will be negligible. For the air cycle, the material problems have always seemed most extreme -- partly because of the presence of oxidation and partly because of the higher reactor temperature necessary. However, as will be discussed in Part IV, the NEPA Division and its subcontractors appear to be having considerable success in developing oxidation-resistant ceramic coatings for temperatures to 2500°F in high-speed air.

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All of the cycles will have to contend to some extent with unknown radiation damage problems. No adequate experimental data are yet available for the behavior of any material at the temperatures and the neutron and fission product fluxes applicable to any of the aircraft reactor cycles. However, it may be hoped that the relatively high temperatures of the aircraft system may be a help with regard to radiation damage, since the high temperature may continuously provide partial annealing and restoration of the damaged areas. It should be noted that radiation damage problems would be very greatly decreased with the liquid fuel arrangements.

Shielding:

The shield around the reactor core must protect against three types of radiation: (a) neutrons, which arise almost entirely in the core (except if the shield should contain uranium), (b) primary gamma quanta from the core, and (c) secondary gamma quanta, originating within the shield. The secondary gammas come from neutron capture and inelastic scattering of neutrons. Each of these three constituents of the radiation must be considered separately in the shielding problem. Because of this complexity, it is rather unlikely that a shield of uniform make-up throughout will prove to be the most efficient from a weight standpoint. Shielding against the gamma radiation is best done by heavy elements, while shielding against the neutrons is most efficient with light elements which quickly slow the neutrons by elastic collision. Complicating features in the problem are that the neutrons are also slowed down by inelastic collision in heavy elements, and that secondary gamma production is going on throughout the shield. In order to reduce the total shield weight, the heavy material should be put as close to the center as possible leaving

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the lighter material to go nearer the outside. The optimum arrangement and proportion of heavy and light materials has not yet been determined with any finality -- either experimentally or theoretically.

However, there now exist a number of combinations which may be fairly close to the best arrangement possible. It seems likely that a very good shield could be made by using lead as the heavy element and either boron or hydrogen, or a mixture of the two, as the light element. The boron would probably best be employed as boron carbide and the hydrogen might be inserted as water or as a hydrocarbon. Alternative materials are uranium, thorium, and iron and tungsten for the heavy materials.

It is clear that the shield must be specifically designed to attenuate the fastest neutrons, those, for example, over about 1 Mev, and the hardest gamma quanta, those from 2 to 5 Mev. If the fastest neutrons and the worst gammas are stopped, the other radiation will automatically have been taken care of.

For the air cycle or the compressed helium cycle there is the question of leakage of neutrons out of the reactor through the air ducts in the shield. This problem has not yet been covered either experimentally or theoretically. The ducts must be expected to add materially to the shield weight. (It is not believed that ducts through the shield will cause important difficulty in the case of the liquid metal cycle.)

Calculations have been based, so far, on the so-called "military tolerance" of 25 Roentgens per mission for aircraft crew members. It is suggested that this tolerance, though doubtless proper for an actual combat mission, may well need to be revised as a design specification for the nuclear aircraft.

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A tolerance limit of 25 Roentgens per flight leaves room for no more than eight flights and no accidents in a crew man's lifetime. Such a situation makes test flying and practice missions very difficult. Certainly a great deal of extended flying will be needed in the early days of the nuclear aircraft and will always be needed for photographic reconnaissance. It is suggested that the tolerance per 24 hour day be reduced to something in the neighborhood of 5 R. This must be expected to cause an appreciable increase in shield weight. It may be noted that some medical work is now under way on the problem of artifically increasing man's tolerance to radiation.

Reactor Neutron Properties:

In the above discussion of the basic design considerations for the aircraft reactor proper, the assumption has been used that heat transfer within the reactor core was almost the prime consideration. This means that in order to keep aircraft gross weight down, the shield perimeter and so the reactor core diameter is to be made as small as possible by any practical means; i.e., the core diameter is to be governed wholly by heat transfer considerations. (Of course the heat transfer arrangement chosen must have been such as to satisfy numerous auxiliary requirements on materials, coolant handling, turbine air temperatures, etc.). It was then implicitly assumed that sufficient uranium would be installed in some fashion within this specified core volume to make the reactor critical. No limitation was expressed as to the amount of uranium which could be devoted to this purpose. It was also not considered whether the reactor could always be made critical at any desired diameter simply by adding enough uranium. Naturally, there exists a minimum reactor core diameter set by the possible amount of uranium which can

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be arranged in a suitable geometry within the core; however, this turns out to be very small and in all interesting cases, smaller than the minimum core diameter permitted by the heat transfer considerations.

