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January 14, 1947

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NUCLEAR-POWERED FLIGHT

By

An Informal Committee

of

THE APPLIED PHYSICS LABORATORY

of

THE JOHNS HOPKINS UNIVERSITY

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NUCLEAR POWERED FLIGHT

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14 January 1947

TO: L. R. Hafstad

FROM: A. E. Ruark

SUBJECT: Transmittal of Progress Report entitled "Nuclear-Powered Flight", by an Informal Committee of the Applied Physics Laboratory of the Johns Hopkins University.

In accordance with your verbal instructions of about 9 June 1946, the Committee has considered the general problem of air vehicles driven by nuclear power. Three copies of the subject report are respectfully submitted herewith. A first draft was submitted October 25, 1946. Since that time many errors have been corrected and much new material has been added. The initial distribution is indicated in the report.

Your comments and those of other interested persons will be appreciated by the Committee. Review by suitable members of APL is hereby requested.

It is believed that any further work on this subject at APL should be carried on by a small staff with fresh instructions, and that the existing large committee should be discharged in the near future.

FOR THE COMMITTEE

Arthur E. Ruark, Chairman;
Technical Supervisor
for Research Laboratory.

AER:rh

Encl. 3 -- Copies 1, 2, and 3 of subject report.

[redacted]

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FOREWORD

In writing this report no use whatever has been made of classified information from the Manhattan Project. This policy was adopted because of our feeling that recipients of this report should understand how far we can go on the basis of generally available information and general physical principles. The authors of each section are primarily responsible for the views expressed therein. Because of pressing duties not all members of the Committee have been able to contribute written material, but thanks are due for their discussions with the other members of the Committee. We express our appreciation for unclassified information on materials suitable for high temperature structures, contributed by Mr. D. J. McKinzie, Chief Engineer; Dr. John R. Dunning, Consultant; and Dr. Alfred O. Nier, Consultant, of the Kellex Corporation. We also express our thanks to Dr. Sebastian Karrer, who kindly acquainted us with the content of his memorandum dated May 13, 1946 entitled "Electrical Generator Using Radioactive Materials."

An early stimulus for the work of this group was a memorandum by R. B. Roberts, which demolished some superstitions as to methods of driving vehicles with nuclear energy. Partly because of Roberts' memorandum, L. R. Hafstad asked A. E. Ruark to organize an informal study. Early exploration of the properties of smoke-filled nuclear energy ram-jets was carried out by George Carlton, later joined by C. F. Meyer. When their preliminary results were known, the group was expanded to its present membership.

ABSTRACT

This report considers the use of nuclear power for supersonic jet propelled missiles, and airplanes operating in the high subsonic range. Nuclear satellite and escape rockets are also briefly discussed. In all cases comparison is made with missiles using conventional fuel to accomplish a comparable task. A payload of 12,000 pounds in the form of a sphere six feet in diameter is assumed. In the case of rockets, a range of 5,000 miles is assumed, for the most part. From the standpoint of aerodynamic and propulsive design, it is not necessary to state a range for missiles flying in the upper atmosphere and carrying no oxygen, because the range is limited only by failure of the nuclear reactor.

Chapter I is a summary of the report.

Consideration of all nuclear propulsion schemes which came to our attention showed that the use of a slow neutron reactor is the most attractive possibility, though reactors making use of both slow and fast neutrons are not ruled out. Accordingly, unshielded cylindrical slow-neutron reactors, pierced with a multitude of holes for heat transfer to the hot gases, have been designed (Chapter II). These reactors utilize substantially pure uranium 235 or plutonium, uniformly mixed with a graphite or beryllium oxide moderator.

Chapter III discusses a nuclear turbojet, a conventional turbojet and a nuclear air turbine driving propellors.

Chapter IV deals with nuclear rockets expelling hydrogen, and with hydrogen-oxygen rockets of the same range, also with single-stage satellite and escape rockets using nuclear power.

Chapter V is concerned with development of basic heat transfer relations for both convective heating of the gas (the scheme adopted), and for radiative

heating of a smoke-filled gas (which is unattractive). A family of nuclear ram jets is presented and the conventional-fuel opposite number is described. A section is devoted to a supersonic nuclear turbojet.

Chapter VI deals briefly with material problems, which constitute the limitation and the chief research problem in all these cases. The lower the temperature of the reactor the larger and heavier the missile must be.

The essential properties of the several types of missiles are ~~displayed~~ tabulated, in Table 1, on the following page. No emphasis is laid on the exact weights and sizes quoted, because the study was made on the basis of unclassified information and there are important uncertainties in the nuclear data used for the reactor designs. The table indicates only orders of magnitude, and serves for comparison of the various types.

Conclusions: The nuclear ram jet and turbojet considered in these preliminary designs are <u>technically feasible provided the enriched reactors can operate at surface temperatures in the neighborhood of 2000°C</u>. A similar statement can be made for the nuclear hydrogen rocket except that the reactor surface temperature should be 2225°C or more. Development of any of these types would certainly be long and costly and the amounts of U235 or plutonium required are large, judged on the basis of present production. Unless there are revolutionary discoveries in regard to lowering the cost of highly enriched fissionable material, it appears unjustifiable to give further consideration to any supersonic vehicle which makes a one-way 5,000-mile trip, resulting in loss of the reactor at the target.

