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DEVELOPMENT OF NUCLEAR ROCKET (U) 5-YEAR PROGRAM

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15 August 1956

Report No. 1164
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DEVELOPMENT OF A NUCLEAR ROCKET (U)

5-YEAR-PROGRAM OUTLINE

Contract AF 33(616)-3767
Project 6-(1-9964)
Task 3089-30344

No. of Pages: 56

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CONTRACT FULFILLMENT STATEMENT

This "5-Year-Program Outline" is submitted in accordance with Item 2(a)6 of Contract AF 33(616)-3767.

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I. INTRODUCTION

A 5-year program leading toward the development of a nuclear rocket is presented here in partial fulfillment of the contract. The program is based on completion, by the end of the 5-year period, of a complete full-scale developmental propulsion system, ready for testing, together with design criteria and the preliminary design of a prototype propulsion system. This schedule is predicated on the achievement of an operational flight vehicle in 10 to 15 years. Since the objective of the first year's effort is, in part, an analysis of the type and magnitude of preferred missions, the schedule of progress and the costs must necessarily be considered only as indicating a general order of magnitude. The estimates contained herein are based on thrust, payload, and range parameters of the average magnitude now being used by the National Laboratories. A total cost variation of as much as a factor of two, up or down, may be anticipated as a result of the final program objective.

As described in greater detail below, the philosophy which has been adopted as a basis for the program is that extensive experience may be gained from the development of a small-scale, non-flyable, nuclear-rocket system. Such a system has the advantage of being less costly and less time-consuming to build. Furthermore, many of the problems of the full-scale system, such as start-up, shutdown, and control during operation can be studied to advantage with the smaller power plant. Not all the problems can be evaluated with the small-scale system; however, it is important as a means of providing engineering confidence before undertaking development and testing of a full-scale system.

The program is also based on the assumption that the reactor programs presently conducted by the National Laboratories will progress sufficiently to provide adequate information for the design of the prototype reactor and components, particularly the controls, for the prototype propulsion system, and that one or more reactors will be available from the current reactor program for use with the small-scale propulsion system.

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I Introduction, (cont.)

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It is estimated that facilities expenditures for development and testing of a nuclear rocket may account for approximately one-half of the total estimated program costs during the first 5 years. Complete integration of the facilities study with power-plant performance studies will be assured by the correlation of anticipated rocket type, size, and operating environment with the appropriate and economic facility operating limits. The facilities study and construction plan will precede the development work and will endeavor to achieve the optimum facility design criteria from the standpoint of economic and technical desirability. Operating complexities resulting from the introduction of radioactivity into conventional rocket-test installations will be resolved by remote handling, shielding, and other accepted safety features to insure no compromise of personnel safety.

The program as detailed herein represents a major expenditure within the framework of the military defense effort. To achieve the time scale assumed, it will be necessary to proceed with the complete first year's effort without delay. Alternatively, should the time period of the program be considered to result in an overly intensive effort, it is readily possible to expand the time scale and reduce the level of effort. A corresponding extension in time before a useful flight vehicle is obtained will result.

A comprehensive description of a 1-year program is contained in Aerojet-General Report No. 1157, entitled "A Continued Investigation of Nuclear Rockets," dated 31 July 1956.

It is to be observed that Report No. 1157 was issued prior to the preparation of the 5-year plan contained herein and that it is now considered necessary to recommend approximately a 50% increase in effort for the first year. This increase is necessary to provide manpower and basic technical knowledge sufficient to serve as a foundation for the second-year program.

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II. TECHNICAL DISCUSSION

A. GENERAL CONSIDERATIONS

1. The plan discussed herein is a first attempt to relate study, design, development manufacturing, testing, and facilities requirements with cost and time for a 5-year program on the development of a nuclear rocket. The program must be considered only as a tentative approach to a realistic plan and will be revised at frequent intervals as technical, economic, and even political factors become apparent. The plan includes important aspects of the weapon-system concepts, particularly in respect to the selection of suitable missions and in the comparison of chemically and nuclearly powered vehicles.

2. The target consideration is the achievement of an operational flight vehicle for a selected mission in a 10- to 15-year period. This goal is considered to be somewhat flexible and must be responsive to many factors. However, commensurate with the stated goal, it is believed that the initial 5 years must provide, not only for a buildup of manpower and facilities, but also for the achievement of operational experience with small-scale nuclear-rocket systems and the development of full-scale components, together with some progress in full-scale reactive test and prototype systems. The yearly milestones were determined on a compromise basis considering manpower training, facilities requirements, and intuition.

3. The basic program is shown graphically in Figure 1, and the corresponding facilities schedule is shown in Figure 2.

B. FIRST-YEAR PROGRAM

1. Preliminary Power-Plant Studies

Nuclear and chemical rockets will be optimized for each mission, utilizing weight, size, and performance data supplied by the various component studies. An overall performance evaluation will then be made for each type of rocket, for each mission. This will involve both manual and machine computation of the trajectories. In addition, a cost and complexity analysis must be made for each case where the two systems are otherwise competitive.