It also appears from preliminary calculations that the amount of uranium needed to make any core critical whose size is governed by the heat transfer situation, will not be greater than a few hundred pounds of U^{235}. Should this amount, as required by an otherwise interesting design, be considered excessive, it will usually be possible to decrease the uranium investment in the machine by going to larger aircraft gross weight. This balance between uranium investment and gross weight of the plane is a parallel balance to the compromise between gross weight and reactor materials stressed so far in this section. It is believed that the materials temperature is really crucial to the operation of the aircraft and that uranium investment should be given a free hand in design planning, within reason, in order to permit achievement of a feasible fuel element. This situation can be re-evaluated later in the development.

The approach of letting the reactor size be governed entirely by the heat transfer requirements can lead in many cases to a fast or intermediate reactor instead of the more familiar thermal type. If this occurs in an otherwise promising design, one must then balance the heat transfer and gross weight gained against the disadvantage of moving into the more unfamiliar nuclear realm.

Conclusions:

The above qualitative sketch of the more important reactor problem has been presented so as to show the relative emphasis now considered important for the various parts of the design. In the following section, a brief survey

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is given of selected parts of the Lexington Report which amplify the above considerations to some extent. A number of the recommendations for future study contained in the Lexington Report are also listed, to illustrate the large number of alternatives in the design yet available in case a fundamental block is met in the more obvious schemes.

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PART III. SOME VIEWPOINTS FROM THE LEXINGTON REPORT

During the summer of 1948, an extensive survey of the possibilities for nuclear powered flight was made by the Lexington Project. The Lexington Report[1)] was so stimulating that the most of the thinking and research on nuclear aircraft during the succeeding 15 months has been devoted to lines suggested therein. The results from such work as well as from other reactor research throughout the Commission, and from widespread aerodynamics research, have now filled out the picture somewhat.

In a number of respects the viewpoints of 1948 have been altered, although not many really new ideas have yet appeared. In the remainder of Part III some of the features of the Lexington Report are outlined as a background against which to consider the newer material.

Conclusions:

The principal conclusions of the Lexington Project were:

1. There is a strong possibility that some version of nuclear powered flight can be achieved. The aircraft is expected to be subsonic. A supersonic plane is not expected without striking improvements in aerodynamics.

2. The operating altitude will probably not be much above 50,000 ft. for any cycle.

3. The uranium content will be in the range of 20-200 lbs of U^{235}.

4. The manned plane and the tug-tow arrangement are the most interesting.

5. A choice of power plant and coolant is not yet possible; however, the three most interesting systems are (a) the open cycle turbojet, (b) the helium-cooled compressor jet, and (c) the bismuth-cooled turbojet. The gross weights

1) LexP-1 -- Nuclear Powered Flight, A Report to the Atomic Energy Commission by the Lexington Project, September 30, 1948.

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suggested for a manned plane, operating at Mach 0.9 and 30,000 ft altitude, using these cycles are:

Bi Turbojet	525,000 lbs.
He-Compressor-jet	650,000 lbs.
Air Turbojet	900,000 lbs.

6. Reactor materials development is the most critical need of the program. As illustration of this, the probable wall temperature of the fuel elements suggested for the most promising cycles are:

Bi Turbojet	1840°F
He-Compressor-jet	1830°F
Air Turbojet	2500°F.