It is conceivable that a nuclear ram jet or turbojet could be made to return from a target at 5,000-mile distance. It is possible that a nuclear ram jet or turbojet may be attractive as a satellite vehicle for large-scale reconnaissance or for a continuing threat to a possible aggressor. The nuclear escape rocket

COMPARISON OF NUCLEAR-POWER AND CONVENTIONAL-FUEL VEHICLES

Missile	Reactor	Mach No.	Reactor Surface Temp. (°C)	Wt. of Missile (lbs.)	Approximate Body Dimensions (ft.)	Wt. of Uranium (lbs.)	See Page	Assumed Neutrons per Fission
Nuclear Turbojet	C	High Subsonic	1950	46000	7 (diam.)	50	3.5	2.1
	BeO		1950	~50000	"	44		2.1
Conventional Turbojet	---	"	1950	85000(1)	"	--	3.7	---
	---	"	1950	48000(2)	"	--		---
Nuclear Air Turbine with Propellor	C	"	1950	59000	"	50	3.8	2.1
	BeO	"	1950	~63000	"	44		2.1
Hydrogen-Nuclear Energy Rocket (3)	C	Very High Supersonic (22,300 ft/sec).	2725	~115000	---	~44	4.22	2.0
			2225	~160000	---	~44	4.25	2.0
Conventional Ram Jet	---	2.2	--	137000(1)	8 x 80	--	5.4	---
				60700(2)	8 x 80	--		---
Nuclear Ram Jet	BeO	2.0	1840	74800(4)	8 x 48	71	5.40	2.1
Nuclear Ram Jet	BeO	2.0	2060	80000(4)	8 x 48	71		2.1
Nuclear Ram Jet	BeO	2.0	2280	85000(4)	8 x 48	71		2.1
Nuclear Turbo Jet	C	1.4	1950	90600	8 x 80	89	5.48	2.1

(1) Takeoff weight; (2) Landing weight.
(3) Payload & controls, etc. about 10 tons. Range about 5000 miles. The corresponding "conventional" hydrogen-oxygen rocket would have essentially the same weight and size as the 2225°C nuclear-rocket.
(4) Permissible weight of missile. As reactor temperature increases, the weight available for structure increases.

Table 1

merits general attention from scientists, though it is hard to think of any important military application of such a vehicle.

To settle such questions definitively, access to classified information on fissionable materials and slow-neutron reactors is necessary, with particular emphasis on reactor control. Basic studies of material properties at high temperatures are essential, and would be of value, not only for exploratory design of nuclear vehicles, but also for improvement of types using conventional fuels.

CHAPTER I. INTRODUCTION AND SUMMARY

By Arthur E. Ruark

1. General Considerations

The extremely compact source of very high energies made possible by recent developments in nuclear research suggests the use of nuclear energy for the propulsion of high performance vehicles. Used in connection with the rocket propulsion principle such a device might offer the possibility of constructing extremely long range rockets, including satellites or even so-called escape vehicles. For vehicles which remain within the earth's atmosphere many other possibilities suggest themselves, in particular ram-jets, turbo-jets, and air turbines with propellers. For the sake of definiteness, we assume, for the vehicles which must remain within the earth's atmosphere, that the payload is a 6' sphere weighing 12,000 lb. For the rocket vehicles we make the same assumption, but shall also consider a zero payload in connection with the possibility of an escape rocket.

It is natural to suppose that the use of nuclear power will make it possible to build a missile of surpassing speed, against which defense would be difficult. However, the thermal limitations of materials prevent us from using the great available energy of the nucleus at any rate we please. In this study it has become clear that we should think of nuclear energy as a means for providing great range. For any range specified, the nuclear energy plane or missile should be compared with an "opposite number" driven by conventional fuel.

Ranges.

This laboratory has made studies (references 1 and 2) which indicate the feasibility of ordinary-fuel ram-jet missiles with ranges of the order of 2,500 to 3,600 miles. The reports of the Gilliland panel (reference 3) give a rough outline of the range and speed domains in which the rocket, ram-jet and turbo-jet, respectively, give the best performance. Since the publication of these reports, design knowledge has been advancing, and more work is meeded to bring the advantage-chart up to date and to extend it to greater ranges.

The shorter the range, the less we have to make use of the assumed "staying power" of the nuclear energy drive. Therefore, we confine our attention to ranges higher than 3,500 miles.

From Alaskan bases, the distance to any point in the Northern hemisphere is less than 7,950 miles. From locations in the northern part of the United States, the distance to any such point is less than 9,400 miles. But these figures are misleading, as top ranges. From Arctic circle locations in Alaska, all the domain above 45° is within a distance of 4,750 miles. Figure 1 at the end of this chapter is a polar world map provided by the Aerodynamics group of APL. Airline distances from several strategic points are marked on it.

For a nuclear-energy vehicle, it is desirable to have the expensive power source return to base. This indicates that we should eventually consider a round trip range of 10,000 miles. But who wishes to have a highly dangerous pile coming back to the base that sent it out? We decided to deal with a range of 5,000 miles, leaving greater ranges for later consideration.

It is reasonable to assign a range to any nuclear-energy missiles, because the power source must work under extreme conditions of temperature in order to cash in on the vast amounts of energy available in nuclear fuel. It may be highly advantageous to work a pile at temperatures so high that the range is determined by corrosion, by the creep of hot materials, rather than by damage due to fission and fission-products.

Recent discussions of satellite vehicles by Galcit, the Glenn L. Martin Company, and the Douglas Aircraft Company, Inc., (Reference 5) indicate the feasibility of hydrogen-oxygen rockets flying at an altitude of 90 miles or more, circling the earth in about 90 minutes and continuing without much loss of altitude for weeks or even months. Such devices are designed for extremely high velocity, with a light load of scientific instruments.

Explanation of Viewpoint.

In a study of this kind it is not feasible at the start to lay down specifications for performance. We had to begin by assuming reasonable types of structure and working out the properties of nuclear power sources with sufficient heat transfer surface to give the necessary net thrust and lift. In searching for designs, no attention was paid to present cost and availability of fissionable materials. Considerations of this kind might block off an answer to the following technical questions. Can a nuclear-powered, high-speed missile be made to fly the payload over the desired range? Does it have any advantage over missiles using conventional fuels? It can be assumed at the outset that a very large, slow airplane can be lifted off the ground by a pile, using more or less conventional methods for transferring heat from the pile to a turbine, and for cooling the working fluid. Our problem is to consider faster and more compact vehicles.

Questions of launching, guidance, navigation, and homing are omitted. It was not possible to give adequate consideration to problems of strength and short-time durability of the power source. Indeed, the necessary data do not exist, and their accumulation is the sine qua non for further progress in this field. We have considered reactor surface temperatures ranging from 1725°C to 2725°C. Inside the reactor material, still higher temperatures would prevail. These surface values lie well below the melting point of carbon, but not much below the melting point of beryllia, which are the only known possibilities for the reactor bodies.

2. Summary of Chapter II, Nuclear Reactors.

In this report the term "fast-neutron reactor" refers to a body of fissionable material with little or no moderator, while "slow-neutron reactor" means a body in which most of the neutron collisions occur against atoms of a moderator.