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2. System Analysis Studies

The system analysis will consist primarily of the studies necessary to define the static and dynamic performance requirements necessary to achieve a given mission with a specified nuclear-powered rocket vehicle. The most feasible power-plant system configurations will be studied, and the mathematical characteristics of the various elements will be established. The synthesis of complete feedback systems will be conducted in sufficient detail to determine the degree of interaction between the various system elements and feedback loops and to specify control and compensating element transfer functions. Correlation of the system analysis with preliminary design studies will insure the realistic specification of controlled variables, control points, and control-system components.

3. Components Studies

The components studies will be performed in two complementary phases. The first of these is an analytical study based on available theory and empirical data. The second is the proposed experimental program, in areas where the theory appears inadequate or data are lacking.

a. Turbopump Systems

The analytical part of this study will consist of a cycle analysis and will include a design and layout program necessary to determine the sizes and weights of the pumping systems. Some of the basic parameters will be propellant weight flow, rocket chamber pressure, properties of the fluid, and suction head above vapor pressure at the pump inlet. Various pump configurations will be considered in this study, as well as the different drive systems which may be used effectively with these pump arrangements.

b. Propellants

An investigation must be made into the properties of various propellants that might be used in a nuclear rocket, including both ammonia and liquid hydrogen. A literature survey must be performed, and an extensive theoretical investigation must be carried out. The investigation

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will involve a determination of the specific impulse, density, handling problems, and corrosiveness of the materials (particularly with respect to the reactor structural and fuel bearing elements).

c. Tanks and Structures

An analytical study and preliminary design of the tanks and structures required for these rockets will be carried out. This will involve a determination of materials, both metals and non-metals, which are compatible with both the rocket and reactor environment (very low temperatures, high-intensity radiation fields, etc.) Various methods of tank construction will be considered in order to determine the minimum value of the ratio of tank weight to contained propellant weight for each of the more promising materials and for the various propellants under consideration. Optimum tank shape, to minimize evaporation losses, and method of attaching the tank to the thrust unit must be considered. Analysis of the structural design and weight will require a knowledge of the location and weight of the payload, turbine, and pumps, and of the maximum acceleration that the missile is to undergo. Lift points and other considerations for ground servicing and handling must also be considered.

d. Controls

The study phase of the controls program will consist of a literature survey, particularly with respect to the control of gas-cooled nuclear reactors and an investigation of the characteristics of various types of controls interrelating rocket system components with the nuclear reactor. Consideration must be given to mechanical, electromechanical, electronic, hydraulic, and pneumatic control devices.

e. Thrust Chamber

The primary problems related to the thrust chamber are (1) selection of a nozzle contour to achieve minimum weight consistent with the best conversion of the potential energy to kinetic energy and (2) cooling the chamber and nozzle walls to temperatures at which structural integrity is maintained. The nozzle contour must be designed to produce a

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maximum thrust coefficient for a minimum weight, and methods of thrust vector control for missile stabilization and guidance must be considered. Heat transfer to the nozzle wall must be investigated, including forced convection and molecular recombination effects, heating by gamma and neutron irradiation, and thermal radiation from the hot face of the reactor core. Several methods of maintaining the nozzle walls at temperatures compatible with the structural integrity of the materials involved must be considered. Foremost among these methods are regenerative-, film-, and transpiration-cooling techniques. Thermal capacity and heat of vaporization of the fluids involved are of primary importance in these investigations.

f. Reactor Study

This study will involve close liaison with the AEC Laboratories with regard to the current rocket reactor design, with particular attention to corrosion, erosion, heat transfer, and control problems. In addition to this, some investigation will be made into more unconventional designs which might allow higher gas temperatures to be used.

4. Experimental Program

a. High-Temperature Materials Investigation

Experimental equipment for the investigation of the mechanical properties of refractory materials at high temperature will be designed, constructed, and placed in operation. A continuing test program will be initiated to obtain the following experimental data on graphite as a function of temperature: tensile stress vs strain at controlled strain rates; tensile creep behavior at different stress levels; tensile stress relaxation behavior at different stress levels; fatigue, damping capacity, and impact properties; and the creep buckling behavior of compressed members. Experimental equipment will be designed for the determination of the torsional creep behavior of pure and fuel-impregnated graphite under reactor irradiation.

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b. Low-Temperature Materials Investigation

Experimental support of the basic program will be accomplished by a series of screening tests of those materials (particularly structural plastics and metal-plastic combinations) whose properties are at liquid-hydrogen temperatures (20°K) not known. This materials feasibility study will be accomplished by preliminary tests at liquid-nitrogen temperatures (77°K). The most promising materials as determined by these tests will be further evaluated at temperatures ranging to 4°K . The dependability of these materials at cryogenic temperatures will in general, be established by subjecting specimens to tensile, bending, and impact tests.

c. High-Temperature Heat Transfer

(1) Experimental equipment for the investigation of heat transfer in, and heat removal from, an extended-surface heat source using a gaseous fluid will be designed, constructed, and placed in operation. A continuing test program will be initiated in which this equipment will be used to investigate the heat-transfer properties of sintered porous structures as a function of material porosity and specific surface, gas pressure, and flow rate, and other fluid or material properties which may be found to be of significant influence.