7. Shield weights are still considerably uncertain. Shielding is of dominant significance.

8. The airframe will be comparatively straightforward unless the required gross weights become tremendous.

9. Full-scale testing will be hazardous and expensive.

The most striking point in the conclusions from the Lexington Report is that although the nuclear airplane is considered possible, the manned version will be an essentially large craft which is not expected to become supersonic. The principal change in general viewpoint of those working on the nuclear aircraft program since the Lexington Report has been in regard to this point. Although the actual feasibility of a nuclear plane cannot be completely demonstrated yet, there are grounds for considerably more optimism in regard to achievable plane weights and speeds. In order to investigate this point, which is of the highest importance for the military end-use, the assumptions upon which the Lexington calculations were based should be most carefully studied.

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Fundamental Assumptions:

A very far-reaching assumption made by Lexington was that the L/D of a supersonic plane would be 3. This figure is of major importance in the question of supersonic feasibility.

Another assumption by Lexington is that the required shield would be a 4-foot thick wall of material having specific gravity 6. The resulting weight of shield for a spherical core of 4-foot diameter would be 320,000 lbs. It is the combination of such large shield weights with the small assumed supersonic L/D which made supersonic nuclear flight seem improbable.

Bismuth Turbojet Cycle:

As an example of the nature of the assumptions necessary for designing nuclear aircraft, the optimum Bi turbojet cycle considered by Lexington for a subsonic craft is outlined below:

A. Aircraft type is taken to be a "Delta Wing" design.

B. The operating altitude is assumed to be 49,000 ft. and the speed 0.9 M.

C. For exploring the field, a number of possible gross weights of the aircraft are selected *a priori*.

D. Subsonic L/D of 15 is assumed. From this, the necessary thrust is calculated for each gross weight.

E. From gross weight, the total weight of the power plant system, including rotating machinery, reactor, shield and ducting is calculated. Based on comparisons with existing aircraft, the ratio of total subsonic power plant weight to gross weight is taken as 65% for planes over 300,000 lbs; for smaller planes, the ratio is slightly less, dropping to 61% at 150,000 lbs gross weight.

F. From the gross weight and the required thrust, the weight of rotating machinery and accessories is estimated. The machinery weight is taken from existing experience to be 2.0 lbs/cu ft/sec of intake air. The amount of air required to achieve the necessary thrust is calculated from existing turbojet experience in terms of the figure 40 lbs thrust/cu ft/second air flow, assuming the turbojet air inlet temperature of 1500°F.

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G. Subtracting machinery weight (plus reasonable estimates for reactor core weight, ducting and accessories) from the allowed total power plant weight, gives the resulting weight permitted for a shield.

H. The permitted U^{235} investment is assumed to be 100 lbs and the reactor is assumed to be thermal and moderated by BeO. From these data, a relation between core diameter and free-flow ratio follows automatically.

I. The bismuth reactor inlet temperature of 1180°F and reactor outlet temperature of 1656°F are assumed. The efficiency of propulsive parts is taken as follows:

Compressor	83.5% (CPR = 6)
Turbine	87%
Exhaust Nozzle	90%
Inlet Diffuser	90%

A shell and tube radiator with 1/8" ID air tubes is used. From these assumptions the relation between reactor core diameter and free-flow ratio is calculated which will transfer the necessary power.

J. From the above two relations, free-flow ratio may be eliminated so as to pick a core diameter which is both adequate for heat transfer and contains no more than the desired amount of uranium.

K. Assuming the core to be a right square cylinder, derive the thickness of shield around the computed core size which is permitted from the allowable weight derived above.

L. Repetition of this process for the various assumed values of gross plane weight provides a curve of gross weight vs. allowable shield thickness.

M. From existing shielding data, chiefly on the MO shield, it is assumed that a mixture of light and heavy material with specific gravity of 6 and thickness of 4 ft. is required to give the necessary attenuation for 25 R exposure to a crew 10 meters distance from the reactor.

N. The last step in the calculation is to pick from the graph the required aircraft gross weight to fly a 4-foot thick shield for the conditions assumed above (Mach 0.9, altitude 49,000 ft.). This gross weight comes out to be 950,000 lbs.