A. Types.

(1) Slow-neutron reactors. (Parts A and B of Chapter II). It requires little consideration to rule out natural uranium. Attention has been focussed on reactors using enriched fissionable material (U235 or Pu239), mixed in a moderator; carbon would be suitable for a rocket carrying liquid hydrogen, while beryllia would be better adapted to a ram-jet or turbojet. Carbon coated with thin layers of oxide may be an alternate possibility as a moderator for ram-jets and turbojets.

Roberts noticed a very interesting possibility connected with the nuclear liquid hydrogen rocket. Since the hydrogen has to be carried anyway, it is worthwhile to consider its use as a combined moderator and pile coolant, prior to the stage at which it is strongly heated and ejected. The difficulties are great: we cannot say at this time that they are insurmountable. The scheme has been studied by Gamow, McClure and Kershner (Appendix 4). The idea of ejecting a mixture of hydrogen and uranium has been considered by Roberts. It is out of the realm of consideration, because the quantities of uranium thrown away would be enormous.

(2) Fast-neutron reactors. In Part C the properties of these reactors are examined. The multiplication factor is examined for sizes very close to the critical one, with a view to (a) controlling the overcritical reactor or (b) using a subcritical one with a subsidiary neutron source to act as a "pilot flame" and maintain the reaction.

Part D contains the following items:

(3) Radioactive fission products. At first sight the use of separated fission products as a source of heat looks very attractive. As Roberts has shown, the proposal falls down for several reasons. Rapid decay makes the supply question very difficult. The radioactivity involved would require remote control during separation, production of the reactor, transportation and insertion into the missile. During and after fabrication, the material would have to be cooled, to dissipate power much in excess of the power available during flight.

(4) Direct use of fission fragments from an enriched pile, in the gas stream. If a large fraction of the fission fragments of a pile could be caused to dissipate their kinetic energy in the gas stream, our problem would be much easier. The difficulty is that the fissionable material would have to be in very thin layers, one micron thick or less. Since we have not arrived at any practical design, the matter has been dropped.

(5) Miscellaneous possibilities. In a memorandum of May, 1946, which furnished a stimulus for this study, Roberts destroyed the superstition that a missile can be driven by direct use of the momentum of fission fragments, alpha particles, accelerated electrons or accelerated ions. The thrusts obtainable by such means are minute. The alpha particle scheme is examined in detail by Gamow in Appendix 2. Sources of the order of one million curies per square cm. would be required. He also considered a method for obtaining neutron-thrust from a fast-neutron reactor. The thrust is minute.

B. General Facts about Slow-Neutron Reactors Using Uranium 235 or Plutonium.

In this discussion we shall suppose that U235 is employed. The rough design equations for a slow-neutron reactor depend on very simple physical ideas. Neutrons produced by fission are assumed to behave like a diffusing gas. As a neutron moves out from the place of origin, it is slowed down by collisions with nuclei, the moderator atoms being the effective "slowers." In any collision the neutron may be absorbed, it may lose a fraction of its energy by exciting the interior structure of the nucleus, or it may be scattered elastically. The essence of the game is to pick a moderator with a low absorption cross-section, so that most of the fissions are produced by collisions of slow neutrons with uranium. The average fission cross-section of U235 for thermal neutrons is over 400×10^{-24} sq. cm. while a rather ill-defined average for fast ones is about 2×10^{-24} sq. cm. (An area of 10^{-24} sq. cm. is called a barn, in the parlance of the Manhattan District.) We have no experimental information on the fission cross-sections for plutonium 239. In "Nuclear Fission and Atomic Energy," Table 9.2, it is suggested that they are about the same as for U235. Apparently, this view is based on rough theories of the fission process.

Optimum Concentration.

The use of a moderator leads to an interesting feature, the fact that for a given shape of pile there is an "optimum" uranium concentration which leads to the use of less uranium than any other concentration. In order that a pile may operate, the number of neutrons absorbed per second in both the uranium and the moderator must be less than the number created. If the concentration of uranium is too low, the action is not self-sustaining. On increasing the concentration, we arrive at a condition in which a very large pile is required. Although U concentration is low, the volume to be supplied is so large that the total mass of U is also large. Further increase of concentration reduces the critical size and the total uranium requirement. There is a limit to this improvement, because decrease of pile size is associated with increasing relative importance of neutron-escape at the pile surface.

When the pile becomes too small, the amount of uranium becomes larger again. This shows that there must be a concentration which leads to the greatest economy of uranium in the barely-critical pile.

The Spherical Reactor.

An understanding of the essentials of rough pile design can be obtained from a study of the simplest case, that of a spherical reactor. Appendix 1, a reproduction of a talk by Dr. R. F. Christy, deals with a spherical reactor consisting of U235 or plutonium in water solution. He gives the following values:

Optimum mass of U235 for critical operation: 1.5 kg.

Critical radius corresponding to this mass: 22 cm.

Power dissipated: 10 kw.

Christy states that the optimum mass is "of the same order" if the moderator is heavy water, graphite, or BeO. Capture by the moderator is much less which implies that the optimum concentration is smaller. However, the neutron paths are longer, so the critical size is greater. All these effects cooperate to make the optimum mass somewhat insensitive to choice of moderator. However, we have reason to believe that it may vary several-fold when the moderator is changed, so that Christy's statement must not be taken to mean that the choice of the moderator is unimportant from the standpoint of uranium economy.

The Critical Condition.