(2) The heat-transfer characteristics of gaseous hydrogen will be studied experimentally at temperatures and pressures at which dissociation effects are significant. Particular attention will be given to the range of temperatures and pressures that correspond to conditions in an actual nozzle.

d. Low-Temperature Heat Transfer

Experimental equipment for the investigation of heat transfer to cryogenic fluids will be designed, constructed, and placed in operation. A continuing test program will be initiated in which the mechanism of convective heat transfer from a flat-plate heating element to a parallel flow of a cryogenic fluid will be investigated as a function of flow rate,

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heat-flux rate, and the thermodynamic state of the fluid relative to its critical point, using the Schlieren technique for flow visualization and determination of density gradients.

e. Turbopumps

Bearing and seal tests will be carried out to determine the feasibility of using hydrogen and other unique propellants as bearing lubricants and sealing fluids.

f. Controls

This work will be concerned with the determination of the operational and other characteristics of control components in an intense radiation field. Completion of the program is contingent upon the availability of radiation time in a suitable reactor.

g. Nozzle Flow Separation

(1) Experiments will be performed in a small-scale, two-dimensional, transparent-walled nozzle to investigate the influence of fluid injection through porous nozzle walls upon the jet-separation characteristics of gas flows at various stagnation temperatures.

(2) Various mechanical and aerodynamic mechanisms to induce flow separation in the expanding section of the nozzle will be investigated in a three-dimensional model.

h. Materials, In-Pile Test Loop

Experimental equipment for the in-pile testing at cryogenic temperatures of selected materials will be designed and constructed. Initiation of a continuing test program will be dependent on the availability of radiation time in a suitable reactor.

i. Pump Cavitation Studies

The combination of large flow rate, high head rise and moderately low suction pressure results in the use of large, slow-speed pumps when conventional techniques are employed - so large, in fact, that it is out of the question to utilize these techniques in airborne

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equipment. Hence new approaches to the pumping problem must be employed. The first fundamental improvement that can be made, is an increase in the suction specific speed of the pump. In this regard, Aerojet has contributed substantially to advances in rocket pumping systems. However, the specification that may arise in the nuclear rocket may require new concepts in the approach to pumping equipment for high suction specific speeds. Fundamental theoretical studies into the mechanics of cavitation in cambered cascades is required in order to fully appreciate the problems and effect improvements. Experimental substantiation of the theoretical program is then required to establish actual limits of operation and to make the theoretical information available for use in the design program.

j. Low-Specific-Speed Pump Performance

The pumping requirements for high-thrust rocket systems using low-density propellants indicate low-specific-speed pumps, that is, pumps with relatively large head rise as compared with the flow rate. Conventionally, such pumps are penalized by low hydraulic efficiency. Relatively little theoretical or experimental research data is available for the range of specific speeds required. A thorough theoretical investigation of the circumstances surrounding the losses in this type of pump is in order, and a moderate experimental program to substantiate the theoretical results will be undertaken.

k. Control Components at Low Temperatures

Selected control components, such as pressure transducers, servomotors and sliding shaft seals, will be tested functionally at temperatures down to 20°K. Tests will be selected to demonstrate fundamental behavior patterns, and development procedures will be instigated where failures occur.

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1. Tank Fabricational Technique, Development

Fabricational techniques for use with lightweight missile tanks will be investigated. Materials found to be of interest in the low-temperature materials tests will be employed. Efforts will be made to establish practical methods for winding, laminating, or spinning tanks of fiber-reinforced plastic or metal-plastic combination.

m. Thrust-Chamber-Cooling Investigation

(1) Transpiration Cooling

A heat-transfer investigation to evaluate methods of transpiration cooling, particularly with cryogenic fluids, will be initiated. A transparent nozzle section supplied with electrically heated working fluid will be designed and fabricated. A combination of Schlieren and thermocouple probe techniques will be used to determine temperature patterns of the boundary layer.

(2) Convective Cooling with Cryogenic Fluids

Experimental equipment for the determination of the temperature distribution in a fluid boundary layer under super-critical pressure conditions will be designed, fabricated, and placed in operation. The apparatus will provide a micrometric thermocouple probe to determine boundary-layer temperature distribution and bulk fluid temperatures.

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C. SECOND-YEAR PROGRAM

1. Research

a. High-Temperature Materials Investigation

The second year of the proposed program will see the completion of the various mechanical-property determinations on pure graphite grades and a shift in emphasis to investigations of the properties of fuel-containing materials. This work will include the in-pile creep investigation of pure and fuel-loaded graphite.

b. Low-Temperature Materials Investigations

Materials screening tests at liquid-nitrogen temperatures will be continued from the previous year's program. All new materials will be subjected to tensile, bending, and impact tests for rapid evaluation of further need for more refined experimental determinations.