Gas Cycles:

The calculations for the open cycle air-cooled reactor are similar in spirit although somewhat more involved, because of the necessity of including

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the reactor core in the aerodynamic part of the system. The pressure drop through the reactor and shield ducts was assumed to be 30% of the compressor outlet stagnation pressure. The fuel wall was taken as 2500°F, and the compressor ratio was taken as 40. The resulting aircraft weights are very sensitive to design altitude. This arises both from the increased machinery weight needed to handle the required mass flow at low pressure and from the increased core size required to give adequate heat transfer with air of lower density. It was concluded by Lexington that there was little likelihood of being able to carry an acceptable shield above 50,000 ft. altitude with the air cycle.

Another sensitive feature is the reactor fuel wall temperature. If this is dropped from 2500°F to 1830°F, the gross weight becomes tremendously high, even at 30,000 ft altitude. It was suggested that fuel temperatures lower than 2300°F would not be practical with the air cycle. Some calculations were made on the effects of bringing the air into the reactor at the center using a split flow. This design will reduce the aircraft gross weight, but at the expense of a strong increase in uranium investment.

The third cycle for which extended calculations were made, was the helium compressor-jet. The standard helium pressure assumed was 1000 psi. The aircraft gross weight is quite sensitive to this figure, varying at 30,000 ft from 575,000 lbs to over a million pounds as the helium pressure is changed in the range of 2000 to 250 psi. One may purchase reduced gross weight at the expense of difficulties of handling extremely high gas pressures.

Suggestions for Future Work:

The Lexington Report made a number of suggestions for alternate designs which should be further explored. The most striking of these was the endorsement of the idea of tug-tow. The tug-tow scheme was expected to require 1/3 to

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1/2 the shield thickness of the manned aircraft. This gives less than 85,000 lbs for a shield of specific gravity 6 surrounding a 4-foot diameter core. The greatly reduced difficulties of constructing such a plane must be balanced against the operational disadvantages of the tug-tow system. It was estimated that a towing cable about 0.6 miles long would be needed.

Some of the other suggestions in the Lexington Report which are still being considered actively were for investigation of:

1. fast reactors,
2. split flow in the air cycle,
3. separated shields, placing the heavy gamma shield material chiefly around the crew instead of the reactor, so as to get the benefit of the inverse square law attenuation over the separation distance,
4. mixed reactors containing zones in the core of different moderators which could operate at different temperatures -- the aim being to reduce core size without increasing uranium investment,
5. reactor cores containing adjacent insulated regions of fuel and moderator at considerably different temperatures; the aim being to get hydrogenous moderator into a high temperature reactor so as to reduce the uranium investment for a given size,
6. shadow shielding; i.e., making the shield thinner on the side away from the crew (however, no more than about 10% of the shield weight was expected to be saved by such a device),
7. study of the possibility of using extremely small channels in the core, even going to porous solids as a device for increasing the heat transfer rates,
8. vapor cycles using a condensable vapor such as steam or mercury, possibly in a ternary system with bismuth in the core itself,
9. studies of control mechanics so as to achieve completely integrated systems. (It was emphasized that mechanical devices will be difficult to arrange which will maintain fast precision movements in the presence of aircraft accelerations.)

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PART IV. MAJOR DEVELOPMENTS SINCE THE LEXINGTON REPORT

During the time since September, 1948, there have been a number of special groups which have investigated features applicable to the nuclear powered aircraft. There has also been continued work in various laboratories along all of the lines involved in the problem. The overall supervision of the nuclear aircraft work has been vested in a joint Committee of the Atomic Energy Commission, the Department of Defense, and the National Advisory Committee for Aeronautics.

Radiation Damage

The field of radiation damage, which was not studied in detail by Lexington, has been thoroughly surveyed by the AEC Committee on Effects of Radiation on Materials. The report of this Committee[1] described the fundamental factors involved in radiation damage to both metals and non-metals. It stressed the amount of research and engineering testing yet remaining to be done before any materials can be considered thoroughly suitable for a high power reactor. The principal reason for optimism on radiation damage in the aircraft reactor is indeed the very high temperature involved, which should lead to partial annealing of the damaged regions continuously.

Of special value in settling these unknown radiation damage questions will be the new Materials Testing Reactor now being constructed at the new Reactor Proving Grounds of the Atomic Energy Commission in Idaho. Both the establishment of this proving ground and the construction of a high-flux materials testing reactor were strongly recommended by the Lexington Report as requisite to the nuclear aircraft development.