The differential equation for the neutron density in a steadily operating pile is

$$\Delta^2 n + n\,(K - 1)/L^2 = 0. \qquad (1)$$

Here K, the reproduction factor, is the ratio of neutrons created to neutrons lost in all possible absorbing processes, including fission; L is the diffusion length, which can be calculated from the mean free paths for scattering and for absorption. One's first reaction is to suppose that steady operation will occur only when K is one. However, K must exceed one so that the leakage current at the surface of the reactor can be provided. The appropriate spherically symmetrical solution is

$$n = \frac{1}{r} \sin\left(\sqrt{\frac{K-1}{L^2}}\, r\right). \qquad (2)$$

With K and L fixed, we may require that the neutron density steadily decreases from center to boundary and that it becomes zero at the boundary. Thus the quantity in parentheses must be π. This means that n is zero at the boundary, but the neutron flux, $-D$ grad n, is not zero. It is just sufficient to take care of the excess of creation over absorption in the sphere as a whole. The reader will detect a flaw in this argument. If n is really zero, the flux at the boundary must be zero, because the velocity of the neutrons is finite. This flaw arises from the use of simple diffusion theory, which pays no attention to the actual velocity of the diffusing neutrons and simply assumes that the net flux is that stated above. In actuality the mean free paths of the neutrons are finite, and diffusion theory does not apply to those which originate within a few mean free paths from the boundary. Finally, n is <u>not</u> zero at the boundary. The assumption that it is zero yields a good approximate value for the critical radius, namely (in the spherical case),

$$R_c = \pi L / \sqrt{K-1}\,. \qquad (3)$$

C. Rough Design of a Cylindrical Reactor Containing Tubes.

(Parts A and B of Chapter II). To reduce weight we assume there is no shielding and no neutron reflector. The reactor must be pierced from end to end with a multiplicity of tubes in which the gas is heated. Absorption of neutrons by the gas is neglected, for simplicity, although this correction may introduce errors of several per cent. The fraction of the cross-section taken up by the tubes is denoted by Γ.

Gamow suggested a simple method of allowing for the tubes. If the length of each tube is great compared with its diameter, we may assume that practically all neutron mean free paths are increased by a factor $1/(1 - \Gamma)$, so that the dimensions of a critical reactor are increased by the same factor. The net result is that the mass of the reactor is increased by a factor

$$\left(\frac{1}{1-\Gamma}\right)^3 \times (1-\Gamma) = \frac{1}{(1-\Gamma)^2},$$

because only a fraction $1 - \Gamma$ of the cross-section is occupied by moderator. Thus we can consider a solid reactor, and when the job is done we may suppose it is replaced by a tubular structure of the same overall shape, the tube area being chosen to provide the surface needed for effective heat transfer to the gas. Let us summarize the investigation..

(1) <u>How the mass of uranium is determined</u>. The first step is solution of Equation (1) to find the condition imposed on the radius r and length h by the requirement that the reactor be at least of critical size. There is one equation of condition,

$$\frac{0.586}{r_c^2} + \frac{1}{h_c^2} = \frac{(1-\Gamma)^2}{L^2 \pi^2}\left(\frac{VC}{1+C} - 1\right). \qquad (4)$$

Here r_c and h_c are the critical radius and the corresponding critical length, and we write

$$r_c/h_c \equiv \mu. \qquad (5)$$

L is the diffusion length in the solid material and V the average number of neutrons produced per fission.

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C is a dimensionless number proportional to uranium concentration. We call it the concentration, but actually its definition is

$$C \equiv \frac{N_U}{N_M} \frac{\sigma_{aU}}{\sigma_{aM}} . \qquad (6)$$

The N's are the numbers of atoms of uranium and moderator, respectively, in one cubic centimeter, and the sigma's are the absorption cross-sections of these substances. For the case of carbon, the density ρ_U of uranium in the mixture is

$$\rho_U = 4.7 \quad 10^{-4} \ C. \qquad (7)$$

By Equations (4), (5), and (7), we see that for each shape and each concentration C, the critical radius, critical length, and thereby the uranium mass, are completely determined (provided, of course, that the concentration is not too low). The mass of uranium, m, turns out to be the product of a function of C, a function of μ, and a factor $(1 - \Gamma)^2$.

(2) Shape. The best shape is independent of the best concentration. By differentiating m with respect to μ we find it is given by $r_c/h_c = 0.542$. Other values can be used, but they require more uranium. In this report, we shall not attempt to optimize the range or speed by changing μ; the value 0.542 is used, unless the contrary is stated.

(3) Temperature effects. The best concentration depends on the temperature. At higher temperatures thermal-neutron absorption cross-sections are smaller, i.e., the mean free paths are greater. Table 2, page 2.13 and Table 4, page 2.33, show the results of critical-reactor calculations for carbon and BeO piles, respectively. The conditions considered are:

(a) Temperatures of 300°K and 3000°K.

(b) Values of V from 2 to 2.4 neutrons per fission, because we do not know V. Within this range the mass values are quite sensitive to the value of V, although the dimensions are not.

(c) Several values of r_c/h_c, including the optimum value 0.54.

(4) Critical Sizes and Uranium Requirements. The results show that if the concentration is properly increased, we do not have to change the pile size appreciably in going from room temperature to the operating temperature. However, when the pile is stocked with uranium to provide critical operation at high temperature, it is highly supercritical at room temperature. This makes the control problem very difficult. Taking V equal to 2.1 and T = 3000°K, we find for a solid reactor of optimum shape the following data (see also Table 5, page 2.34).

Material	r_c, cm.	h_c, cm	Uranium, kg.	Moderator, kg.
Carbon	56	103	9.1	5000
BeO	55	101	7.2	6350

(5) Depletion is negligible in a 5,000 mile flight. This simplifies operating conditions, but it means what we already knew, that the bulk of the uranium serves only to make the pile operate. Only about 25 grams are used as fuel in the flight of a particular 5000-mile rocket (page 4.17).

(6) Poisoning and Control Problems. The poisoning in a 5000-mile flight is mainly due to a single exceptional isotope, xenon 135, which has an absorption cross-section for slow neutrons of 3.5 million barns, far greater than that of any other known isotope. Information on this isotope was released, but has since been reclassified; therefore these remarks about its cross-section must be treated as confidential. It is formed in relatively large quantities (about 6% of all fissions) either directly, or as a member of the chain

$$\underset{(6.7\text{ hr.})}{\text{I }135} \longrightarrow \underset{(9.2\text{ hr.})}{\text{Xe }135}$$

or of the chain

$$\underset{(<2\text{ min.})}{\text{Te }135} \longrightarrow \underset{(6.7\text{ hr.})}{\text{I }135} \longrightarrow \text{Xe }135 \begin{array}{l} 9.2\text{ hr. } (90\%) \\ 13\text{ min. } (10\%) \end{array}$$

As long as the pile operates, Xe 135 is rapidly destroyed by neutron-absorption, the equilibrium amount is low, and the extra uranium required to overcome this neutron-loss is always less than 10% of the total. In a 5000-mile missile the extra amount will be considerably less than 10%. Thus the effect of poisoning on the uranium requirement is not serious for these missiles.

