# LOS ALAMOS SCIENTIFIC LABORATORY

OF THE UNIVERSITY OF CALIFORNIA

LOS ALAMOS, NEW MEXICO

[redacted]

CONTRACT W-7405-ENG. 36 WITH THE
U.S. ATOMIC ENERGY COMMISSION

NOTICE

EACH COPY OF THIS REPORT MUST BE ACCOMPANIED BY A COPY OF: LAMS-2130



APPROVED FOR PUBLIC RELEASE

[redacted]



LOS ALAMOS SCIENTIFIC LABORATORY
of the
UNIVERSITY OF CALIFORNIA

Report written:
April 1956



LAMS-2036 This document consists of 49 pages

C.2

[redacted]

# THE LASL NUCLEAR ROCKET PROPULSION PROGRAM



by

R. E. Schreiber



All Los Alamos reports present the opinions of the author or authors and do not necessarily reflect the views of the Los Alamos Scientific Laboratory. Furthermore, this LAMS report is an informal document which has been prepared for a special purpose and is not considered suitable for general distribution. It is accordingly requested that no distribution be made without the permission of the Office of the Director of the Laboratory.

NUCLEAR PROPULSION



[redacted]

[redacted]



NUCLEAR PROPULSION

| Report distributed: JUN 20 1956 | LAMS-2036 |
|---|---|
| AEC Classified Technical Library (Skinner, DMA) | 1 |
| AEC Classified Technical Library (Starbird, DMA) | 2 |
| AEC Classified Technical Library (Keirn, DRD) | 3-4 |
| AEC Classified Technical Library (Davis, DRD) | 5 |
| AEC Classified Technical Library (Schmidt, DRD) | 6 |
| Aerojet General Corporation | 7 |
| Albuquerque Operations (Ager) | 8 |
| Armed Forces Special Weapons Project, Field Command (Capt. Montague) | 9 |
| Manager, San Francisco Operations | 10 |
| North American Aviation, Missile Development Division | 11 |
| North American Aviation, Rocketdyne Division | 12 |
| University of California Radiation Laboratory, Livermore (York) | 13 |
| University of California Radiation Laboratory, Livermore (Gordon) | 14 |
| Western Development Division (ARDC) | 15 |
| Wright Air Development Center | 16 |
| Los Alamos Report Library | 17-60 |





[redacted]

ABSTRACT

The immediate objective of the LASL nuclear propulsion (Rover) program is the development of a heat exchanger reactor system utilizing uranium-graphite fuel elements and ammonia propellant. This program is regarded as the first step in the development of nuclear propulsion systems for missiles. The major tasks of the program include the investigation of materials at high temperatures, development of fuel elements, investigation of basic reactor characteristics, investigation of engine control problems, detailed engine design and ground testing. The organization and scheduling of the initial development program have been worked out in some detail. Only rather general ideas exist concerning the projection of this work beyond 1958.






[redacted] [redacted]

[redacted]





[redacted]

## CONTENTS







[redacted] [redacted]

[redacted]





[redacted]

[redacted]



## INTRODUCTION

The Los Alamos Scientific Laboratory nuclear propulsion program has been underway now for approximately one year. After some oscillations, objectives and scope of the work have become relatively stable and it appears useful to present a general picture of the program and its implications. Specific technical details have been avoided deliberately since new data are being generated at an accelerating rate and today's latest results may be obsolete next week. While only a few specific credits are given in the text of this report, the ideas presented here have been contributed by many people involved in the LASL Rover program.

It will be noted that there is no section on nuclear rocket missile performance. Enough analysis of systems was done at the beginning of the program to demonstrate that a nuclear rocket propulsion system could outperform a chemical system in long-range, high-payload applications provided that the nuclear system functioned as predicted. Until the basic characteristics of the nuclear system are known, further detailed missile system studies appear to be both unnecessary and misleading.

The reader of this report may be struck by the bold note of optimism indicated by the lack of "weasel" words and of alternate plans to be pursued in case of failure. Let it be said here that the possibility of major disappointments has been recognized but that there are so many ways in which this can happen that the only sensible course is to plan on the basis of success rather than to dilute effort by many parallel approaches. If there is a major setback, a specific remedy must of course be found, but this is considered to be cheaper than a general scheme of backup programs. The schedule reflects the same optimism in the sense that only nominal development times are allowed for each phase of activity.

## GENERAL PROGRAM SUMMARY

The LASL nuclear propulsion (Rover) program has the general objective of utilizing nuclear energy for the propulsion of missiles. Of the various theoretical possibilities, the use of rocket propulsion via a heat exchange between a fission reactor and a fluid propellant appears to be the most reasonable starting point and constitutes the immediate objective of the program. This work requires research and development in the fields of high temperature materials, basic reactor performance, fluid dynamics, heat transfer, fuel element characteristics, engine control and engine testing techniques. A reactor using uranium-loaded graphite has been chosen for the first model. A power level of about 1500 MW appears appropriate for the first test device. The major efforts are concentrated on basic reactor and associated engine components and there is no attempt at this stage to examine the general problem of a complete nuclear missile. The current program is aimed at a first nuclear heating test of the uranium-graphite device in the latter half of calendar 1958.

Before discussing the specific tasks involved in the current program, something should be said concerning the consequences of this work

[redacted]

and of more ambitious applications of nuclear energy to propulsion. Since 1946 there have been a variety of proposals along this line. These are summarized in the Appendix, compiled by R. W. Bussard, and previously issued in slightly different form as a local LASL memorandum. The general consensus of these studies has been that the most available device is a nuclearly heated rocket propulsion system. If this can provide an exhaust temperature of 2500° to 2700°C to a low molecular weight propellant it will offer significant advantages over existing chemical rocket systems for large ranges and payloads. The disadvantage of the nuclear rocket system is the fact that an appreciable motor weight is required even for small thrusts, so that the effect of a high specific impulse is nullified up to some minimum payload and vehicle velocity increment. Specific examples have been presented, for example, in LAMS-1870. Studies of this sort are subject to a variety of uncertainties stemming from lack of information regarding actual characteristics of nuclear rocket systems (and, for that matter, those of very large chemical rocket missiles). It seems safest, therefore, only to draw the following general conclusion: That the heat-exchanger nuclear rocket appears sufficiently promising to justify a development program extending at least to the point of determining the basic characteristics of such a system. This conclusion is essentially the basis for the present LASL work.

The development of the heat-exchanger engine should only be the first step in the application of nuclear energy to propulsion. When one considers that the amount of nuclear energy in a kilogram of fissionable





[redacted]

material is some $10^7$ times that in a kilogram of chemical fuel, it seems clear that the use of nuclear energy is the course to pursue if order of magnitude gains in propulsive energy are desired. Progress in this direction may be either evolutionary or step-wise, depending upon the creation of new ideas. The evolutionary process is naturally the more predictable of the two processes. Several variations of the heat-exchanger system have been proposed. The direct fission heating of propellant by the use of thin films of fissionable material offers one obvious direction for exploration. This development depends almost entirely upon the ability of thin films to survive in the environment of hot, fast moving propellant. It is therefore essentially a materials problem which is related to our first problem of providing relatively thick solid fuel elements, although much more difficult.