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1) AEC-500, "Survey of Effects of Radiation on Materials", by B. L. Averbach, D. S. Billington, J. W. Irvine, Jr., W. E. Johnson, A. R. Kaufman, A. W. Lawson, Jr., J. R. Low, S. Untermyer, and J. C. Slater, September 30, 1949.

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A large program of radiation damage measurements on many types of materials is now underway throughout the AEC. This extensive work involving both reactor irradiation and accelerator bombardment is certain to provide much needed fundamental information from which some of the radiation effects to be expected from the aircraft reactor may be deduced. However, experiments at the simultaneous high fluxes and high temperatures to be met in the aircraft case probably cannot be performed until the first prototype ANP reactor operates on a test stand.

Shielding:

Information on shielding has progressed to a considerable extent during the last 15 months. On the theoretical side, Bethe[1)], and Tonks and Hurwitz have analyzed the shielding problem and concluded that a shield to adequately surround a 4-foot diameter core might be built at 220,000 lbs instead of the 320,000 lbs assumed by Lexington. The weights for smaller reactors would be proportionately less. Further theoretical work[2)] was also done by the Summer Shielding Session held in Oak Ridge in 1949. This work provides a firm basis for analyzing the forthcoming new experiments.

The principal feature of the newly developed theory is the proposal of a principle governing the best proportion of heavy and light materials in the inner region of the shield. It was shown that the ratio of heavy to light material over a considerable range of the thickness should be adjusted so as to lead to equal neutron attenuation length and gamma attenuation length. This is the so-called "matched" section of the shield. It is contemplated that a shield would consist of an inner thin layer of perhaps boron to stop

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1) ORNL Central Files No. 49-6-149, "Report on the Status of Shielding Information for the NEPA Project", by H. A. Bethe, June 10, 1949.

2) ORNL-415 - ORNL-440, inclusive; TID-256.

some of the neutrons, immediately followed by a layer of pure heavy material such as lead, to quickly reduce the primary gamma radiation to a level comparable to the fast neutron flux. Then would come the matched section, in which the level of primary and secondary gammas and fast neutrons would be simultaneously reduced. On the outside would be a region of pure capturing light material such as boron carbide, to stop the remaining neutrons.

Recent theoretical designs by NEPA have contemplated replacing the boron carbide region by water or by gasoline. The latter has a good hydrogen density and might well be convenient as an emergency fuel for landing the aircraft on chemical engines in the event of a nuclear stoppage. A further theoretical development by the NEPA Project is in the realm of the "separated shield", the scheme in which the shielding around the reactor core is predominantly light material for neutrons only. The crew is then placed at the extreme end of the aircraft and the crew quarters are surrounded by a relatively thin layer of the heavy material for protection against the gamma radiation. The distance of separation between crew and reactor, as contemplated at present, is 100 feet. It is believed that this device will produce a very marked saving in weight, especially for larger core diameters. For reactor core diameters less than about 2.5 ft the separated shield is not believed at present to lead to a great deal of advantage.

Further theoretical work has been done on the possibility of "shadow shielding". This is the arrangement in which the shield on the side away from the crew is made thinner than the shield on the side nearest the crew. The savings to be gained by this method do not yet seem extreme, but it may prove somewhat useful.

Additional calculations have been made by NEPA personnel on the advantages to be gained from a shield built almost entirely of uranium hydride. It appears that the weight savings would be considerable; however, the difficulties of handling this material at the high temperatures prevailing in the inner region of the aircraft shield might be prohibitive.

In the absence of adequate experimental shielding data, it is not yet possible to really define shield weight with accuracy; however, the large number of possibilities for at least partially reducing the weight which are mentioned above, give grounds for optimism that a 220,000 lb shield is adequate for a 4-foot reactor running at several hundred thousand KW.

On the experimental side, the new shield testing facility of the Oak Ridge National Laboratory Reactor, the so-called "lid tank", has now yielded definitive measurements on water as a shielding agent. This represents the beginning of an extended program of measurements which will include numerous heavy metal, boron, and water combinations. Another new shield testing facility is being proposed for construction, in which full-scale samples of aircraft reactor shields -- including ducts -- could be tested at the full design attenuation.