The effect of poisoning on the control characteristics appears to be much more serious. It may cause the reactor to oscillate in energy in such a way that control is greatly complicated. The reason for this is easily explained. The function of the controls is to maintain the average reproduction factor at the value unity. That is, the operation must be of the on-off type, because the neutron flux grows steadily when K is greater than one. (While it is limited by the decrease of K when the temperature rises, we cannot afford to let the temperature rise far above the design level. Thus control rods must be provided). Now consider what happens when operation is interrupted. The destruction of Xe 135 ceases, and more is produced by decay of I 135. Thus the control rods must be moved further to start the operation again. The longer the interruption, the more pronounced this effect becomes. Estimates indicate that this effect may be a major difficulty. Further study is required before definite statements can be made.

One point emphasized by Dr. LeGalley of BuOrd in conversation must be brought out. Our discussion refers to the worst case, in which all the poison xenon is retained in the reactor. It is a heavy rare gas. We have no evidence at all on the rate at which this large atom can diffuse through graphite or BeO. It is not possible to make even a rough estimate because the damage to the moderator by fast particles, radiation and nonuniform heating cannot be envisioned. Experiments on xenon diffusion at high temperature are needed.

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D. Fast Neutron Reactors. (Part C).

It may be possible to design a fast neutron reactor which serves first for propulsion and then for an A-bomb at the end of the flight. Whether this is true or not, these reactors must be studied. Presumably they would be fairly free from poisoning effects; there is no reason to believe that slow-neutron swallowers such as Xe 135 would have exceptional cross-sections for fast neutrons.

The first step is to study the multiplication factor K of a spherical fast neutron reactor with a radius in the neighborhood of the critical value. The result is

$$K = 1 + 0.97 \frac{R - R_{cr}}{R_{cr}} . \qquad (8)$$

The critical radius R_{cr} is probably about 5 cm and the critical mass about 10 kg; we adopt these values.

The next question is, can we control a slightly overcritical reactor to obtain useful power? Aside from the fact that it would be hard to obtain personnel for such a project, it turns out to be very difficult, technically.

Therefore we consider the slightly subcritical reactor, a device suggested by Gamow, in which the chain of fissions started by a single neutron eventually dies out, but in which each fission chain contains hundreds or thousands of steps. (We call the number of steps the amplification factor.) Now, the action of a slightly subcritical reactor could be maintained by a neutron source, generating a power which is small compared with that liberated by the main reactor. A rough estimate shows that with existing neutron sources such as polonium or radium-beryllium, the power dissipated would be several per cent of the main power and the amounts of active material needed are embarrassingly large. These difficulties could be overcome if we had better neutron sources available. A spontaneously fissioning material with suitable halflife would be ideal for the purpose. We do not present any missile designs using fast reactors, since the exact amplification properties would have to be known to avoid guesswork, but the possibility of such devices must be kept in mind.

It must be remembered that the detailed conclusions of this chapter about the critical size, optimum concentration and optimum shape of reactors may be afflicted with considerable errors. There are uncertainties in regard to the cross-sections and the number of neutrons per fission. Also we have used the actual densities of graphite and BeO crystals, while the bulk densities of the moderator material may be appreciably smaller. We cannot say what maximum density may be attainable by proper fabrication. The degree of compactness will also affect the thermal conductivity. The whole treatment is based on a simplified solution of the diffusion equation, which itself is only an approximate description of conditions in the pile. The neutron diffusion constant depends on temperature, which itself varies within the pile, depending on the neutron density and the surface heat flow conditions. Thus the real problem involves two coupled differential equations, one for the neutron density and one for the temperature. Indeed, the uranium concentration should be graded to uniformize the temperature.

Attention should be focussed on the ideas developed and the general trend of the data, not on the numerical values presented. These values cannot be wrong in order of magnitude, but we can be fairly certain that the sizes and weights presented are underestimates.

3. <u>SUMMARY OF CHAPTER III. PRELIMINARY DESIGN OF LONG RANGE PILOTLESS AIRCRAFT</u>

It is desired to find the optimum type of design of a fast pilotless airplane to carry a payload of 12,000 lbs. a distance of at least 5,000 miles. The three possibilities discussed are:

The turbo-jet with nuclear energy as the heat source.

Turbo-jet with conventional fuel.

An air turbine driving a conventional propeller, with nuclear energy again supply heat. Families of such vehicles could be designed, but in this report computations are carried through for only one of each type.

The body shape is that of an elongated tear drop with the nose cut off to permit the entrance of the air and the tail cut off to allow it to exhaust through a jet at the rear. The maximum body diameter is 7 feet and length is of the order of 40 - 50 feet.

In the case of the nuclear turbo-jet the reactor design is determined by the simultaneous solution of equations expressing the following requirements:

(1) Mass flow necessary to produce the thrust required for flight under the postulated conditions.

(2) Optimum critical reactor size as a function of the cross-sectional free area through which the air flows. This relation follows from the study of cylindrical enriched reactors given in Chapter II.

(3) Heat transfer relationships, leading to a length-diameter ratio for each tube perforating the reactor. For these calculations a reactor wall temperature of 4000°R. is assumed,--a value not believed unrealistically high from the materials standpoint.