The use of a liquid reactor in place of solid fuel elements has also been suggested in several versions. This scheme at least changes the problem, although it is not clear that it makes it easier. If the fissionable fuel is liquid, the propellant can be bubbled through it and achieve rapid heat exchange. Centrifugal separation of the fuel and propellant has been suggested by several independent sources.

The shock heating of propellants is also possible in principle. These methods generally involve the preheating of the propellant by a nuclear heat exchanger and subsequent superheating by means of shock waves which traverse the volume of the propellant through a system of orifices and baffles.

[redacted]

There is also the straightforward method of chemical combustion following a nuclear preheat. At the most, this gives an increase in exhaust velocity of about 25 percent.

In general, the methods outlined above are basically variations of the conventional rocket in which the useful energy is limited by the heat capacity of propellant carried along in the rocket. While it is not clear that all such methods deserve to be explored in detail, the current work with simple heat exchangers appears to be a necessary prelude to further work in this direction.

Another class of rockets is generally typified by the fizzling bomb concept. At a sufficiently high rate of reaction, a substantial energy release can be achieved by an explosive fission reaction in which the recoiling mass of the reactor itself furnishes the impulse to drive the vehicle. Highly moderated reactors should be used, both for low critical mass and to provide inexpensive material to be ejected. Possible methods range all of the way from a single shot, through multiple explosions, to a continuous reaction analogous to a solid propellant chemical rocket. All such schemes are characterized by the incompatability of reasonable accelerations and economical use of active material. Roughly speaking, the time of an explosive nuclear reaction is equal to the shock wave transit time across the reacting zone. Unless some ingenious cushion is built in, this time also characterizes the impulse given to the missile. If this impulse is to give the missile a velocity increment of several thousand feet per second, the resultant accelerations are fairly fantastic.





[redacted]

In principle, a slower reaction with reasonable fissionable material economy could be achieved with a gaseous reactor that retains preferentially the fissionable fuel, but no schemes yet proposed seem workable.

The use of externally exploded nuclear bombs has been suggested by several people. The missile is thrown upward by the shock wave or absorbs radiant energy in its tail which is then exchanged to propellant ejected immediately after the blast. Everett and Ulam (LAMS-1955) have suggested that the external shock could be cushioned either by a magnetic field which repels the ions in the shock wave or by a curtain of propellant, which might be ordinary water, which would be vaporized and provide a relatively soft push of expanding steam.

The point in mentioning these more exotic proposals is to bring out the fact that the enormous amount of energy available from the fission process permits the consideration of vast variety of techniques.

Finally, a few practical ideas exist concerning the development of low thrust, high specific impulse devices for use in free-field space.

If one accepts the basic premise that the delivery of military or scientific payloads over large distances, including satellites and space flight, is of national importance, the need to apply nuclear energy is obvious. One can then philosophize concerning the method of application. The philosophy back of the LASL program is that a direct attack on the heat-exchanger rocket reactor not only offers a useful application in itself, but it also provides a suitable environment for the development of more advanced ideas which may take longer to reduce to practice.

[redacted]

## MAJOR TASKS

Propellant exhaust temperatures up to 2500°C are desired. There exists little information on the behavior of solid materials at such temperatures and one major program is that of determining physical and chemical properties of graphite, uranium-graphite mixes, and of various combinations of metal carbides and graphite up to their melting or decomposition temperatures. The properties of propellants and their interaction with fuel elements are of equal importance.

The reactor itself must be designed as a highly efficient and predictable heat exchanger if it is to perform its function. Both theoretical and experimental studies of heat exchange between fuel elements and the propellant are therefore required. For the experimental measurements, electrically heated fuel element mockups are used, since nuclear heating cannot be used locally at the required level. Several power levels are contemplated.

Early work is being done at levels up to about 150 KVA. This power is adequate for basic corrosion and heat exchange studies but is not enough for scale or component testing. A test facility for higher powers is being built in two phases. Phase I will provide 500 KW of motor-generator power and about 1 MW of battery power. Phase II will expand the battery power to about 10 MW. The amount of electrical power





[redacted]

[redacted]



appears large until it is compared with the roughly 1500 MW power level of the first test device and its power density of about 100 MW/ft$^3$. Since the length of flow path cannot be shortened if full gas temperature is achieved, this means that a 10 MW test gives a sample of only 1/10 ft$^3$ or a section through the length of the reactor about 2.5 in. in diameter

The design of the reactor itself must take into account not only the usual neutronic considerations, but also those arising from heat transfer requirements, high mechanical loadings, the balance between local power generation and cooling rates and the rather complex problem of startup, control and shut-down. Multi-group calculational methods are used in combination with mockup experiments to establish the critical mass, required fuel loading and control characteristics of the reactor. For preliminary work, a mockup assembly known as "Honeycomb" is being constructed. Graphite slabs, oralloy foils, plastics simulating propellant and beryllium reflector blocks can be assembled into this machine in various arrays in order to study the nuclear behavior. Later, a more exact mockup of the final test device, known as Zepo, will be assembled. Finally, the NTS test device will be assembled and operated at very low power before it is shipped to the test site. All of this experimental work will be monitored by appropriate calculational studies.

The problem of engine control appears to be quite formidable. The high level of power and the desire to work close to the upper temperature limit of the device calls for a rather precise control both of the nuclear power generation and of the cooling rate controlled by the propellant



[redacted]

[redacted]

supply system. In order to be useful for missile propulsion, the nuclear engine must be started and brought up to power in a minute or less. During this time the reactor must be operating on a fast but controllable positive period while the reactivity is being perturbed by propellant density variations, thermal expansion and even an appreciable change in thermal neutron cross section due to the change in temperature of the moderating materials. For testing purposes at least, a programmed shutdown must be accomplished in a manner which leaves the reactor intact. An analog simulator is being ordered for analysis of the control problem. It can be used either to simulate the entire engine system or to supply signals to the actual hardware items. These studies will be used to develop an automatic programmer for use in the NTS testing.

The study of high temperature material properties has been discussed above. Once these are known and combined with information on propellant corrosion, coating and fuel loading specifications and mechanical requirements, there remains the considerable problem of fabricating fuel elements of known and adequate properties. CMR-Division has the responsibility for this work. To this end it has in progress five programs divided into two main groups.

Group A. Graphite Based Fuel Elements

1. Development of fabrication methods based on the manufacture of graphite from mixtures of uranium compounds with petroleum coke, graphite flour or lampblack, and pitch. The processes involved include mixing, extrusion (or molding), coking and graphitization.