Reactor Materials:

The materials picture now looks somewhat brighter than in 1948. For reactors containing principally metals, there is the added flexibility to be gained from the use of zirconium. This element is available in a ductile form, and it has been found to have quite useful properties in general. Its alloys have yet to be explored.

For a ceramic reactor, as in the air-cooled cycle, the NEPA Project quotes evidence of considerable success with coatings to withstand oxidation at 2500°F. Several types have been found so far which will stand up for 100 hours at 2500°F in still air. Some have stood up for considerable time with air flowing past at approximately Mach 1.0. One of the best coatings contains a mixture of iron, titanium, chromium and aluminum, which has protected the beryllium-carbide underbody from oxidation for more than 1000 hours at 2500°F. It may be noted in passing that a coating which will protect the underbody against oxidation in rapidly moving air might also be expected to prevent diffusion of fission products from the inside outward. It is to be hoped that the fission products will not diffuse outward more rapidly than oxygen will diffuse inward.

A materials matter on which there is yet no real progress but considerable new calculations is the question of separated Li^7 isotope for use as a primary reactor fluid. Design and cost estimates are now being prepared on the possibility of large scale Li isotope separation by various agencies of the Atomic Energy Commission, using any of several separation processes. It is hoped at present that the expense will be sufficiently low as to render Li a primary coolant material of interest. In any case materials studies on liquid Li systems are being carried forward, since Li may well be the best secondary working fluid in a ternary cycle system.

<u>Intermediate Reactors</u>:

Although little work has been done on the possibility of passing from a thermal reactor for the aircraft, to an intermediate or a fast reactor, the feasibility of making reliable intermediate reactor calculations has been greatly improved by the recent critical experiments at the Knolls Atomic Power Laboratory.

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Another uncertainty in epithermal reactor calculations has now been decreased by the new measurements on the Xe^{135} absorption band at the Oak Ridge National Laboratory. This is also important for thermal reactors since it bears on the added U^{235} investment which must be assumed to overcome poison during operation of the aircraft at the extremely high neutron fluxes which will be required.

Tug-Tow:

The Lexington suggestion for a tug-tow system is now being investigated from the operational standpoint by the Air Force. It would not appear to be necessary to carry out reactor development aimed specifically at this system until it is proven operationally sound. Any reactor which will power a single-unit manned plane will be more than adequate for a tug-tow system.

Reprocessing:

The question of uranium hold-up in the reprocessing of the aircraft reactor fuel elements was not investigated by Lexington, although it was suggested that the continuous hold-up might run to as much as 10 - 20 times the uranium content of a reactor core. However, two techniques now appear to be within sight which would greatly reduce this. These are the use of fuel elements something like the General Electric pin type, which might permit running to at least 15% depletion, and the use of remote metallurgy to refabricate the material with no more than about 10 days cooling time. It seems likely that such methods might keep the amount of fuel continuously undergoing chemical and metallurgical processing as low at 100 lbs per flying aircraft. Of course considerably more than this amount must be tied up in a complete operation of a task force of nuclear airplanes, because of logistic reasons.

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Miscellaneous:

In addition to the above larger pieces of work, advances in numerous details of calculation and laboratory experiments are being made at NEPA, North American, RAND, Battelle Memorial Institute, KAPL, Bureau of Standards, and other sites active in atomic energy work. Among the new items now being surveyed which offer possibilities of giving extra degrees of freedom to the design may be mentioned:

a) The use of molten NaOH as a primary reactor coolant. Some rough experiments indicate that its heat transfer properties at high temperature are very similar to those of room temperature water. The reason for using such a material is to get hydrogen into the reactor and so, because of its moderating action, to reduce the uranium investment needed for a given core diameter.

b) The possibility of obtaining self-controlling core materials which do not require moving control mechanisms is being explored. The line of attack now under way is to include in the core a liquid at a temperature and pressure not too far below its critical point. The resulting swift change of density with temperature would have a strong regulating effect on the neutron flux.