The materials which are deemed to have the greatest promise for application to the tank and airframe will be tested at temperatures ranging from 4°K to approximately 500°K . The mechanical property tests at these temperatures will include tensile, bending, column compression, fatigue, and impact tests.

Materials irradiation at cryogenic temperatures will be performed with a cryogenic in-pile loop. Specimens will be subject to irradiation in this loop and then tested at cryogenic temperatures with the equipment described above operated remotely. Preparations will be made during this year for mechanical property tests while the material is irradiated in a cryogenic environment, with and without stress.

c. High-Temperature Heat Transfer

The laboratory-scale investigation of heat removal from power-producing, porous structures will be completed early in the second year of the proposed program, and pilot-scale experiments on the extended-surface configurations which appear most attractive from heat-transfer and practical manufacturing considerations will be pursued.

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d. Low-Temperature Heat Transfer

The laboratory-scale investigation of the dynamics of convective heat transfer to an inert cryogenic fluid, using optical techniques for observation of local conditions, will be completed during the second year of the proposed program, and the extension of this measurement to additional fluids will be investigated. In addition, the average-value experiments on heat transfer to similar fluids, initiated during the first year of the program, will be completed during the second year.

Cryogenic heat-transfer loops will be utilized to determine the thermal conductivity of the various structural materials, bonds, and insulating materials. These tests will be used to evaluate the necessity of insulating the tank. Some of the structural materials under consideration may have adequate insulation properties to combine both the structural and insulation characteristics required. These heat-transfer loops may be modified readily to provide a means for determining the film coefficient of the propellant at characteristic velocities encountered during flight due to sloshing. Determination of these coefficients will be required in order to properly evaluate heat transfer into the tanks.

The expansion of various materials as the temperature is varied from 4°K to 500°K will be determined by using a dilatometer modified to operate at cryogenic temperatures. Structural materials will also be subjected to thermal shock in order to simulate conditions during propellant charging of the tank. These tests will essentially be thermal fatigue tests, and it may be possible to correlate this data with normal fatigue data.

Propellant transmission tests will be made to evaluate the optimum combinations of materials and arrangements for large-quantity propellant transport.

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e. Turbo Machinery

Research efforts are required in several fields of study in order that the basic problems which arise from the application of turbopumps may be solved. Some of the problems which require development of basic data are those associated with the operation of bearings and seals in liquid hydrogen, the extension of some fundamental work in fluid mechanics, particularly cavitation phenomena, the problems of turbo machinery associated with high head, low-specific-speed pumping equipment.

(1) Material Compatibility Investigation

Little or no data exist concerning the characteristics of the rubbing of materials in liquid hydrogen and utilizing liquid hydrogen as a lubricant. Although it is not necessary in all conceivable designs that hydrogen-lubricated bearings and hydrogen seals be used, nevertheless, this fundamental information is needed in considering all possible pumping systems and determining optimum configurations.

(2) Pump Cavitation Studies

Cavitation studies, on an increasingly practical basis, will be continued during the second year of the program. Specially it is planned to introduce the effect of a vane with varying angles of attack and under various conditions of centrifugal force.

f. Thrust Chamber

The program of research in thrust chambers for the second year is intended to provide sufficient basic information to support the immediate needs of the small-scale development program, as well as the long term requirements of the full-scale development program. Accordingly, during the second year, experimental programs will be continued and concluded in the areas of contour aerodynamics, induced jet separation in the nozzle, and thrust vector control. Other research efforts during the second program year include heat-transfer phenomena related to thrust-chamber

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performance, the investigation of radiation effects on the physical properties of the structural materials of the thrust chamber, and thrust augmentation for a chemically reactive exhaust jet.

2. General Studies

a. The results of the overall propulsion system analysis during the first year will be used to assist in determining the type of nuclear rocket for the specified mission or missions selected. More detailed system analysis will be initiated to complement the preliminary design for the full-scale reactor. Further analysis and system integration studies will be conducted for the National Laboratories type of small-scale reactor. Special system studies will be made of problems associated with flight dynamics and the type of flight control required for the specified mission or missions.

b. Certain components of a nuclear rocket will present unusual difficulties of design, either because of their physical complexity, or because of their novelty. Some of these difficulties will be amenable to mathematical analysis. Many of these problems will occur in the detail design and cannot be foreseen, but among the foreseeable problems are the determination of the energy spectrum of the flux, close monitoring of power level and of propellant flow to give the required specific impulse, analysis of transients in power and in propellant flow during a fast startup, programing of thrust if required, and rapid and accurate shutdown, which may be required on some missions. In addition, many problems exist in guidance, heat transfer and cooling, fluid mechanics, and thermal and acceleration stress.

c. Certain proposed working fluids such as hydrogen and ammonia will react with the ambient air when exhausted at high temperatures. A study will be made of the utilization of this extra available energy during flight in the atmosphere.