[redacted]

2. Development of fabrication methods based on impregnating previously shaped graphite pieces with uranium salts, followed by drying, ignition and conversion of the uranium compound to oxides or carbides. The possibility of complex mixtures of uranium with other metals to secure higher melting point oxides or carbides or other compounds is not being neglected.

3. Development of methods of coating graphite with refractory compounds to reduce sublimation, chemical attack and erosion under the extreme temperature and gas velocity conditions existing in the reactor. The major problems include (a) securing sufficiently high melting points, (b) compatibility at operating temperatures with the graphite, with the uranium containing substance, and with the gas atmosphere, (c) uniformity of thickness, and (d) adequate adherence to the graphite.

Group B. Fuel Elements Based on High Melting Point Metals

4. Studies on the physical metallurgy of the very high melting metals, e.g., Mo, W, Ta, Cb, Re (?), and their alloys containing uranium, including phase equilibria, high temperature properties, workability, etc.

5. Development of fabrication methods for producing fuel elements of these metallic materials. Extrusion, forging, swaging, rolling, drawing and other processes may be involved.

In connection with the above programs, provisions are being made for the measurement at reactor working temperatures of such properties as tensile strength, creep, thermal expansion, thermal conductivity, and others which may be of interest on both graphites and metallic materials.

For all the programs except (4), one of the major problems is to develop methods which are suitable for use in producing large numbers of pieces for the fuel elements. In the case of graphite based elements, present reactor designs and fabrication schedules indicate that one or more thousands of pieces per month must be fabricated and coated. Furthermore, very soon after the material and fuel element design have been selected, the Division must be in a position to begin production. It is already known that whatever graphite based fuel element is chosen, certain rather large-scale installations will be required; plans are being made and equipment ordered to secure them. Designs of metal based reactors are not far enough along to make a similar statement but obviously similar considerations apply.

The investigation of fuel elements based on high melting point metals offers the possibility of applying different materials (and different techniques) to future generations of reactors. Since these metals have practically no neutron moderating properties, a metal-based reactor requires a separate moderating component if the critical mass is to be reasonably low. The analysis and design of such a reactor is somewhat complicated and for this reason it is not considered suitable for the initial program.

As mentioned earlier, it is planned that there be a first test of





[redacted]

a nuclear rocket test device in the latter half of calendar 1958. Such a test requires a remote site because of the high radiation level during test, the rather high probability of local contamination from fission fragments in the propellant exhaust and the general safety problems involved in this scale of operation. The Nevada Test Site has been selected for this work because of the economy and ease of operation provided by the adaption of an existing test facility. Preliminary plans have been worked out with the Albuquerque Operations Office and the Livermore Project of UCRL for joint usage of a test area in the southwest portion of the NTS and adjacent USAF bombing range. The two laboratories will have separate test facilities near one another which are serviced by a common administrative area.

The LASL test area will initially contain two test cells, a control room, assembly building, disassembly building, hot storage area, tank farm and possibly several instrument bunkers. The test cell will house the test reactor itself on a thrust stand and will have shielded compartments for the control and diagnostic equipment. It also contains a pump room which houses the propellant pump and its control equipment. Since a five minute test at full power releases a fission energy equivalent to about 0.2 KT, everything in the immediate vicinity of the test device must be regarded as expendable, although one hopes that enough protection can be provided to permit salvage of equipment after a suitable cooling-off period. The pump must be located close to the test device in order to provide the high pressure and high rate of flow necessary to the test. Even without piping losses, something like 4000 hp is required. We anticipate the use of a gas turbine drive in a setup similar to that used in chemical rockets, although there will be no effort to develop a compact, light-weight unit for this test. The development of the pump and its controls will be contracted to a suitable commercial organization.

Upon completion of the test, remote methods of removing the test device to a shielded disassembly building are required. When this has been accomplished, the device will be disassembled by remote manipulators and interesting components returned to LASL in shielded containers for post-mortem studies. The assembly building, control room and instrument shelters are either conventional structures or are closely related to those now used in bomb tests. The tank farm for propellant and coolant supplies will be installed by a contractor.

ORGANIZATION

In April, 1955, N Division was formed in order to serve as a center for the nuclear propulsion work. There are four Groups concerned with (1) materials and testing, (2) basic reactor neutronics, (3) engine design and testing, and (4) engine controls and instrumentation. The Division is in the process of growing up to a population of some ninety people and currently has about seventy. One Group (N-2) devotes approximately one half of its effort to critical assembly work related to the warhead work.

As mentioned before, CMR Division has the basic responsibility for the development and fabrication of the fuel elements. This work occupies approximately fifty-five people at present and is spread through seven groups, most of which also carry on activities related to the warhead program.

Problems of inspection and non-destructive testing are being studied by GMX-1. Work on the extrusion of carbon and carbon-uranium mixes is done in GMX-2 in collaboration with CMR work.

Members of T Division participate in the calculational program, both as consultants on special problems and as participants in the computational work.

[redacted]

The Nevada testing work is regarded as a joint enterprise between N and J Divisions. The administrative setup for this work closely parallels that of warhead testing, with the Test Director and his staff furnished by J Division. The extent of participation by the scientific groups of J Division depends upon the relative priority of warhead and rocket testing work. Thus far, this scientific participation by J Division has been carried on under a policy of no interference with current warhead testing programs.

In addition to the participation by members of the technical divisions, the usual support facilities of the laboratory are available to the propulsion program.

Both the AEC and DOD have expressed concern lest the rocket propulsion work divert too much effort from the LASL warhead development effort. For this reason, any work which can sensibly be farmed out to off-site contractors will be handled in this fashion. Thus it is planned that much of the equipment for the NTS testing, including pumps, tank farm, data transmission and recording, test stand and hot disassembly building, be handled largely by outside contractors. This technique is most successful if the particular project can be adequately isolated from the rest of the program. Close technical control must be maintained in general, and this may require some contractor representatives to be in residence at Los Alamos.

Since the nuclear rocket has a number of features in common with chemical rockets, arrangements have been made for missile organizations





[redacted]

to provide staff members in residence at Los Alamos. These are known as Industrial Staff Members. Their assignments are subject to ground rules formulated by the LASL and agreed to by the parent organization. At the present time there is one ISM each from North American Aviation and Aerojet-General. There have been some negotiations with the Westinghouse Research Laboratory, Convair, Bendix Aviation, and Reaction Motors, Inc., but no definite commitments made.

There has been no attempt to project organizational planning to the work beyond ground testing of nuclear rocket propulsion systems. If the success of such testing and the general missile situation justify the development of a flying test bed or an operational missile, it is clear that the LASL is not prepared to accept the entire job of such a development. Some partnership arrangement with a missile development organization would be in order. Some speculation regarding such a program is presented at the end of this report.

