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# THE NUCLEAR RAMJET PROPULSION SYSTEM

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# THE NUCLEAR RAMJET PROPULSION SYSTEM

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In presenting this article on nuclear ramjet propulsion systems for your consideration, I find myself faced by two formidable difficulties. In the first place, no such propulsion systems exist as yet so that I must present conjectures rather than demonstrated performance. In the second place, all of the research and development now in process on this subject is either Air Force Secret or AEC-SRD, or both, so that I may not even tell you if the conjectures are true or not. Within this rather restricted framework there do remain, however, some interesting and exciting possibilities to discuss.

While nuclear ramjet propulsion systems have been imagined in many forms over the past thirteen years, it is generally considered that the most practical device consists of a suitable inlet diffusor system followed by a single-pass, straight-through heat exchanger which of course couples into a typical exhaust nozzle. Figure 1 illustrates such an "engine".

The nuclear reactor in such a system usually is conceived to be identical with the heat exchanger. Several possibilities present themselves at least conceptually to the reactor designer within this simple framework, and these possibilities are governed by the aerodynamic requirements of flight, the nuclear requirements of the reactor, the chemical problems associated with breathing air (both wet and dry), and the mechanical properties of materials at rather elevated temperatures. The aerodynamic requirements of flight are illustrated in a qualitative manner in Fig. 2, which gives some typical relations between flight Mach number, heat-exchanger wall temperature, and a number proportional to net thrust coefficient, for a duct containing a reasonable reactor.

Although qualitatively given, these curves illustrate two major points which directly determine reactor design. In the first place, net thrust--and therefore presumably performance of a given missile--will be improved rather rapidly with increasing wall temperature. Furthermore, since some minimum value of the net thrust will be required to fly the missile at all,

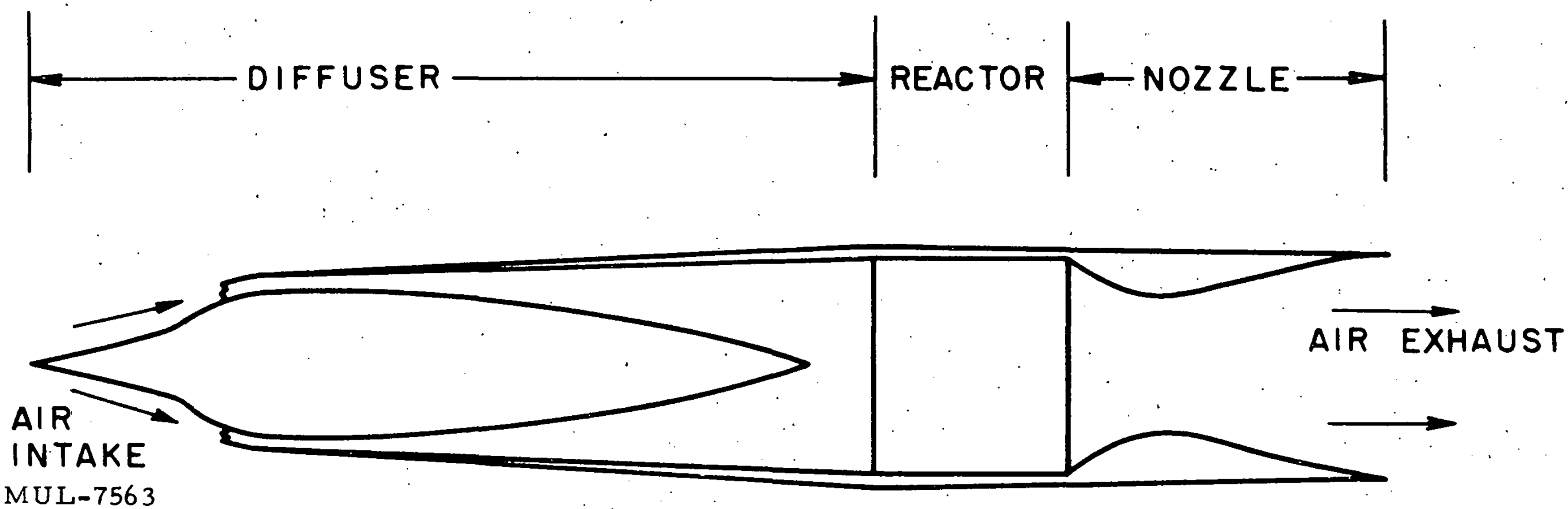


Fig. 1. Conceptual arrangement of a nuclear ramjet.