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3. Preliminary Propulsion-System Design

a. As the broad power-plant studies progress to a point where specific missions and requirements are delineated, design specifications for the propulsion system and components will be written. It is planned that the design specifications for the small-scale components will be established by the end of the first-year program, in order to permit the detailed design to proceed. Thereafter, the full-scale design specifications will be prepared during the first half of the second year.

b. Simultaneously with the formulation of design specifications for the small-scale system, the preliminary design of the small-scale components will be completed; i.e., by the end of the first year. The preliminary design of the small-scale propulsion system will have been started by that time, and will be completed in the first half of the second-year program. The various components — turbopumps, tank and structures, controls, thrust chamber, and reactor — will be integrated in alternative system configurations, and small-scale propulsion-system layouts will be completed.

c. The completion of the preliminary small-scale component design will overlap with the beginning of the preliminary full-scale component design. Improvements and changes in design will be effected as the detailed specifications evolve, and it is anticipated that the preliminary design of the full-scale components will be completed by the end of the second year. Preliminary design of the full-scale propulsion system will be started as early as the component design data permit. Several arrangements of the components will be evaluated. It is expected that this phase will extend into the third year.

4. Small-Scale Systems Development

a. General

At the beginning of the second-year program, the first step in the direct development effort, consisting of small-scale

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component and system development, will be initiated. With the attainment of certain goals during the first year's study effort, particularly the establishment of design specifications and preliminary design layouts of the major components, detailed design leading to fabrication and testing can begin. There are several reasons for developing first the small-scale systems before attacking directly the full-scale effort. While it is recognized that small-scale work does not resolve all the problems which may ultimately be encountered, it is thought that many of the major development problems of the nuclear propulsion system can be resolved most effectively by the small-scale program. The small-scale components are inexpensive to build and test, and, perhaps more significantly, test results may be achieved earlier. The power, system capacity, and facility requirements of 1/10-scale components, for example, are such as to permit direct application of operational experience and, in some instances, actual hardware from other programs in progress at Aerojet. For this reason, it is anticipated that the testing of small-scale components can be initiated much sooner than full-scale. There are additional advantages in operational safety and availability of test sites, which will save both time and funds in attacking the gross development problems. A significant factor is also considered to be the psychological advantage of having demonstrated satisfactory operation on the smaller scale before attempting to operate the full-scale equipment. The small-scale development program includes:

(1) Small-scale component development. This phase will extend over more than 2 years and will comprise design, fabrication, and development tests of 1/10-scale components. Completion of the phase will be marked by the attainment of a level of development which warrants the use of the components in the complete small-scale propulsion system.

(2) Development of the small-scale system without reactor, comprising additional design, fabrication, and testing at 1/10 scale. Tests will be conducted on cold-flow sub-systems and also on the complete

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system using a non-nuclear heat source. This technique permits operation in relatively close test sites. These tests continue into the third year.

(3) Development of the small-scale propulsion system with reactor. This phase, included here for reference only, comprises design modification, installation at a proper site, and testing to demonstrate satisfactory operation. This work will not be conducted during the second year.

Even after the basic design principles are demonstrated satisfactorily, and emphasis has shifted to full-scale development effort, it is anticipated that small-scale development work will continue, either on the component level or the complete system level, as a means of screening initial design modifications which will be evolved continually throughout the program.

b. Small-Scale Component Development

During the second year, the initial detailed design of those small-scale components which require major development effort will be completed. Fabrication of a sufficient quantity of component assemblies will also be completed, and the test program will be initiated. Of course, there are several different types of components being developed simultaneously, requiring different time schedules for design and fabrication, so that tests of some of the components will be initiated much sooner than other. The schedules shown in Figure 1 are idealized for the purpose of presenting an average schedule estimate relative to other phases of the overall development effort. Moreover, the design, fabrication, and test work will overlap to a large extent even for one type of component. Wherever possible, exploratory tests of existing components will be initiated as soon as possible in order to demonstrate principles of operation applicable to the nuclear propulsion system; these tests are not shown in Figure 1 as discrete tasks, but are included under research and study programs. The research and study work will continue throughout

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the development program, and results will be fed into the design phases in a continuing effort to improve reliability, safety, and performance of the components. The individual component development plans are treated in more detail in the following paragraphs.

(1) Turbopumps

The turbopump assembly, which is a component of the propulsion system, is itself an assembly of subcomponents that require separate development. The elements making up the turbopump assembly are pump items, turbine items, and bearing and seal components. The arrangement of these components as to number of stages or number of series or parallel items constitutes a field of study to be considered separately. This study will be initiated during the first-year program and will continue into the second year.

(a) Pump Components

During the second year, the design of several pump configurations which were started during the first-year program will be completed. It is anticipated that the fabrication of all the items necessary for the pump development program can be completed during the second year and that some testing will be accomplished. It is anticipated that pump components for high-speed main-stage pumps will be developed, as well as components for booster pumps which may be shown to be necessary during the pump-feed system studies.