## TIME SCALES

Soon after the start of the Los Alamos program, the question was raised concerning the most expeditious way of proceeding. Literature searches revealed that there was very little in the way of basic information on the properties of material at temperatures in the range of 2000° to 3000°C. Such information is obviously of basic importance to the development of a high temperature reactor. If the development were to proceed step-wise, a period of at least two years could be spent profitably on the development of basic materials information. On the other hand, a program following this philosophy might run for a decade before any definitive results were obtained. The other extreme would be that of picking a date for a definitive test and developing the best device that could be made available in that time. The philosophy of development which evolved from these considerations may be stated as follows:

> There exists a very strong interaction between the several activities involved in the development program. They must therefore proceed essentially in parallel in order to provide mutual guidance. The sum total of information available from materials

research, low-power reactor operations, small scale heat transfer experiments, etc., is not adequate to predict the performance of the complete rocket system. Ground testing of the complete rocket reactor is therefore an essential part of the development program and is not simply proof testing of a predictable device. Initial tests should be made on relatively simple systems in order to permit diagnosis of results. Ground testing should be started as early as possible and should be considered as a continuing (although perhaps intermittent) operation.

The choice of a uranium-graphite reactor as the first test device was made near the end of 1955. The considerations leading to this choice are given in LAMS-1983.* The reactor is to be homogeneous except possibly for a central carbon or beryllium island, to have plate or tubular fuel elements, a beryllium tamper, use ammonia propellant, have a full power rating of about 1500 MW and a core power density of about 100 MW/ft$^3$.

A target schedule for the development of the reactor itself and of the facilities needed for its development and testing is reproduced as Figure I. This schedule is obviously subject to frequent revision as information develops. Aside from the uncertainties of actual technical progress, the availability of facilities is subject to the problems of

* LAMS-1983: "Nuclear Rocket Reactors; a Six-Month Study Review" by R. W. Bussard.

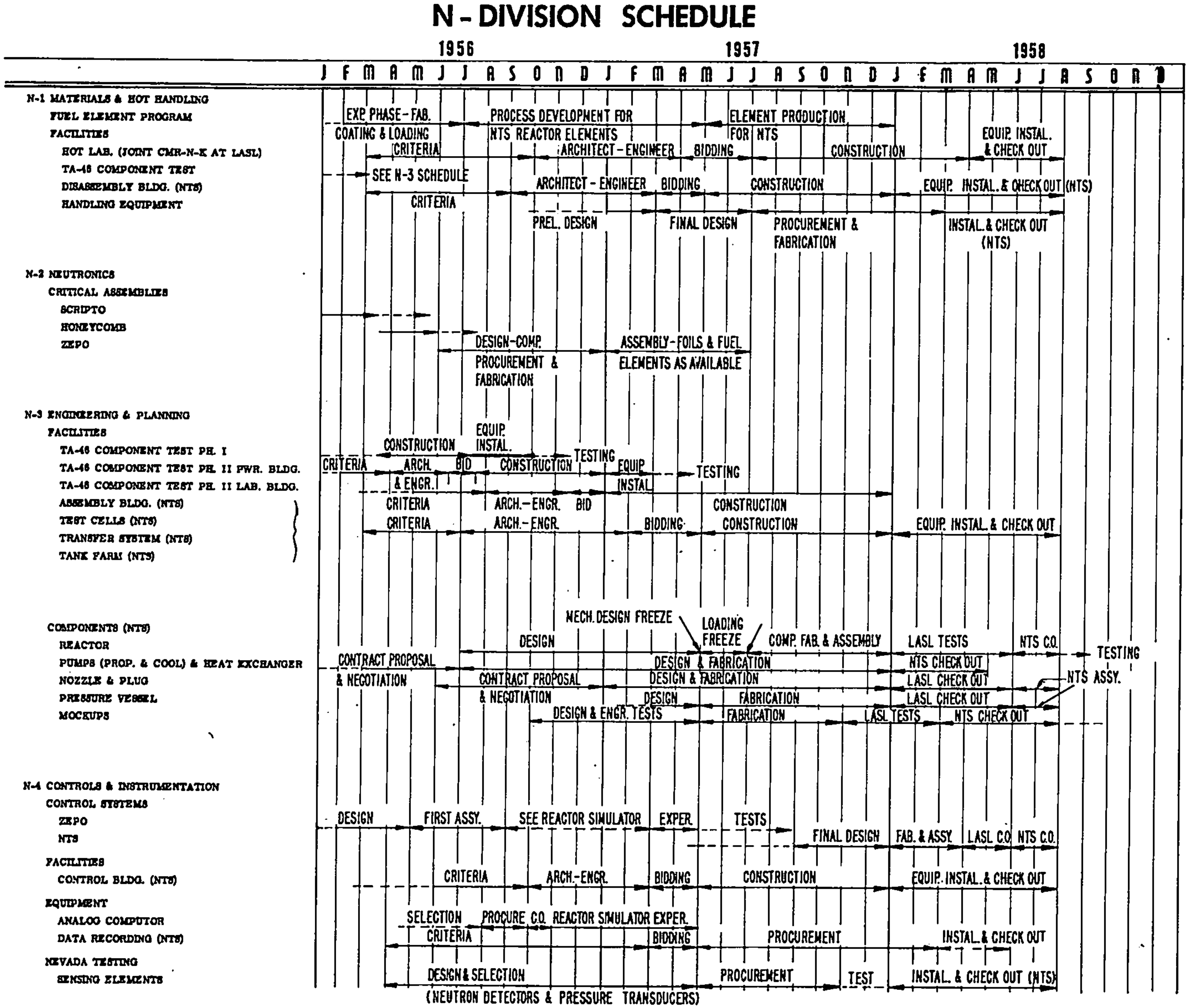


Figure I. Target schedule.

governmental budgetary considerations. Roughly speaking, the program can be divided into six month periods as follows:

1. January-June 1956: Continuation of basic research and general design studies.
2. July-December 1956: Specific design studies.
3. January-June 1957: Evaluation of design and design release.
4. July-December 1957: Fabrication of test device and instrumentation.
5. January-June 1958: Preparation for NTS test.
6. July-December 1958: NTS testing and post-mortem.

A rough abstract of the schedule is as follows:

First Period: Activities include the investigation of a variety of uranium-graphite fabrication processes and testing of the resultant product; basic studies and trial operations on metallic carbide coating processes; development of physical testing methods; heat transfer studies and experiments; critical mass and fission distribution measurements on the Honeycomb machine; multi-group reactor neutronic survey calculations; corrosion studies on coated fuel samples; establishment of a servo control and simulator laboratory; establishment of tentative criteria for the NTS testing work, and a large effort in the general planning of facilities.

Second Period: The basic design features of the NTS device start to jell; the fabrication method for fuel elements is selected; design and assembly of the Zepo neutron mockup is underway; detailed reactor calculations on specific designs; corrosion, heat transfer, and engine startup

[redacted]

studies are underway at the 1 megawatt facility; contracts are executed for NTS auxiliary equipment, such as pumps, nozzles, handling gear, hot laboratory tooling and data recording; engine control studies and experiments are underway and the final criteria for the NTS testing are established.