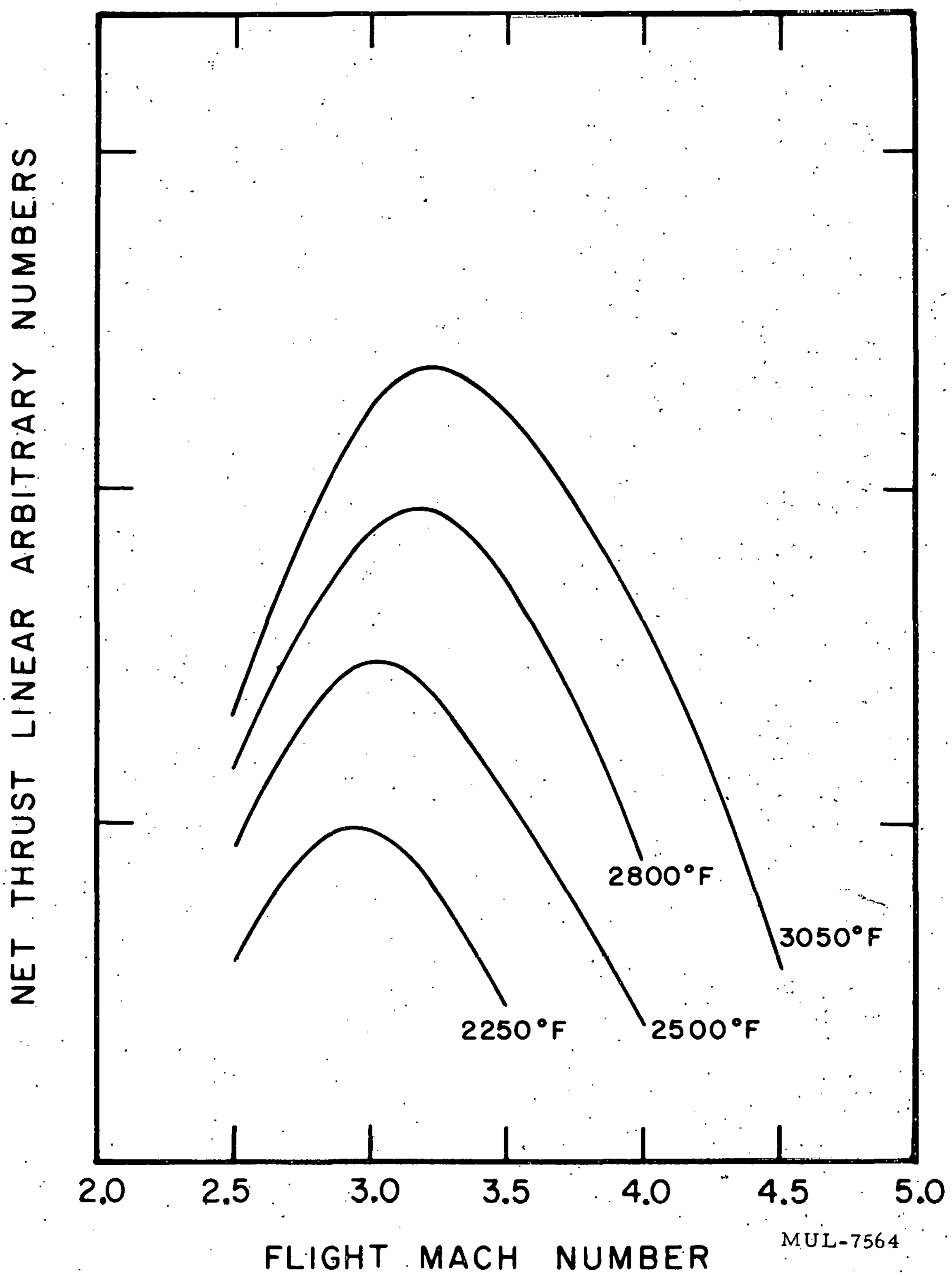


Fig. 2. Typical relations between flight Mach number, heat-exchanger wall temperature, and a number proportional to net thrust coefficient, for a duct containing a reasonable reactor.

there is a corresponding minimum reactor wall temperature (for a given geometric configuration) which must be attained. This minimum turns out to be rather high in terms of materials normally associated with reactor construction. Thus for nuclear ramjet reactors there is an enormous premium in performance to be attained by developing systems that can operate satisfactorily at the highest possible temperatures.