(b) Turbine Components

The design of several turbine configurations initiated during the first-year program will be completed during the second year. Fabrication of these elements will be completed during the second year, and preliminary testing will be started. The turbines associated with the high-speed main-stage pumps will undoubtedly be high-speed vapor or gas-driven turbines operating at moderate to high temperatures and large gas flow rates. In addition to this type of turbine, it is

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entirely possible that low-power, hydraulic turbines operating with liquid hydrogen will be included in this program, inasmuch as this type of drive is well suited to booster-pump operation. Previous studies have shown this system, namely the hydraulic-turbine-drive booster pump with the high-energy fluid coming from the main stage pump, to be a very desirable element in a hydrogen turbopump system.

(c) Bearing Development

The bearing development program will consist of a continuation of the designs started during the first year and the fabrication of test items and their evaluation, much of which will be accomplished during this second year. Submerged hydrogen-lubricated bearings, either hydrodynamic or hydrostatic, and low-temperature anti-friction-type bearings will all be considered and evaluated.

(d) Seal Development

The seal development program, with a schedule similar to the bearing development program, will consist of the evaluation of labyrinth seals, face-type seals, and lip seals of types suitable for application in liquid-hydrogen systems. It is thought that most of the development work on seals can be accomplished during the second-year period, in time to furnish information for the design of the small-scale turbopump.

(e) Turbopump Assembly

During the year, the design of the turbopump assembly for the small-scale propulsion system will be initiated. There will be insufficient time to incorporate in the design of the turbopump all the information derived from the subcomponent development programs listed above. The turbopump design, however, will be made after the design studies of the subcomponent or the component programs described above and, as a result, will benefit from these studies. In addition, the design of the small-scale turbopump can anticipate changes shown to be desirable from the development programs of each subcomponent and be

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sufficiently flexible to incorporate many changes which are shown to be desirable. It may be required to design two turbopumps with different capabilities for incorporating changes so that a more optimum design may be arrived at for testing in the small-scale propulsion system. The fabrication of these turbopumps will be initiated but not completed during the second year.

(2) Tanks and Structures

Models of various sizes will be utilized in the development of the tank and structures. Tank models may range from approximately 1 ft in length to 1/10 of the actual tank size. The different-sized models will be used to establish the scale factors, based on fabrication techniques and materials previously investigated. Certain tests are not readily adapted to large-scale models, such as radiation tests, for instance, and will therefore be made with the small models.

Comprehensive load tests at room temperature will include hydrostatic water tests, vibration tests, thrust and air load tests, and thrust load-distribution tests.

The necessary techniques and handling equipment for transferring propellant from the storage tank to the propellant tank will be developed with the small-scale models. This development program is aimed at the establishment of the necessary equipment for the transport of large quantities of propellant.

The load tests, at room temperature will be extended to include cryogenic temperatures for those configurations considered best for the final design. Included with these tests will be certain heat-transfer experiments to determine the following conditions: thermal gradients, thermal shock due to propellant filling, ice formation on tank, internal convective heat transfer, aerodynamic heat transfer, thermal stress, and heat transfer due to sloshing.

Model ground-handling equipment for the missile transport and launching will be developed and tested in conjunction with the tank and air frame.

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(3) Controls

On the basis of the preliminary design work to be completed during the first year, the design of controls components will be undertaken. The general philosophy of controls design will be to consider several alternatives for each major control function and to evaluate alternative power sources for the controls, such as hydraulic, pneumatic, or electrical. Of the three major classes of controls required for the nuclear propulsion system (thrust controls, reactor controls, and flight attitude controls), the major emphasis will be placed during the second year upon thrust controls, and their interrelation to reactor controls. Some typical controls applications and types which will be designed during this phase are as follows:

(a) Propellant Flow Controls for Steady-State Operation

Various types of control methods are possible for this function and will be evaluated. One type of control which may prove to be suitable is the proportional-feedback servo control, regulating the turbine-supply gases, and sensing propellant pressure or flow rate.

(b) Turbine Speed Controls

A requirement for turbine speed control may be established either as a primary thrust control or as a secondary safety control. For such a purpose, Aerojet has developed both centrifugal fly-weight units and alternators in combination with frequency-sensitive filter circuits. The latter type would appear to be more reliable and readily applicable to the nuclear propulsion system.

(c) Malfunction Controls

Automatic controls, for regulation of propellant flow in response to an abnormal excursion of parameters affecting safety, have been developed for use in chemical rocket systems and may well find application in the nuclear rocket.

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(d) Starting and Shutdown Transients Controls

Precise regulation of rate of change of propellant flow may be a particular requirement of the nuclear propulsion system, in order to bring the starting and shutdown characteristics of the hydraulic system into conformance with the requirements of the reactor.

(e) Reactor Controls

The design of reactor controls will be studied during this phase of the program, particularly from the standpoint of interaction of control functions between the reactor and the fluid systems. The detailed design of reactor controls will depend upon the availability of specific design requirements growing out of reactor development work by the National Laboratories.

(f) Flight Controls

Although flight controls are of major importance to the missile, it is likely that the detailed design will not be undertaken during the small-scale development phase. However, the studies of thrust vector control being undertaken during the first-year work may produce some data which will lead to detailed component design and development.