The procedure in evaluating (1) is to model the nuclear design after a commercial gasoline burning prototype. A gasoline turbo-jet of recent design uses 1.08 lbs. of fuel per hour per pound of thrust in producing a thrust of 4000 lbs. It is shown in Section 2 of Part A that from such a thrust a speed of approximately 600 MPH can be realized at 40,000 ft. for this design. From this information the power consumption of the vehicle follows at once. Now the intake and exit stagnation temperatures at the reactor are known. The former is 625°R, which is calculated from the value existing at the compressor intake, plus an increment due to compression. The latter is 2000°R, which the turbine structure will stand. From these temperatures and the total heat requirement the mass flow is determined. From this figure the gas stream cross-sectional area and hence the overall reactor dimensions can be calculated, as mentioned in (2). Then the application of the heat transfer equations outlined in (3) gives us the diameter, and finally the total number, of the tubes perforating the reactor. Thus the three conditions enumerated above can be met simultaneously to give a unique reactor design of the following dimensions:

Diameter	6 ft.
Length	5.5 ft.
Weight (assuming carbon moderator with average density of 138 lb/ft^3)	12,800 lbs.
(Fraction of cross-sectional area allotted to gas stream)	.41
Diameter of individual tube	1.57 in.
Number of tubes	868

The power added to the gas stream turns out to be approximately 33,600 H.P. while the power output of the engine (thrust times velocity) is 6,400 H.P. This gives an overall efficiency of 19%.

The weight breakdown, wing area required and approximate performance are as follows for the three types considered.

Design Type	1 Turbo-jet Nuclear Energy	2 Turbo-jet Conventional Fuel	3 Nuclear Air Turbine with Propellers
Piles or fuel weight, lbs.*	13,500	36,700	13,500
Payload	12,000	12,000	12,000
Power Plant	2,300	2,300	6,000
Propellers, gear boxes, etc.	- -	- -	4,000
Structure	18,200	34,000	23,500
Gross weight at take-off, lbs.	46,000	85,000	59,000
Gross weight at landing	46,000	48,300	59,000
Thrust at flight speed, lbs.	4,000	4,000	3,800
Approximate average air speed, MPH	600	465	550
Wing area, sq. ft.	440	1,870	685
Maximum range	**	4,000	**

** Probably limited only by material failure.

* Approximate for carbon reactor. See page 3.18 for details on C and BeO reactors.

On the basis of these figures, it is concluded that the nuclear turbo-jet has the best performance for a pilotless airplane operating in the domain of high subsonic speed. This conclusion depends on the assumptions that the reactor weights of Chapter II are substantially correct and that the reactor materials will stand up to their task. Cost is not considered; performance only has been analyzed.

4. Summary of Chapter IV. Nuclear Energy for Rocket Propulsion.

This chapter deals with rockets in which liquid hydrogen is heated by an enriched pile. Such a device may be compared with a liquid-hydrogen liquid-oxygen rocket. The optimum specific impulse (pounds of thrust developed by a discharge rate of one pound per second) for the latter is expected with a ratio of 5 moles of hydrogen to one of oxygen. This specific impulse would be about 395 lb. sec. per lb., and the exit temperature about 2760°K. On the other hand, a nuclear energy rocket would yield a specific impulse of 730 lb. sec. per lb. when ejecting hydrogen at 2500°K, or 2225°C. These figures alone do not furnish a valid comparison of the two types. With a fuel of low molecular weight the tank and structure weight required to carry it increases. Furthermore, in a long-range nuclear energy rocket, the reactor must be carried all the way, because there is no advantage in jettisoning it when the missile gets outside the atmosphere and the fuel is exhausted. A detailed calculation (Table 3 in Chapter IV) shows the weight distribution for hydrogen-oxygen rockets and hydrogen nuclear rockets having ranges from 1000 miles to infinity (escape), when working at the exit temperatures mentioned. No impossibility is encountered at these temperatures, up to ranges of 10,000 miles. Thus the question to be attacked is whether a suitable nuclear reactor of the weight allowed by the overall design can be provided. The requirements are that the reactor must have enough surface, and the operating temperature must be high enough, to heat the hydrogen to 2500°K. A number of high-surface designs could be considered. Suppose the reactor is a bundle of rods of radius X. Let j be the average rate of energy transfer per unit of heating surface. Then for a carbon structure, it is found that

$$j/X = 7.4 \times 10^9 \qquad (8)$$

where j is in ergs per sq. cm. per sec, and X is in cm.

Now considering heat transfer by radiation above, X must be about 0.6 cm., on the assumption that all radiation can be absorbed in the gas channels, by loading the gas with an opaque smoke. This would be most difficult. On the other hand, the size found for the reactor elements together with the optimum pile size calculated in Chapter II, suggests that heat transfer by conduction may be very effective. We calculate this transfer by standard equations (their validity under such conditions is not experimentally established, but one must have general faith that they yield answers correct in order of magnitude). It is found, for example, that a pile with circular tubes as heating channels will supply the necessary heat, under the following specifications:

Assumed surface temperature,	$3000^{\circ}K$
Length and diameter	7.4 feet
Tube diameter, about	1.5 cm.
Minimum wall thickness between tubes	0.52 cm.
Per cent of cross-section occupied by tubes	50%
Weight	10.8 tons

Now it happens that this pile is slightly larger than the critical, optimum concentration carbon pile discussed in Chapter II. We can say they are identical within the limits of accuracy of the calculations. The critical uranium requirement of the nuclear energy rocket outlined above is about 36 kg. of U235.

Although the precision of the nuclear energy and rocket calculations may not warrant more detailed figures, the effect of various design parameters can be indicated by calculation which should show the proper relative sizes. Accordingly dimensions of several complete families of rockets are presented. It is found that an increase in the rate of flow of gas over that assumed in the example above can lead to a decrease in reactor weight of as much as 60%. Correspondingly, the initial rocket weights for a ten ton payload can be brought down to values of the order of 60 tons. Also decrease in the critical dimensions of the reactor (for example by the use of higher U235 concentration) can lead to a very considerable decrease in the required reactor size.

Calculations at lower gas temperatures, down to 1600°K, indicate that, with a 5000 mile range and payload (including controls, etc.) of the order of 10 tons a nuclear energy rocket might compete with a hydrogen-oxygen rocket with gas temperatures as low as 2000°K but cannot compete at much lower gas temperatures. Reactor temperature must be several hundred degrees above the gas temperature.

It is interesting that application of the design procedure outlined indicates that a one-stage satellite rocket carrying a 10-ton payload can be driven by nuclear energy; the rocket weight involved is less than 100 tons and the reactor weight is about 4.5 tons. This assumes the feasibility of mass flows (per unit area) of approximately 40 gr./cm^2sec.