The second major point to note is that other quantities being equal this net thrust coefficient tends to maximize near Mach 3. Thus, if a reactor wall temperature is determined by the behavior of a material at elevated temperatures, the best missile performance could be anticipated near such a Mach number. This fact, in turn, indicates that the reactor must be designed to stand a considerable pressure across its face. At sea level, for example, the stagnation pressure for Mach 3 is approximately 550 psi. Such a pressure is not very formidable when structural weight is unimportant. However, when coupled with high temperatures, weight limitations, and the peculiar structural materials appropriate to the reactor neutronics, it can be supposed that many new research and development problems will be encountered.

The wall-temperature requirement, when coupled with the oxidizing effects of hot air, forces the choice of wall surfaces at least capable of withstanding oxygen attack for long periods. Such materials are high-melting-point metals, certain intermetallic compounds, and the oxides. It is true that a few other types of materials will resist oxidation by forming oxide surface layers while in use, but we shall class these materials along with the oxides. It is also true that oxides will withstand higher temperatures in air by several hundred degrees (F) at least than the best of the present metals. Furthermore, it is desirable, but not mandatory, to avoid thin coatings of oxides on air-passage walls to protect an otherwise combustible structural substrate. Thus, from the "chemical" point of view alone, it might be desirable to form the reactor body of solid oxides or from those materials that could be counted on to form a self-generating protective oxide coating. However, chemistry and aerodynamics are not in themselves sufficient. The reactor must also live with the behavior of neutrons. Here the choices become a little more complex because we must select in some manner the way in which we wish to distribute the nuclear fuel, and in addition it is necessary to determine the amount of such fuel that may be invested in a given propulsion system. The amount of fuel to be spent influences design by deciding the choice between a "fast" reactor and a "moderated" reactor. In a fast reactor the neutrons emerging from the fission process are not slowed down, and because the fission cross section for such "fast" neutrons is very much smaller than the fission cross section for very slow neutrons, for a given size and average density, a "fast" reactor will in general require much more nuclear fuel than a moderated reactor. It turns out that for any reasonable missile size, a fast reactor is extremely expensive in terms of the nuclear fuel.

Thus an economic argument now has coerced the reactor designer into a serious consideration of moderated reactors. However, the business of slowing neutrons down is best done by atoms which individually are as close as possible to a neutron in mass. Thus, for moderating a ramjet reactor, the elements which suggest themselves are hydrogen, beryllium and carbon. Helium has been omitted since there is no known way to render it solid at elevated temperatures, while lithium and boron have been omitted since in the natural state they not only slow neutrons but also devour them. The elements heavier than carbon are rather unattractive since they do not slow the neutrons very effectively. At this point two general possibilities present themselves. The fuel, and with it the heat transfer to the air, can be separated from the materials used to slow the neutrons. Such a reactor is called a heterogeneous reactor. On the other hand, the nuclear fuel could be mixed with the moderating material so that the moderation and heat transfer to the gas are carried on by the same substance. However, while uranium forms a very refractory oxide--namely, $UO_2$--it also forms a volatile oxide when heated to a high temperature in the presence of air. Consequently, if a heterogeneous reactor is selected, the uranium fuel (presumably in the form of $UO_2$) must be protected against direct contact with the air stream.

This alternative then forces the development of some suitable canning procedure. If these cans are metal, then the aerodynamic performance is restricted to that obtained with high-temperature metals. As indicated earlier, such temperatures are not very attractive for nuclear ramjet engine applications. It is possible to consider "cans" or fuel elements consisting of a high-temperature ceramic. Such a selection again forces the development of new materials techniques and presents more complications than the remaining choice, which is the homogeneous reactor. If a homogeneous reactor is selected, its core may be imagined to be a right cylinder of height roughly equal to its diameter. This cylinder is drilled with closely spaced holes such that the open area is roughly half the area of one end of the cylinder. The length-to-diameter ratio of the holes might be approximately 200.

At this point in the analysis the demands of flight thermodynamics, chemistry, a portion of reactor physics, and a brief consideration of the economics of uranium-235, have indicated that a nuclear ramjet reactor might logically be a homogeneous moderated reactor fabricated somehow of a high-temperature oxide of a light metal; or it might possibly be fabricated of a carbide that will form a self-protective oxide coating. Among the light metal oxides there exists only one that is a good moderator--namely, BeO. Among the carbides the most reasonable from the chemical point of view would be SiC. However, it is well known that BeO is a far superior neutron moderator. It is also possible that certain of the intermetallic compounds of beryllium could be used in such a homogeneous reactor. The main point to notice now is that the choices that can be made in the foreseeable future are indeed severely limited.