(4) Thrust Chambers

The results of the first year's study will be applied to the design, fabrication, and testing of a small-scale nozzle. During the second year, the contour of the nozzle and the method of inducing flow separation will have evolved from the nozzle aerodynamic study and research program. The selection of the working fluid will determine the heat-transfer rates in the nozzle and also the type of cooling which can be applied to the nozzle. The general, nozzle heat-transfer

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study for this working fluid will be utilized in a detailed heat-transfer analysis necessary for the proper design of the nozzle.

Should the study performed during the first year show thrust augmentation to be desirable for the nuclear rocket, the method for activating it will be studied and designed during this period.

The nozzle aerodynamics study performed during the first year and continued throughout the second year will indicate the type or types of thrust vector control applicable to the nuclear rocket, and the optimum type will be selected for incorporation into the nozzle design by the end of this period.

A program of development testing for the small-scale thrust chamber will be conducted utilizing both the heated working fluid and the flow of gases from chemical rockets. For such tests with the heated working fluid, an enormous amount of electrical power is required to simulate the reactor heating. To decrease this power requirement, only a 90° segment of the small-scale nozzle will be fabricated and used for the development testing of the cooling technique and its attendant nozzle conservation. To further decrease the power requirement, a contoured plug will be fabricated to block approximately 80% of the flow area nearest the nozzle axis. The contour of the plug will be such that the boundary layer on the nozzle wall will not be affected by the presence of the plug.

Rather than attempt to supply heat from an electrical source at the same rate that is required by the working fluid, it is planned to electrically preheat a quantity of porous graphite and then pass the cold working fluid through this graphite heat source, thus heating the working fluid to the required temperature.

Chemical rockets will be utilized in the development testing of separation control, thrust vector control and, if applicable, thrust augmentation. It may be possible to obtain data from these rockets applicable to the heat-transfer work also.

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c. Small-Scale Propulsion System Without Reactor

(1) The design of the small-scale propulsion system without reactor will be initiated early in the second year, as soon as sufficient information is available from the preliminary design and the detailed component design efforts. The system design work will consist primarily of detailed design of those parts of the system which are not included in the components phase and assembly design of the complete small-scale system. In general, the individual major components will have been designed under the component design phase, although some design modification may be in order as a result of tests and study work in progress. One of the major problems to be resolved for the small-scale propulsion system will be the design and operation of a nonreactive heat source. It is considered that the best heat source for this purpose will be a chemical thrust chamber and heat exchanger system. Although this may be "small scale" relative to the prototype nuclear propulsion system, it is apparent that it may not be truly small scale in terms of presently developed equipment and operating procedures. Chemical combustion systems of the size required for the 1/10-scale system are within the range of present experience, but the design of suitable heat-exchange equipment to provide system operation at reasonable power levels remains a serious problem. Despite some uncertainties in this regard, the desirability of operating a nonreactive, thermally hot, propulsion system appears to be a paramount consideration. With such a system, the number of test runs which may be conducted per unit time is many times greater and the cost is much lower than for a complete system with reactor. The nonreactive system would provide the bulk of the test results required for development at 1/10 scale and would be used for development tests intermittently, even after the reactive system has been operated successfully.

(2) The fabrication of components for the small-scale system will be initiated before the end of the second year. A sufficient number of components will be fabricated to provide for testing two complete small-scale systems, two cold-flow sub-systems, and supporting spare parts.

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5. Full-Scale Component Development

a. During the latter phases of the preliminary design of the full-scale components, it is planned to start the detailed design of the turbopumps, tank and structures, controls, and thrust chamber. The long lead time required for the fabrication of these components requires that the design work be initiated in advance of the availability of test results from the small-scale program. This design effort will utilize the concepts originated during the preliminary design phase and incorporate them into specific designs from which models of the components can be fabricated. To allow proper integration of the component development work into the overall effort, it will be necessary to complete the design phase during the second year. The various components mentioned above will then be fabricated and tested. In order to expedite the overall program, the design of the components will be completed in stages so that any subassembly of a component may be fabricated at the earliest possible time. The design effort will be supported by the results obtained from the research program, as well as by the test data which may be available from the small-scale component development effort.

b. During this period, some preliminary consideration must be given to the design features of the prototype reactor. It is currently anticipated that this design will be based upon configurations currently under investigation by the National Laboratories. There will, however, be many problems associated with the anticipated change in physical dimensions and power level. This work will be primarily concerned with detailed component design (fuel and control elements, structure, etc).

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D. THIRD-YEAR PROGRAM

1. Research

All research originated during the previous year will be continued with the addition of those programs necessary for the full support of the development work. The mechanical properties tests of materials and components in an irradiation field at cryogenic temperature will be emphasized during this year. General emphasis must be placed on in-pile and radiation flux field tests.

2. Study

Integration studies will begin on the application of preliminary design and analysis to the system requirements for a full-scale nuclear power plant and associated vehicle components.

Dynamic correlation of the test results of the small-scale propulsion system coupled with the electronic reactor simulator will be started. A more refined, system tolerance evaluation will be completed using these results. All small-scale subsystem power plant and vehicle control analyses will also be revised as necessary to conform with current test information.