c) An attempt to experimentally check the thermal relaxation times involved in the integrated control of reactor plus power plant is now under way on a moderate scale. It may well turn out that the handling of the thermal time lags, due to the large heat capacity of the extensive circulating systems and of the heat exchangers, may prove as difficult for the aircraft operation as the actual control of the pile neutron flux. It may be most desirable to control the aircraft thrust by some auxiliary means of wasting turbine power at times, rather than by making any changes in the heat production level.

d) Some consideration is being given to the possibility of using liquid metal alloy coolants having melting points considerably above room temperature. It is thought, for example, that the radioactive heat in a core which had once been operated would be sufficient to keep many alloys melted for quite a long time. If such things could be arranged, it might be possible to find liquid metals less corrosive than Bi, Pb, or Li.

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PART V. SAMPLE CALCULATIONS WITH NEWER DATA

The NEPA Project has made many detailed calculations of possible nuclear aircraft characteristics. These are continually being revised as new data and new viewpoints appear. Neither NEPA nor any other ANP group yet feels that it has sufficient fundamental data to seriously compare the different possible cycles on an equally informed basis. Also, it is by no means possible yet to accurately specify the performance characteristics obtainable from any of the cycles. However, as an illustration of the way some of the current thinking is running, a partial list of the design figures for four recent NEPA suggestions are given below.*

* The specifications for these four preliminary design ideas were provided for this report in advance of publication through the courtesy of the NEPA Division, Fairchild Engine and Airplane Corporation. More details will be available in NEPA Quarterly Reports.

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Cycle	Bi-Li-Air Turbojet	Bi-Li-Air Turbojet	He-Air Compressor-Jet	Open Air Turbojet
Aircraft				
Design flight Mach No.	0.8	1.5	1.5	1.5
Design altitude (ft.)	45,000	45,000	45,000	45,000
Design point L/D	19.0	6.67	6.5	6.5
Component Weights(lb.)				
Turbojets and air ducting	34,700	80,000	94,000	140,000
Radiators	6,300	30,000	96,000	
Helium machinery			11,000	
Liquid pumps and lines	6,000	5,000		
Reactor and shield	110,000	200,000	176,000	265,000
Airframe and equip.	118,000	175,000	213,000	235,000
Payload	10,000	10,000	10,000	10,000
Gross Weight	285,000	500,000	600,000	650,000
Turbojets				
Number used	6	12		12
Total design point thrust (lb.)*	16,460	75,000	92,300	100,000
Total design point air flow (lb./sec.)	366		2470	2150
Total frontal area (ft.^{2})	74.1	162	190	165
Air Compressor				
Pressure ratio	5	4	4	20
Air Radiator				
Air inlet temp.(°F)	289	433	430	
Coolant inlet temp. (°F)	1525	1600	1753	
Total frontal area (ft.^{2})	59.3	242	370	
Air Turbine				
Inlet temperature (°F)	1400	1400	1500	2100
Inlet pressure (psi)	13.2	23.5	20.8	93.8

* Some of these designs include extra thrust for emergency use over and above the figure which would be gotten by dividing gross weight by L/D.

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	Bi-Li-Air Turbojet	Bi-Li-Air Turbojet	He-Air Compressor-Jet	Open Air Turbojet
Intermediate Heat Exchanger (at design point)				
Bi flow rate (lb/sec)	8,800	18,200		
Bi inlet temp.(°F)	1,585	1,740		
Bi outlet temp. (°F)	1,285	940		
Li flow rate (lb/sec)	206	390		
Li inlet temp. (°F)	1,225	800		
Li outlet temp. (°F)	1,525	1,600		
Reactor				
Flow arrangement	Straight	Straight	Split	Split
Core diameter (ft.)	1.98	3.28	3.2	5.93
Reflector thickness (in.)	2.5	2.5	6	3.1
Moderator and reflector material	Be_2C+1/3C	Be_2C+1/3C	Be_2C+1/3C	Be_2C+1/3C
Free flow ratio	0.35	0.30	0.30	0.40
Tube hydraulic diameter (in.)	0.14	0.24	0.105	0.17
Heat transfer area (ft.^{2})	734	1,660	2,910	15,650
Bi velocity (ft/sec)	13.3			
Uranium investment -- 90% enriched (lb)	~ 200	~100	75	180
Median energy for fission (ev)	~ 1000	0.10	0.7	0.2
Power (KW)	111,000	558,000	730,000	690,000
Virgin flux (N/cm^2/sec)	2.3×10^{14}	2.4×10^{14}	2×10^{14}	8.3×10^{13}
Max. power density (KW/in.^{3})	28.	20.	37.2	6.32
Max. heat flux (BTU/ft.^{2}/hr.)	900,000	1,600,000	1,110,000	198,000
Max. wall temp. (°F)	1,601	~ 1,750	2,500	
Shield				
Type	Unit	Unit	Separated	
Reactor-Crew Separation (ft.)	35	100	100	
Reactor shield wt.(lb.)			117,000	
Crew shield wt. (lb.)			45,000	