The mechanical design of such a homogeneous reactor must include means of carrying three major classes of stress. To begin with, there are the stresses associated with the pressure drop through the reactor, and, as indicated earlier, this stress is of the order of hundreds of psi when spread over the entire reactor. When concentrated at various support points it contributes loads like thousands of psi. Next, in order to transfer heat from the fuel to the air stream there must be a temperature drop in the fuel-bearing materials; and, for typical ceramics and power densities that would be of interest for possible missile applications, stresses of many thousand psi result as a consequence of these temperature differences. Such stresses are referred to as "thermal stresses" when occurring in the steady state, and "thermal shock" when occurring under transient conditions. Finally, there are the stresses resulting from "g" loadings associated with flight. Since in principle such ramjet power plants can operate from sea level to quite high altitudes, rather large "gust loadings" must be anticipated.

Now, it is certainly true that most of the technology of Western Civilization rests on the fact that metals yield. That is, in a given mechanical device, small and inevitable errors in design, fabrication, and material properties can equalize under large loads because overstressed areas can yield without major loss of strength. On the other hand, the oxides and carbides, which were selected up to this point as suitable ramjet reactor materials, are all very hard and brittle substances. Thus, even though these materials are fabricated in such a way that suitable strengths are obtained (at high temperatures), it is true that they do not ordinarily possess the familiar yield characteristics of metals. Clearly, then, two areas of work are indicated: one, by ingenious design to minimize the need for yield in the material; and secondly, by ingenious research to impart at least some "give" to otherwise recalcitrant substances. All this must be done, of course, without vitiating the high-temperature and neutronic properties of these substances.

If, somehow, materials have been developed and fabricated so that a useful ramjet reactor could be fabricated, it is still necessary to consider a few annoying problems. The first of these has to do with the variation of the degree of criticality of a homogeneous moderated reactor as the temperature varies from ambient to the very high operating temperature desired. Such variations may be equivalent to having to increase the amount of fuel in the reactor by 50% or more to maintain criticality during "warm up." Since no "hot moderator" reactors have been run to date, it is desirable to run a "critical measurement" program on a variety of systems constructed inside a large high-temperature oven. Such an oven has been constructed in Nevada by this Laboratory and has been measuring hot "crits" since last February (see Fig. 3). This large negative temperature coefficient of reactivity has a good and a bad future. On the good side, it makes the reactor rather safe, since if it "runs away" it will get too hot and shut down the power increase. On the bad side, it makes necessary a very large "control swing" associated with a large excess reactivity potential built into the system. If improperly handled, such a large excess reactivity can lead to a very fast reactor "period" (rate of rise of power) which can have embarrassing consequences. Otherwise, this large swing in control as the temperature rises would not appear to be very troublesome.

Another annoying problem in this type of propulsion system has to do with the large flux of neutrons and gamma radiations given off by the reactor. These radiations contribute a large heat load to structural materials inside the