Third Period: The complete specifications for the NTS device are established and all arrangements for fabrication and assembly are completed; manufacture of (probably) two devices is started; major attention is given to actual test procedures and programming; construction of NTS facilities is underway; work with Zepo and 1 MW testing continues to check design details; first serious consideration is given to possible designs for 1959 test program.

Fourth Period: Manufacture of at least one NTS test device is completed and assembly started; construction of NTS facilities is in final phase and installation of equipment starts; engine control and master test programmer design is completed and construction started; construction of hot laboratory at LASL starts; contractors for auxiliary equipment start deliveries.

Fifth Period: Test and LASL checkout of first NTS device is completed and device moved to NTS; assembly of second device starts; installation and checkout of all equipment in NTS goes on frantically; overall operational planning for NTS testing is completed; all contractor-furnished equipment is installed and checked.





[redacted]

Sixth Period: Dry runs and live runs on first test device are carried out; first device is disassembled at NTS and interesting parts returned to LASL for detailed study in hot laboratory; decision made concerning test of second device and test carried out if so determined; ideas and schedules concerning 1959 tests are reviewed; people take vacations.

The reference to a first and second NTS test device may be somewhat confusing. These are currently thought to be two units of the same basic design, differing only in the details of instrumentation. The program of testing remains to be determined, but one possibility is the following: The first unit will be heavily instrumented, including internal thermocouples which may not withstand full operating temperature. The testing of this unit will consist mostly of transient studies, including the programming of startup, shutdown and brief power excursions. Sustained high power will be avoided both to prevent the possible burnout of internal instrumentation and to keep the integrated radioactivity low so that post-mortem work on the reactor and subsequent work in the neighborhood of the test cell will not be too difficult. If this first test is successful, the second unit will be brought to full power and used essentially as a demonstration of rated performance. If the first test shows up minor design defects, some rework of the second unit might be possible before it is tested. If the first test shows up basic difficulties, the second test would be cancelled.

There does not exist any detailed planning beyond the first tests

[redacted]



at NTS in the latter half of 1958. Fiscal planning has been projected into FY 1958 for work in calendar 1959 essentially on the basis of transposing our current program costs by one year. In addition, funds for development of facilities for testing a device with hydrogen propellant have been requested. It appears fruitless to project detailed technical planning very far in view of present ignorance. Unless some radically different type of device is chosen, a modest projection of the facilities and personnel required to achieve the first tests should permit the development and testing of two or three models per year.

The foregoing projection of planning represents about the minimum level of effort--short of dropping the work after the first test--which makes any technical sense. While it appears a bit early to talk of flying test beds or the development of an operational missile, some speculation in this direction appears useful. At the urging of AFSWP, estimates have been made concerning the time at which a flying missile could be produced. We believe that a first test flight could be made in calendar 1962 on our present schedule, provided that such a program were authorized and started early in calendar 1958. This program would presumably involve the collaborative efforts of LASL and some experienced missile development organization. The first step would be the establishment of the objective of the program and the selection of the missile development organization. There would then follow some period of mutual indoctrination and agreement on detailed distribution of tasks. It could be hoped that the state of the missile art would be such that





[redacted]

[redacted]



considerable use could be made of existing components so that the long period of preliminary design which now characterizes rocket missile programs could be shortened. There would be new problems of radiation damage, communication and control in a field of intense ionization, etc., which would call for a number of investigations. Experience with ANP and stationary reactors should be of assistance here. The total effort involved in such a program would be very considerable, but the major part would come from the missile contractor. It is believed that the LASL effort could be expanded to provide a flyable nuclear rocket engine by 1962, although this effort might well interfere with the exploration of more advanced nuclear propulsion ideas. Whether the LASL effort should be concentrated on new exploration or on the exploitation of first concepts appears to be a policy matter beyond the scope of this program review.





[redacted]

[redacted]

APPENDIX

# NUCLEAR POWERED ROCKETS: A HISTORICAL SURVEY AND LITERATURE SUMMARY

R. W. Bussard

Nuclear rockets have been proposed and discussed for nearly ten years and many interesting studies have been made of the possible ways of applying nuclear energy to rocket propulsion. The effort involved in tracking down the literature, classified and open, on the subject often proves formidable, and consequently many of the interesting ideas in the field are being and have been rediscovered by independent effort.

This report presents capsule summaries of the various proposals and studies made over the past ten years. The reports are summarized in chronological order, starting with the year 1946 and continuing up through the second meeting of the Nuclear Missiles Subcommittee of the SAB in late March, 1955, the outgrowth of which was the formation of the Rover program at LASL and at the Livermore Project of UCRL. No claim of completeness is made for the listings and it is hoped that no major work has been overlooked. It has been impossible to summarize adequately many of the more comprehensive studies, thus the interested reader is cheerfully referred to the document itself.





[redacted]

[redacted]



1946

R. Serber of the RAND Project (then with Douglas Aircraft Co.) published [1] some brief fundamental considerations of the application of fission energy to rocket propulsion. The conventional pile-heating-a-working-fluid-of-low-molecular-weight approach was deemed most reasonable. It was concluded that the degree of improvement attainable over chemical rockets would depend "entirely on how well the difficulties of heat transfer and high temperatures (material problems) can be solved".

1946/1947

An informal study committee within the Applied Physics Lab., Johns Hopkins University, investigated many aspects of the application of nuclear energy to vehicle flight propulsion. This study was carried out under the general chairmanship of A. E. Ruark with the following committee members: Beer, Bonney, Carlton, J. E. Cook, Gamow, Kershner, Lemmon, McClure, Meyer, Porter, Roberts, Silverman, N. M. Smith, Jr., Swartz, Van Allen, and Vicars. Since none of the participants had official access to Manhattan Project data at the time of writing the study summary report,[2] all were denied access to their own report when it was classified Secret, Restricted Data, by the AEC shortly after its issuance as a Military Confidential document by Johns Hopkins University Applied Physics Lab.

The summary report[2] considered the nuclear propulsion of rockets, ramjets, and other aircraft. Unless otherwise stated the remarks herein



[redacted]

pertain to the rocket system studies only.

Thermal and fast neutron reactors, separated fission products, direct use of fission fragments to heat gas, self-heating mixtures of moderator and fuel (both thrown away), thrust from fission fragment momentum, alpha particle recoil, and electron and ion accelerators were considered for vehicle propulsion systems. Cylindrical thermal reactors using enriched fuel and heating a working fluid were concluded most attractive and designs involving perforated (hexagonal hole array) graphite cylinders were analyzed. Reactor coolant gas temperatures of 1630°K to 2760°K were used and hydrogen was chosen as the propellant. Graphite was concluded the soundest choice for a reactor structural and fuel bearing material for rockets while BeO was preferred for ramjets. Hydrogen moderated reactors were considered in which the neutron thermalization was accomplished in the liquid hydrogen coolant prior to its passage through the primary heat transfer sections of the reactor.