In conclusion, the nuclear energy rocket for a payload of 6 to 10 tons can be made superior to any conventional rocket in the sense that the weight required for a given range is smaller or the range obtainable at a given weight is greater. It must be emphasized that these conclusions are based on several assumptions, namely:

(a) Substantial validity of the reactor design carried out in Chapter II.

(b) Feasibility of a reactor operating at a surface temperature of 3000°K for about 200 seconds without structural failure, under the gas pressures encountered.

(c) Sufficiently slow erosion of carbon by hydrogen at the temperatures specified herein.

5. <u>Summary of Chapter V.</u> <u>Supersonic Nuclear-Powered Ram-Jets and Turbo-Jets.</u>

This chapter indicates the technical feasibility of supersonic ram-jets and turbo-jets using nuclear power under certain assumptions and restrictions on the characteristics of the reactor, the flight conditions and the aerodynamic design. These conditions are outlined in the conclusions and discussions section of Chapter V. To have a basis for evaluating such designs it is necessary to compare them with a previously conceived design using conventional fuels.

<u>Conventional Design</u>. Part A of the chapter is therefore devoted to a description of a long-range ram-jet-propelled guided missile, using gasoline as a fuel. This is essentially a summary of a previous report issued by this laboratory. It is concluded that such a design can have a range of 3,070 miles when flown at a Mach number of 2.2 and an altitude of 70,000 feet. The statement is also made that a range of 5,000 miles is in the realm of possibility if certain increases in ram-jet performance can eventually be obtained.

<u>Designs Using Nuclear Energy</u>. It is necessary to lay aside the unsolved questions of mechanical and chemical integrity and to make designs covering a range of operating temperatures which does not completely rule out the use of desirable reactor materials, and which, in the light of existing experience, may provide sufficient thrust to meet our speed requirement. Aside from these considerations, it is desirable to have on record basic calculations concerning heat transfer to a gas stream, by radiation and by convection, in single-tube and multi-tube reactors. It is also desirable to study the aerodynamic characteristics, particularly the internal drag of such reactors, the reactor weights and volumes involved, and the effect of these factors on the size and weight of the bird.

Heat Transfer in Reactor-Heated Ram-Jets. In Part B, a nuclear ram-jet flying at 50-60,000 feet at a Mach number of 2 is considered. First, a formula is derived for the power required per unit volume of reactor material, in preparation for determining the design necessary for transfer of the heat to the gas.

The possibility of radiant heat transfer from a single large tube to a gas-containing smoke was analyzed early in this investigation, It became clear that such a device has no value in connection with 5000-mile vehicles. (See also Part F.) However, the analysis of radiant transfer to a smoke-filled gas is presented because of its possible value in other fields.

A study of convective heating then shows that it is hopeless to consider a single large tube. Such a design is ruled out for a 5000 mile vehicle because the reactor weight would be very great. A multi-tube reactor is clearly indicated. The important result of this section is an equation connecting the temperatures, the ratio of length to diameter, L/D, for a single tube and other quantities; namely,

$$\ln \frac{T_w - T_{do}}{T_w - T_{eo}} = \frac{0.003\ L/D}{(D\rho_i M_i A_i/A_d)^{0.2}} \qquad (5a)$$

Here lengths are in feet, and density in lb./cu.ft.; ρ_i is the intake density and M_i the flight Mach number, while A_i/A_d is the ratio of intake and diffuser areas. T_w is the wall-surface temperature, and T_{do}, T_{eo} are the stagnation temperatures at the entrance and exit of a reactor tube. (The diffuser area is defined to be the gas-stream area in the reactor itself.)

Propulsion and Aerodynamic Analysis.

The subsequent analysis now runs as follows:

(a) The relation between gas exit temperature and net thrust coefficient is worked out for any type of reactor-heated ram-jet or turbo-jet, in form suitable for numerical computation, in Part C.

(b) The aerodynamic analysis could be carried out for whole families of ram-jets. The calculations of Part D are restricted to a flight altitude of 50,000 feet and a Mach number of 2.0. For these conditions, the ratio of body cross section to intake area is chosen to be 3.33 (on the basis of previous calculations) and the reactor is chosen to be a cylinder of the following properties:

Diameter,	8 ft.
Length,	7 ft. approx.
Γ	0.556

(Γ is determined from the bird diameter and the diameter of the critical reactor of optimum shape and concentration.) Stability considerations make possible a reasonable determination of the tail area. By trial, a wing area and a missile weight (74,400 lbs.) are found which satisfy the relation Lift = Weight. Then drags are computed, and it is found that the drag coefficient is 0.371; this then is the value of the thrust coefficient required for flight under the specified conditions.

<u>Connection of Reactor Surface Temperature and Weight which Can Be Flown.</u>

The weights discussed in Part D are necessarily estimates; therefore it is reasonable to calculate a series of values of total weight, corresponding to various reactor temperatures. This is done as follows in Part E.

(a) Γ is 0.556, so the gas-stream area in the reactor is 28 sq. ft., for an 8 ft. bird diameter.

(b) It is assumed, as an educated guess, that the exit gas stagnation temperature is 1000°F. less than the wall-surface temperature. (Equation 5a is employed.) The thrust coefficient can then be computed for a series of reactor temperatures (Table 2, p. 5.43).

(c) For each thrust coefficient, C_t', we have a vlue of the missile weight, namely,

$$W_b = (\text{Lift}/\text{Drag})qA_B C_t'.$$

Here q is the dynamic head, A_B the body cross-section. The value 6 for optimum lift/drag appears to be attainable.

The results, in Figs. 5-4 and 5-5, show the total weight as a function of T_w; also the weights available for structure for the cases of carbon and B_eO as moderators. The conclusion is that a wall temperature of 3600°R (2000°K) or more is required to provide sufficient structure weight in this type of vehicle.

The designs considered may be far from optimum. It may be that a larger reactor and greater length/diameter ratio for the reactor will improve performance and permit lower reactor temperatures. However this may be, a nuclear ram-jet with 12,000 lb. payload appears feasible, subject only to the usual restriction, that the reactor must stand up at the operating temperature of about 3600°R.

In similar vein, in Part G the analysis of a supersonic turbo-jet with exhaust heating, capable of flight at a Mach number of 1.4 is presented. It seems likely that such a design is feasible if reactor wall temperatures of at least 4000°R are used but the uranium requirements are twice as large as those in the ram-jet since two reactors are required. The structure of the vehicle is also much more complicated than that of the ram-jet because of the addition of the turbine-compressor unit.