Comparison among these figures shows some of the changes in performance characteristics which can be expected by altering the design assumptions. It

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is especially to be noted that by accepting a moderately fast reactor the weight of an only slightly subsonic medium-altitude plane might be brought down to the B-36 class, with unlimited range of course.

The design suggestions shown above were worked out for a plane cruising at the rated speed and altitude. The NEPA Division has also made calculations on landing conditions. If the nuclear aircraft actually has to land under nuclear power and carrying the full shield weight, extra performance above the cruising specifications must be built into the design at several points. Assuming a landing speed of 150 mi/hr, and a maximum allowable sinking speed during normal landing of 10 ft/sec, the required turbojet thrust for the Mach 0.8, 45,000 ft., Bi-cooled example rises from 16,460 lbs to 32,200 lbs. The reactor power is also doubled, to become 222,000 KW, and the heat flux in the core rises to 1,800,000 BTU/ft^2/hr. The power density becomes 56 KW/in^3.

At the Oak Ridge National Laboratory some much more qualitative calculations have recently been made to illustrate the point stressed in Part I of this report -- the interchangeability of fuel element temperature and aircraft gross weight. The following weight estimates are for Mach 1.05 at 60,000 ft., with liquid Bi cooling. Although an L/D of only 7.0 was assumed -- instead of the 10 now believed eventually possible for these conditions -- the results are probably somewhat optimistic. This is partly due to an assumed gross weight of only twice the shield weight; possibly 3 times the shield weight would be more realistic at 60,000 ft. altitude.

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Core Diameter	Aircraft Gross Weight	Reactor Power	Power Density	Max. Fuel Wall Temp.
0.0 ft.	136,000 lbs.	135,000 KW	--	--
0.5	164,000	156,000	88 KW/cm^3	6730°F
1.0	195,000	194,000	13.1	2419
1.5	229,000	227,000	4.6	1706
2.0	266,000	249,000	2.2	1439
2.5	308,000	307,000	1.3	1315
3.0	352,000	350,000	.87	1247
3.5	399,000	398,000	.63	1214
4.0	451,000	450,000	.47	1164

Those above reactors of core diameter less than about 2.5 ft. would have to be epi-thermal to fast.

It should be emphasized again at this point that new experimental knowledge in shielding may produce a relatively great effect on the aircraft gross weights derived from purely theoretical calculations.

It would indeed be rash to quote definite performance predictions for any nuclear aircraft at the present time. About as far as one could go would be to estimate that the region of Mach 1.0 and 60,000 ft. might be reached with a gross weight in the range 350,000 - 450,000 lbs., provided an L/D of about 9 were available.

In general, it does appear that -- mainly because of the fact that higher L/D and lower shield weight seem more likely now than at the time of the Lexington Report -- there is no reason to believe that supersonic flight cannot be achieved with nuclear power.

In spite of the theoretical feasibility of nuclear flight, the fact that not one kilowatt of mechanical power has as yet been extracted from uranium fission presents a serious psychological barrier to the whole development. It is felt that the enormous technical problems which must be overcome in developing a power plant of hundreds of megawatts will be approached most realistically by building some non-flying, lower performance, power reactors as a first step.

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