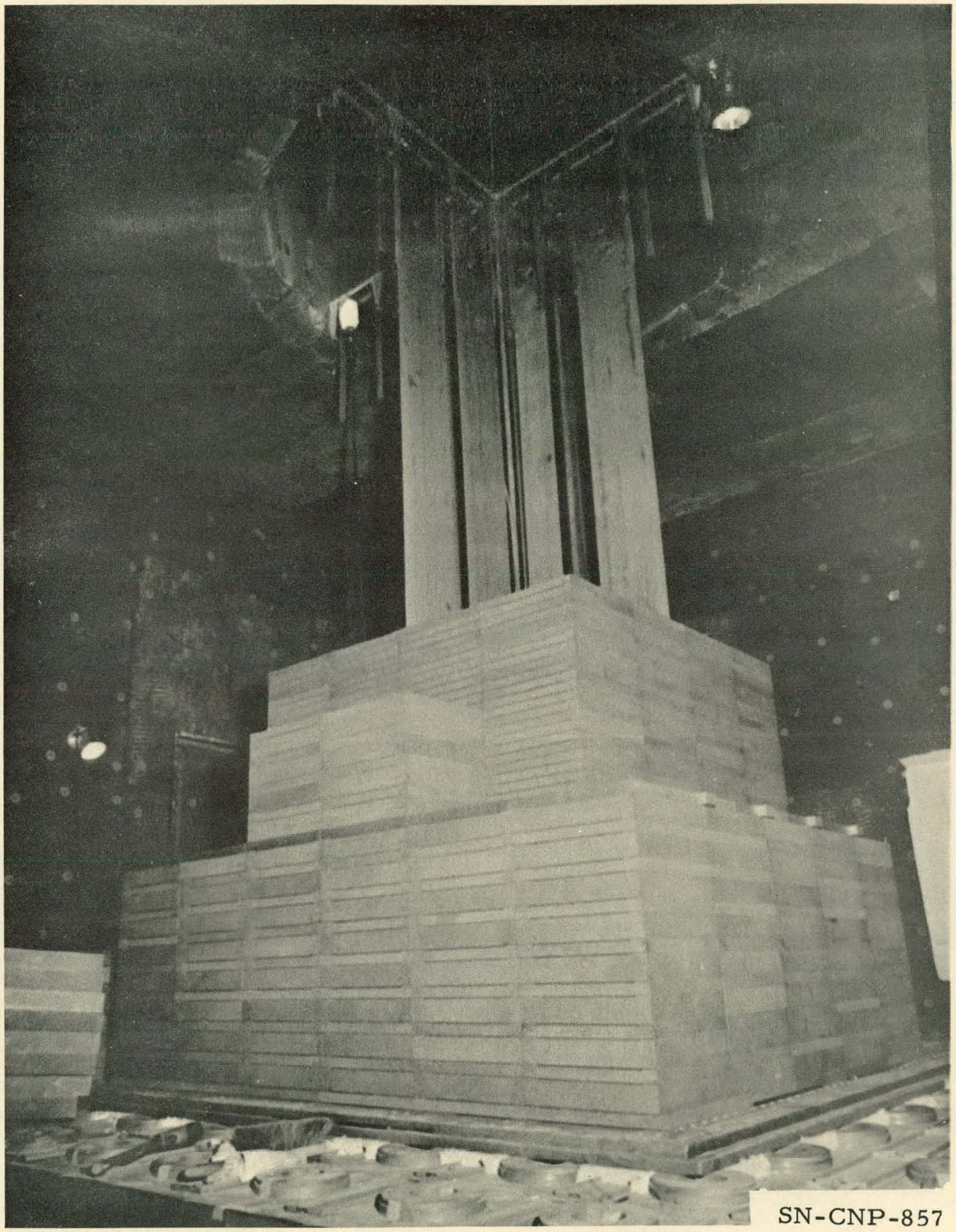


Fig. 3. View of core being assembled in oven.

reactor, and also create an unpleasant environment for materials outside the reactor. Even though the missile is unmanned, the heating effects of these radiations must be taken into account very carefully. Furthermore, the radiations are intense enough to make it necessary to avoid certain materials altogether, or to shield them heavily. Thus, many components of the propulsion system, even though not directly involved in the reactor design, must be specially developed for such environments. Of course, since the stagnation temperature of Mach 3 air at sea level is about 1000°F, environmental problems are severe even without the reactor radiations.

The reactor radiations, while intense, do not lead to problems with personnel who happen to be under such a power plant passing overhead at flight speed even for very low altitudes. Also, in launching such a device, the reactor can be brought up to power during the boosting phase so that personnel near the launching point need not be exposed to excessive radiation even though unprotected.

The question of launching necessarily suggests the question of regulating the reactor power during flight. If it is desired to use a homogeneous reactor in such a ramjet, it will be necessary to live with a power plant that turns off and on rather slowly. The heat capacity of the reactor is of course quite large; and this feature makes variations of power in the gas stream quite sluggish even though reactor power generation rates can be relatively rapid.

In addition to the sluggish response to demands for power change, a nuclear reactor cannot be turned off in a very short period of time owing to the heat liberated by radioactive nuclei created during the operating period. If it is desired to land, or recover, a ramjet missile, this power-plant feature will require special provisions for "shutdown" cooling (as it is called) once the normal ram-air cooling has stopped. For typical types of ramjet power plants the after-heating rate is of the order of megawatts immediately after shutdown, and decays rather rapidly from this value.