In making the study, "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 <u>sine qua non</u> for further progress in this field."

The use of separated fission products was discarded as impractical from the standpoint of manufacture and handling. The use of fission fragments to heat the gas directly would yield fine performance but require that the fissioning fuel be spread in a thin film ($2 \times 10^{-4}$ cm) in direct contact with the coolant gas. A reactor which "burns" like a carbon arc was briefly considered and tentatively abandoned because no way could be seen to assure fission heating of only the exposed surface of the pile. Fission fragment and alpha recoil ("atomic paint") was shown to be unattractive, producing only about 3 kg (fission fragments) to 60 kg (alphas) thrust per 100 MW heat dissipation. Similarly electron and ion beam devices were examined and discarded because of the high current and/or high heat dump requirements per unit thrust.

1946/1947

The NEPA (Nuclear Energy for the Propulsion of Aircraft) Project, formed in May 1946 and continuing to the Spring of 1951, investigated nuclear rockets and ramjets as well as other aircraft. In 1946 Northrop Aircraft, on a subcontract from NEPA, performed a simple analysis of a nuclear rocket system in which hydrogen was used as the working fluid, being heated under high pressure in a fissioning reactor.(3) Effects of drag and burning time on rocket performance were neglected. It was concluded that nuclear heated hydrogen systems could produce very high ( > 15,000 ft/sec) vehicle terminal velocities.

Some reactor control problems common to airplanes, ramjets, and rockets (all nuclear powered) were briefly considered (4) by NEPA in 1946. Also in 1946, a reactor pilot plant was proposed (5) to be used "as a research tool for establishing fundamental engineering data for design" of nuclear propulsion systems presumably suitable for rockets, airplanes, and ramjets. Some simple rocket vehicle analyses and comparisons with chemical oxygen-hydrogen rockets were made during 1947, in which it was concluded that "for reactor temperatures of about 2500°C and above, the nuclear hydrogen rocket may be an attractive device".[6,7] Uranium-uranium carbide systems were analyzed for use in rocket reactor designs.

1946/1947

In early 1947, H. S. Seifert and M. M. Mills, then at JPL, published an unclassified memo [8] discussing the possibilities of use of fission fragment recoil, radiation pressure, and/or reactor heated inert working fluid to provide thrust for rocket use. The inert working fluid method was concluded the only practical one of the three considered.

1946/1947

While the NEPA Project was gaining momentum, North American Aviation's Aerophysics Laboratory performed a monumental study on nuclear rockets and ramjets [9] growing out of an earlier preliminary look at the possibilities of the field.[10] The study covered the design of an ICBM capable of carrying 8000 lbs. about 10,000 miles. A wide class of propellants was considered (Li, B, $NH_3$, $CH_4$, $H_2$, etc.) and hydrogen was chosen as the best for nuclear rocket use despite its low liquid density. Mixtures of liquid hydrogen and methane were thought to present some advantages over hydrogen alone. The nuclear reactor used was in every case a graphite assembly impregnated with uranium and operated at about 5700°F (3160°C).

Several reactor structural and flow designs were investigated

[redacted]



with preference expressed for a configuration of triangular-spaced holes in graphite blocks. Reactor shim control was proposed to be by injection of a boron compound into the propellant, thus distributing the neutron poison uniformly across the reactor core and avoiding local flux depressions characteristic of isolated control rods. Comparisons were made of nuclear rocket performance with that of alcohol-oxygen and hydrogen-oxygen multi-staged chemical rockets. These indicated lower gross weights for the nuclear hydrogen rocket for ranges greater than 2000 miles. Detailed component (pumps, turbines, etc.) studies were made for the 10,000 mile range missile and considerations of structural arrangement, flight stability, etc., were presented. Experimental work was done on the impregnation of graphite with uranium, and on the development of protective tantalum carbide films for prevention of graphite erosion by hot hydrogen.

1947

Although not with the NEPA program, H. S. Tsien discussed the design and characteristic features of a porous graphite rocket reactor during the course of MIT Nuclear Science and Engineering Seminars LIV and LV, May 13 and 15, 1947.[11] His design involved the use of uranium loaded, conical, porous graphite tubes of 1/8 inch wall thickness. Many such tubes stacked together in hex array within a thrust chamber were used to form the reactor. Hydrogen was pumped into the spaces between tubes, vaporized, and passed through the wall, reaching a discharge temperature of 6000°R (3350°K).





[redacted]

[redacted]

1947

In late 1947, N. M. Smith, Jr., (then with NEPA) presented two lectures at Oak Ridge on Nuclear Powered Rockets in the Pile Technology series sponsored by the NEPA program.(12) The lectures comprised a review, revision, and summary of the earlier Johns Hopkins APL work.(2)

1948

The following year W. K. Ergen, with the NEPA Project, published a short memo concerned with Tsien's proposal;(13) in particular, with some aspects of the gas flow arising from the rapidly changing physical properties during flow through the reactor. He concluded that the flow phenomena could not be adequately described by the use of average temperature physical properties and would be characterized by local asymmetries and hot-spotting due to viscosity variation with temperature.

The NEPA project continued to investigate nuclear rockets by design studies of orbiting rocket vehicles and other vehicles suited for more conventional military use such as the delivery of a warhead payload at a range of 5000 to 10,000 miles.(14) NEPA proposed to investigate experimentally, "the specific impulse of possible nuclear rocket propellants for a range of temperatures and specific heat ratios". Further tests were to be run "to extend data on the viscosity and thermal conductivity of hydrogen". (15)





[redacted]

1948

In the Spring of 1948, MIT contracted with the AEC to evaluate the possibilities of nuclear propulsion of aircraft. This effort continued through the summer of 1948 and became known as the Lexington Project. In the Lexington Project summary report [16] it is concluded that liquid hydrogen would be the best nuclear rocket propellant, and that nuclear rocket performance superior to that of chemical rockets will require reactor wall temperatures such as 4000°F (2200°C). A short project report [17] was also issued which discussed the use of nuclear-powered rockets in general terms as long-range missiles.

1948/1949

While the NEPA Project and North American work were underway, A. V. Cleaver and L. R. Shepherd, writing in consecutive issues of the Journal of the British Interplanetary Society.[18] analyzed the possibilities of nuclear powered rocket flight. Heat transfer reactors were investigated, in which a gas is heated by a hot fuel element, as were gaseous reactors, generating fission heat within a gaseous mixture of fuel and diluent. Gaseous reactors were concluded impractical from the standpoint of system pressure or dimensional requirements. It was noted that monatomic hydrogen would be an ideal propellant but that it presented storage difficulties in the liquid state. The use of $NH_3$, dissociating at 1000°K, was suggested, and mean molecular weights and heat capacities of $NH_3$ at 50 atmospheres and 3000°K-5000°K were given. Consideration of vehicles moving in free space led to propulsive systems involving the acceleration of heavy ions, with very low absolute thrust production, to produce milli-g accelerations.