6. Summary of Chapter VI, High Temperature Materials

Earlier chapters dealt with very high reactor surface temperatures, from 2000°K to 3000°K. Physical and Chemical data in this range are required for further progress. We shall give some facts which will help to outline the general trend of necessary investigations.

A. Materials for Piles and Their Supports. Table 1 of Chapter VI summarizes the melting points of materials which can be considered for the pile moderator or for supporting structures. It is indicated that carbon is the most probable choice for a moderator for rockets. Carbides of some fourth and fifth group elements, (Hf, Ta, Zr) and their alloys and mixtures, may be useful for supporting structures. (These carbides and a few related ones are the highest-melting compounds known; M.P. of 3800 to 3900°C. Reactors for ram-jets and turbo-jets should be B_eO, though a carbon skeleton or matrix coated with B_eO is a remote possibility. Tungsten, which has the highest tensile strength of any known metal at room temperature, might be used in minor quantities as reinforcing material deep within the refractory matrix.

B. Control Rods. The materials suggested for control rods are typified by the following:

CrB or CdC enclosed in carbon tubes.

TaC or HfC with small percentages of gadolinium or its compounds.

Materials containing a few per cent of the cadmium isotope 113.

C. Protection of atomic warhead from neutrons. If the warhead body is TNT, then a one-mm layer of gadolinia deep in its structure will provide sufficient protection. Alternatively, about 1 ft. of highly hydrogenous material and a thin layer of gadolinia will suffice. Protection of liquid-hydrogen fuel against boiling under the influence of nuclear radiations can be accomplished in similar fashion.

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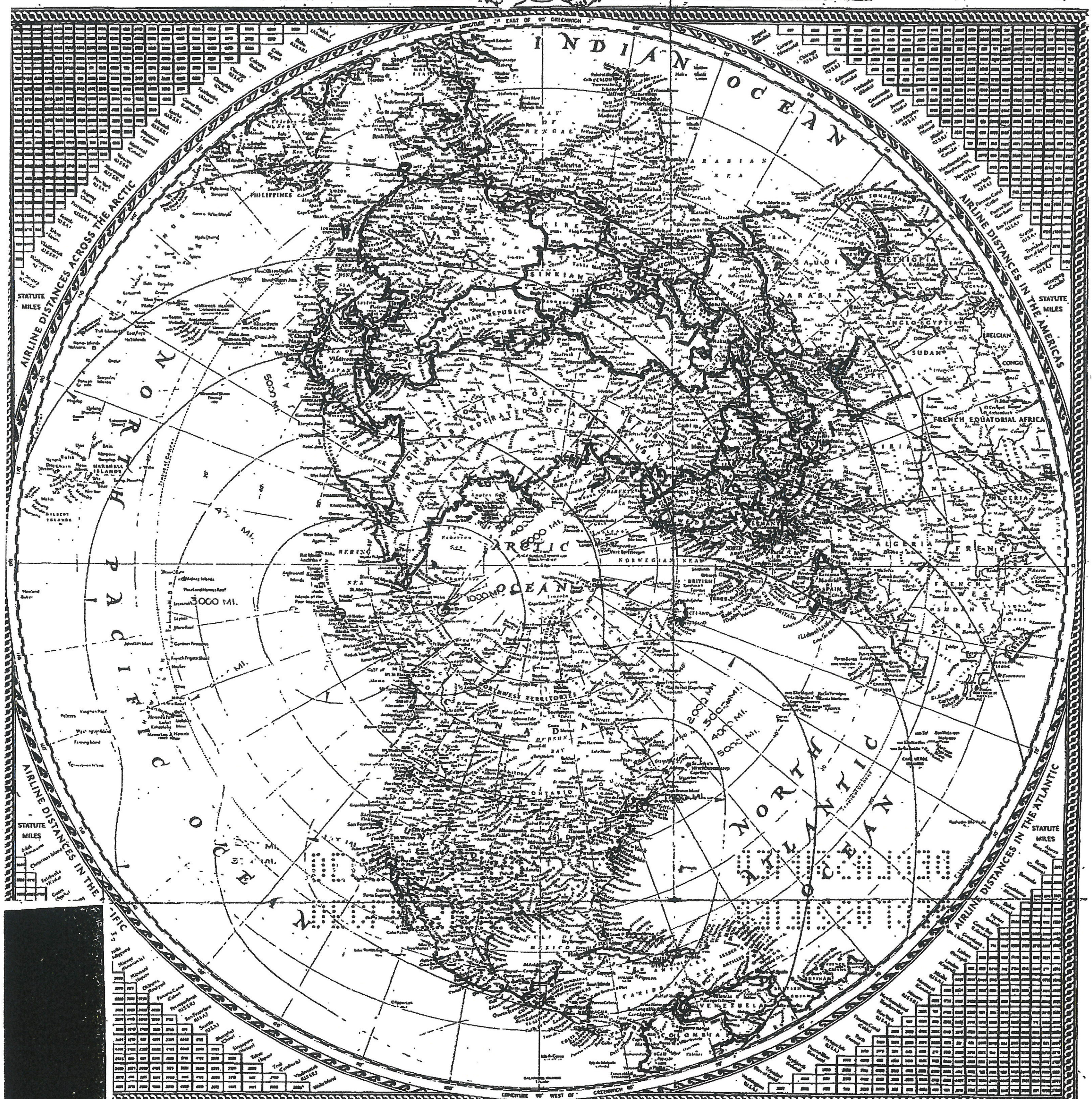

[redacted]

Drawn in the Map Department of the National Geographic Society for

THE NATIONAL GEOGRAPHIC MAGAZINE

Gilbert Grosvenor, Editor

Scale true along the meridians, 632 miles to the inch

Legend

Azimuthal Equidistant Projection. Elevations and Depths in Feet

Principal U.S. Air Bases overseas and kick off Bases in United States ★

European Boundaries on the map are those of January 1, 1938

Russian Boundaries according to treaties and claims as of Dec. 1, 1945

Relief Desert Glaciers

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