Nuclear ramjet propulsion systems have essentially one advantage over chemical systems of the same weight (including fuel), namely, a relatively long cruising radius. Contrary to popular belief, this range is not infinite. Several factors can limit the life of a reactor for ramjet applications to periods of time from a few hours to a few days depending on the methods of construction. The most obvious limit is actual fuel consumption. If we assume that a reasonable size for a missile might require a power plant producing about 490 Mw* (megawatts), then the power plant will have to burn 500 grams of uranium for every 24 hours of operation. (A useful number to remember is that 1 Mw day ≃ 1 gram of fission uranium.) If the reactor requires, let us say, something like 50 kg of uranium to keep it critical, then the reactor is burning roughly 1% of its uranium/day. Thus, if accumulation of reactor poisons can be avoided, we see that many days of operation would be reasonable from a fuel burnup point of view.

However, when a uranium atom fissions in a material, the material near the fissioning atom is disrupted by the flying fission fragments. Such radiation damage in power reactors operating at much lower temperatures can limit the structural life of these materials to a few percent burnup (depending on the detailed nature of the material). For ramjet reactors, an interesting by-product of the high-temperature operation is the possibility that at least some of this sort of damage can "anneal" out of the material, thus appreciably increasing the reactor life.

One problem that bothers the designer of reactors to be used near people is the necessity of confining all the fission products to the reactor fuel elements. In the case of a nuclear ramjet missile it is interesting to note that this problem is not severe. In the first place, again using a 490-Mw* size as an illustration, a typical mission might produce somewhat less than 100 grams of fission product. Of these it might be expected that some large percentage would naturally remain in the fuel elements. Thus the quantity released into the air stream might be a few grams. Furthermore, this few grams must, by the very nature of the ramjet, be distributed over the thousands of miles of its flight path. Consequently the fission activity introduced locally into the atmosphere is minute compared with even the most minute atomic weapon. (A 20-kiloton fission bomb "burns" about 1000 grams of fissionable material.) Thus, for actual military use, such a ramjet power

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*This value is given in the unclassified Russian journal Application of Atomic Engines in Aviation by G. N. Nesterenko, A. L. Sobolev, and Yu. N. Sushkov, page 113, line 7, for a typical nuclear engine design operating condition. The journal was published by the Military Press of the Ministry of Defense of the USSR, Moscow, 1957.

plant need not be designed for complete retention of fission activity. For routine testing, however, and for training missions in peacetime, it is desirable to develop materials that really hold the emission of fission fragments to extremely small values.

I believe that the nature of the challenge facing the designer of a ramjet engine reactor has been illustrated rather completely by the discussion up to this point. It may be of interest to itemize the major research and development areas which must be entered if one wishes to actually produce such an engine.

1. High-temperature ceramic materials must be developed--both in the laboratory and in production--to a high degree of reliability with respect to mechanical properties.

2. Techniques for distributing the fuel in appropriate amounts in such ceramic materials have to be evolved, and these techniques must result in a material which does not "leak" fuel at high temperatures. It would be nice if this material did not leak fission fragments either.

3. These materials must be developed to possess the further characteristic that chemical attack by the various components of "air" on the flow-passage walls does not unduly limit the useful life of the reactor.

4. Ingenious mechanical design features must be evolved to enable these novel materials to be exploited effectively.

5. The nuclear physics of hot moderator systems must be explored in great detail both experimentally and theoretically.

6. Novel control systems, compatible with flight requirements, must be developed. In some cases new materials must be evolved for portions of such systems.

7. Since the cost of testing a complete full-size reactor is quite high, methods for fully testing components and subassemblies must be worked out.

8. A series of reactors must be built and tested with care in order to "evaluate" a satisfactory finished product. It might be expected that the first reactor of such a type to be built would succeed in defining new problems rather than in providing answers to existing questions.

9. Since many fabrication methods of a new sort are required, it will be necessary to develop manufacturing practices, product-control methods, and inspection techniques with a sharp eye on the various cost factors involved, if such reactors are to become suitably inexpensive. This feature

might turn out to be no small order since many of the materials of interest are by no means items of commerce today.

10. Finally, every item in a proposed missile outside the reactor must be engineered to be compatible with an intense radiation environment and, furthermore, tested in such environments.

It has been publicly announced that this Laboratory is presently constructing facilities at the Nevada Test Site for the purpose of operating engineering test reactors in connection with Project Pluto. The development of a reactor to test in such facilities would clearly indicate a serious start upon this development road rather than the end of such a journey.

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