<u>1949</u>

L. R. Shepherd later analyzed some shielding problems common to nuclear powered rockets,[19] pointing out that large amounts of energy will be deposited in the propellant near the rocket motor by gamma ray degradation. The use of a nuclear-chemical step rocket was discussed as a means of alleviating the shielding problem.

<u>1952</u>

Little work was done in the nuclear rocket field from middle 1949 until early 1952, at which time a study of nuclear rocket performance possibilities was undertaken by Convair, Fort Worth. The study[20,21] was made on rockets of approximately the same size (and tankage volume) as the German V-2, with arbitrary reactor heated gas temperatures as high as 10,000°K. An analysis was made of comparative performance resulting from the use of any of three propellants, water, ammonia, or hydrogen. It was concluded that hydrogen was the least desirable (worst vehicle performance, under the ground rules of the analyses) and ammonia the best of the three. The study concluded with several reactor designs for operation with ammonia at temperatures of $\sim$2000°K. It was pointed out that the vehicle size (V-2) chosen for study was probably considerably smaller than the "optimum" size for nuclear rockets.

Later in 1952 a thorough survey of the nuclear rocket literature was made.(22) The present paper has drawn heavily on this literature survey.

1953

The next document in the field was a study made at Oak Ridge in early 1953.(23) This was a generalized study of rocket vehicle performance based upon reactor designs which appeared capable of construction with then current reactor engineering knowledge and available known materials. Graphite was chosen as the reactor core structural material due to its known (useful) high temperature, high strength properties. Ammonia, hydrogen, methane, hydrazine, water, and an ammonia-hydrogen mixture were investigated as propellants, and charts of vehicle performance were presented for each propellant studied. Four possible reactor core designs were considered, each having a lower ratio of heat transfer surface area to heat transfer structure volume than its predecessor. Starting with a design based on use of porous graphite tubes (after Tsien, ref. (11)), the core heat transfer structures were coarsened to packed sphere beds, packed rods, and finally, stacked plates. Laminar flow heat exchangers offered greater heat transfer per unit pressure drop than turbulent flow systems but required physical dimensions so small as to make their construction appear extremely questionable. As a consequence the turbulent flow regime was deemed of most practical interest.

From the standpoint of fabrication difficulties and heat exchange performance the stacked plate core was chosen as the best design. The

[redacted]

packed rod core offered comparable performance but was thought more difficult to construct. In every case the fissioning fuel was to be in a surface coating of uranium carbide applied to the graphite structural elements in order to minimize internal power generation and thermal stress problems within the graphite structure. It was concluded that the use of hydrogenous propellants necessitated protective coating of the fuel elements. The carbides of niobium, zirconium, molybdenum, and tantalum (see ref. (9) ) were discussed as possible protective coating materials. Criticality calculations were made for a range of assumed reactor core constituencies and volume fractions. These calculations were based upon reflected, homogeneous cylindrical geometries and were generally by use of modified two-group diffusion theory (multi-lethargy groups were used for all systems in which an appreciable fraction of the fissions were caused by non-thermal neutrons).

Results of the vehicle performance study indicated that nuclear hydrogen rockets would be lighter in weight than chemical rockets for vehicle burnout velocities greater than 15,000 ft/sec with payloads greater than 1000 lbs.

<u>1953</u>

Later in 1953 a survey report on the work done in the nuclear powered aircraft and guided missile field was compiled as an ORSORT student summer project.[24] Although primarily concerned with the nuclear airplane program, some review and criticism of nuclear rocket work was presented.





[redacted]

## 1954

The next real activity in nuclear rocket work was that resulting from the first meeting of the Nuclear Missiles Subcommittee of the SAB on October 18, 1954. This subcommittee meeting heard presentations of further analyses from North American, Lockheed, LASL, UCRL, ORNL, Allied Research Associates, and Martin. The LASL, UCRL and Lockheed discussions generally pertained to the use of unconventional means for the production of thrust, such as fissioning gaseous systems, burning "cigarettes" or internally burning reactors, or the use of radiation from bomb bursts to heat a working fluid (BATO). Martin proposed to obtain thrust from thermonuclear processes achieved in a transient (pulsed) shock wave heated system. In general, none of these unconventional methods offered any real hope of successful achievement in the near future. The Allied Research Associates proposal was an expansion of the material presented in ref. (23) with greater emphasis on performance of specific rocket vehicles. North American's presentation was made largely by people who had not been connected with the 1946-1947 NAA study. Further investigations had been made into the high temperature properties of uranium loaded graphite, and heat transfer design analyses of two rocket reactors were presented. Indications were that 1 $gm/cm^3$ U loaded graphite had a strength vs temperature curve which was flat up to nearly 5000°F. Normal graphite nearly doubles in strength from room temperature to about 5000°F. The 1954 North American results were much less optimistic than those of the 1947 study. Estimated reactor weights for something like an Atlas mission (nuclear ground launched) were of the order of 20,000-30,000 lbs. The ORNL presentation was an extension of the previous work at ORNL with emphasis placed on high Reynolds number flow with large fuel element to gas temperature differences to enable the construction of heavier and more rugged cores than those required for low (turbulent) Reynolds number flow. A discussion of nuclear ground launch radiation hazards and of possible launch site contamination from fission products was also presented. The air-scattered gamma ray dose one mile from the launch site of a single stage nuclear hydrogen Atlas missile at take-off was given as about 1 rep/hr; at 1/4 mile it is about 2000 rep/hr. Also mentioned was the fact that fission product decay heat would cause melting and/or vaporization of the reactor within about 30 seconds after shut-down if the coolant (propellant) is shut off or exhausted. A more complete summary of this meeting was issued in February, 1955,(25) together with a list of references pertinent to the meeting presentations.

Following this SAB Subcommittee meeting both LASL and UCRL continued investigations in the field. The LASL work through March, 1955, is covered by many K-Division memos and by the minutes of the Condor Committee meetings, also issued as K-Division memos at that time.

<u>1954/1955</u>

The next major nuclear rocket study was performed by the GE-ANP Advanced Design section at Lockland, Ohio, and published in February, 1955.(26) It involved a "conventional" heat transfer rocket using tubular, coated, graphite fuel elements for a cylindrical reactor to heat

[redacted] [redacted]

hydrogen gas to about 4500°F. The reactor contained $3.6 \times 10^6$ individual fuel elements stacked in hexagonal array in hexagonal unit cells which were joined to form the reactor core. A vehicle performance comparison was made between the chemically powered Atlas missile (circa 1953-54) and a two stage nuclear-chemical rocket with the nuclear step first (nuclear ground launch). It was concluded that the nuclear-chemical system weight could be reduced to about 1/2 of that for the 1953 model Atlas missile (about 440,000 lbs. gross weight) for the same performance (range). Atmospheric drag and the effect of finite burning time was neglected in the nuclear rocket vehicle performance study.

1955

W. C. Cooley (of the GE-ANP group) at that time proposed [27] a revival of the fission-product direct gas-heating scheme (see ref. (2) ). This proposal was to coat the outside of tubes (of graphite or other material capable of use at 4000°F-5000°F) with a thin layer of uranium metal (or compound) fuel; assemble many such tubes together to form a reactor; pass gas through the tubes to raise the gas temperature to 4000°F-5000°F by convection heat transfer from the inside walls; reverse the gas flow outside the tubes and allow gas heating to about 10,000°F by fission fragment KE-absorption. The system would thus be a two pass reversed flow heat exchanger with counter-current hot (7000°F) and cold (3000°F) gas flows in a single flow stream. By this method the tube was to run at nearly constant temperature throughout its length.

UNCLASSIFIED



[redacted] [redacted]

[redacted] [redacted]

1955

In preparation for the second meeting of the Nuclear Missiles SAB Subcommittee, held at RAND on March 23, 1955, LASL issued (28) a ballistic rocket vehicle feasibility study, comparing two stage chemical-nuclear (chemical launch) systems with the current (1955) predicted chemical Atlas performance. By use of one SM-64 (Navaho) booster the required second (nuclear) stage weight was reduced to 24,000 lbs. for hydrogen and 65,000 lbs. for ammonia propelled rockets for the Atlas 1 MT mission. Super-Atlas missions appeared capable of achievement by use of either ammonia nuclear powered or hydrogen second stage rockets boosted by one Navaho booster. A plate type graphite reactor core was used in all vehicle analyses. Maximum graphite temperature was 5200°F and maximum gas temperature was 4500°F. No attempt was made to optimize the booster size, reactor system pressure, booster or nuclear vehicle acceleration, or vehicle flight path. Criticality calculations based upon reflected homogeneous spherical geometry indicated critical mass requirements considerably higher than those of the ORNL work. (23) Subsequent calculations (reported at later Condor Committee meetings) have reduced the critical mass requirements to 30 kg or less for a 1 MT Atlas vehicle reactor of the type described in ref. (28).

The second SAB Subcommittee meeting heard from GE, UCRL, and LASL. The GE proposal was that discussed previously; the LASL presentation was that of ref. (28); and the UCRL report covered both "exotic" and graphite heat exchange systems. UCRL reported it has concluded the fizzling and





[redacted] [redacted]

[redacted] [redacted]

gaseous reactors seem to have one order of magnitude of impossibility inherent in their makeup and that they therefore do not appear promising for application to rocket use. W. Brobeck of UCRL reported on an expendable tank rocket (continuous staging) which would perform the Atlas mission with a gross take-off weight of about 80,000 lbs. Hydrogen was used as the propellant and graphite as the reactor structural material.





[redacted] [redacted]

[redacted] [redacted]



## REFERENCES


(1) The Use of Atomic Power for Rockets, R. Serber, Douglas Aircraft Co., July 5, 1946.

(2) Nuclear Powered Flight, APL/JHU-TG-20, January 14, 1947.

(3) Rocket Computations, R. Cornog, NEPA-508, August 3, 1946.

(4) Controls for Nuclear Powered Aircraft, L. A. Ohlinger, NEPA-511, November 21, 1946.

(5) Pilot Plant for Nuclear Powered Aircraft, L. A. Ohlinger, NEPA-505, August 13, 1946.

(6) Rocket Performance Factors, M. L. Lesser, NEPA-175, March 21, 1947.

(7) An Estimate of Nuclear Rocket Performance, R. E. Adams, NEPA-283, September 15, 1947.

(8) Problems in the Application of Nuclear Energy to Rocket Propulsion, H. S. Seifert and M. M. Mills, JPL-Memo-3-4, January 23, 1947.

(9) Feasibility of Nuclear Powered Rockets and Ramjets, NA 47-15, February 11, 1947.

(10) A Preliminary Study on the Use of Nuclear Power in Rocket Missiles, H. P. Yockey, T. F. Dixon, NA-46-574, July 1, 1946.

(11) Rockets and Other Thermal Jets Using Nuclear Energy, With a General Discussion on the Use of Porous Pile Materials, H. S. Tsien, 1947, published in The Science and Engineering of Nuclear Power, Vol. II, edited by C. Goodman, Addison-Wesley Press, 1949, p.177-195.

(12) Pile Technology Lectures 31 and 32 "Nuclear Powered Rockets", N. M. Smith, Jr., M-3891, no date, but about October 1947.

(13) Preliminary Remarks on H. S. Tsien's Seminars, "Rockets --------", W. K. Ergen, NEPA-544, June 1, 1948.

(14) See, for example: Determination of Propellant Tank Weights and Optimum Pump Inlet Pressure for Orbiting Rocket, A. N. MacDonald, NEPA-457 March 10, 1948, and other reports referenced in the above.

(15) Program and Requirement of NEPA Project, Fiscal Year 1949, NEPA-535, May 1, 1948.

(16) Nuclear-Powered Flight, LEXP-1, September 30, 1948.

(17) The Feasibility of Nuclear-Powered Rockets, E. M. Redding, LP-148, September 8, 1948.

(18) The Atomic Rocket I, II, III and IV, A. V. Cleaver and L. R. Shepherd, Journal of the British Interplanetary Society, September 1948, November 1948, January 1949, and March 1949.

(19) Note on Shielding of Atomic Rockets, L. R. Shepherd, Journal of the British Interplanetary Society, July, 1949.

(20) Monthly Progress Report MX-1589, CVAC-FW, CVAC-PR-1, February 29, 1952.

(21) Nuclear Rocket Study, CVAC-FW, R. E. Adams, FZA-9-504, March 1, 1952.

(22) The Application of Nuclear Energy to Rocket Propulsion, A Literature Search, E. P. Carter, ORNL, Y-931, December 29, 1952.

(23) Nuclear Energy for Rocket Propulsion, R. W. Bussard, ORNL, CF-53-6-6, July 2, 1953, later published in "Reactor Science and Technology", TID-2011, December 1953.

(24) A Survey of the Application of Nuclear Power for the Propulsion of Aircraft and Guided Missiles, W. H. Thiel (CVAC-SD), ORNL, CF-53-8-223, August 1953.

(25) Nuclear Propulsion of Missiles, COPL-84, February 8, 1955.

(26) Conceptual Design of a Nuclear-Powered Ballistic Missile, W. C. Cooley, GE-ANP, XDC-55-2-20, February 1955.

(27) Private Discussions, W. C. Cooley and R. W. Bussard, at ORNL, February 1955.

(28) The Feasibility of Nuclear-Powered Long Range Ballistic Missiles, LAMS-1870, March 1955.