3. Small-Scale Component Development

a. Turbopumps

With regard to small-scale component development, the third-year program consists of testing those items previously designed and fabricated. The complete testing phase of this development program extends over a period of approximately 1 year, terminating near the end of the third-year period. It is anticipated that a complete evaluation can be made of the various components during this period. The conclusions will then be utilized in the development of the small-scale turbopump assembly insofar as this is possible. During the year, this turbopump assembly will be ready for use with the small-scale propulsion system.

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b. Tanks and Structures

The development of small-scale tank and airframe models will be continued during the year with a test program similar to that in the previous year. An extensive program of testing tanks and airframes in a radiation field at cryogenic temperatures will be undertaken in conjunction with a component-test reactor of suitable size and neutron flux density. The various tests envisioned in conjunction with a component-test reactor are as follows: Load tests of the tank and airframe at cryogenic temperatures, vibration tests at cryogenic temperatures, propellant heating, tank and airframe heating, and radiation effects on the thrust-transmitting members and auxiliary equipment supports.

The 1/10-scale, tank model tests will be completed during the third year. Ground handling equipment for the 1/10-scale model of the missile will be developed and tested, as well as the necessary equipment for propellant transmission. Necessary scale factors will be determined from these tests to permit the design of the full-scale tank and airframe.

c. Controls

A testing program, directed to establish the functional and operational characteristics of the control components, will be conducted. It is estimated that this phase will include more than 30 separate components. Consequently, it will be necessary that all components in this phase be treated as a group. The following tests are partially or entirely applicable to all of the controls components:

- Calibration
- Static leakage
- Proof pressure
- Extreme temperature
- Fluid resistance
- Vibration
- Control functional
- Endurance

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Ignition proof

Burst pressure

Humidity

Altitude

Sand and dust

The test program is further complicated by the fact that some of the listed tests must be conducted with irradiated components or in a radiation field. Initial emphasis will be placed on components used in "series" in the system. The "overload" test concept will be used to detect and correct detail failures that indicate insufficient safety margin. Based on this, the test levels used in terms of pressure, vibration amplitude, extreme temperature and timing will be increased over normal design values to determine the reliability and safety margin. Each component will be subject to testing, modification, substitution or retesting until it has achieved its specified performance. When the predetermined target performance has been achieved, the component is released for incorporation in the system testing.

d. Thrust Chambers

Development testing of the small-scale segment will be completed by the end of this period. All tests with chemical rockets simulating the small-scale design will also end. The results of the development tests in nozzle cooling, thrust vector control, separation control, and thrust augmentation will be incorporated into the design of the small-scale nozzle, and a "prototype" small-scale nozzle will be fabricated for use with the small-scale propulsion system.

4. Small-Scale Propulsion System Without Reactor

In continuation of the development of the small-scale, nonreactive, propulsion system, the third year's work will comprise completion of the design work, fabrication of components, and assembly of the complete system. Test work will be initiated, but this will probably be limited to

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cold-flow tests of subsystems and check-out of the chemical combustion equipment. The subsystems for cold-flow tests will consist of tanks, turbopump, gas generator, propellant controls, and associated fluid lines, which will be tested to establish hydraulic and transient-response characteristics in preparation for complete-system firing tests.

5. Small-Scale Propulsion System with Reactor

This third phase of the small-scale systems development program will begin during the third year with design improvement of components and adaptation of the system for use in a reactor. By this time, it is anticipated that the reactor projects of the Government Laboratories will have progressed to an advanced experimental stage which will provide specific design and operational data, and detailed evaluation of the propulsion-system installation. It is assumed, for planning purposes, that a reactor suitable for small-scale propulsion-system tests will result from the development effort of the Government Laboratories. The objective of this phase of the system development program is the demonstration of satisfactory operation of the complete small-scale system, and it is considered that this objective may be reached with a relatively small number of tests with the reactor, by virtue of more extensive testing of the nonreactive system. In view of the expense and difficulties involved in testing the complete reactor propulsion system, it is essential that extreme care and thorough planning be exercised in carrying out the tests. The success of the development program depends upon the proper execution of the reactor system tests, supported in depth by adequate testing of the nonreactive propulsion system. The tests planned for this system will be primarily to check heat-transfer characteristics, reactor and overall control system response, and stability of the reactor operation under changing flow-rate conditions.

6. Full-Scale-Component Development

a. Turbopumps

The fabrication phase of the full-scale-component development program will continue through most of the year. The test program will be initiated near the end of the third year.

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b. Tanks and Structures

The design of the full-scale tank and airframe will be essentially completed at this time, and fabrication of the full-scale model will be continued during this year. During the fabrication period, experience from the research phase will assist in the establishment of controls for materials and fabrication techniques. Simultaneously with the fabrication of the full-scale tank and airframe, the ground handling equipment for the missile will be built, as well as the equipment required for handling the propellants.

During this year, as the various parts for the full-scale model are completed, duplicates of these parts will be subjected to tests, preferably to failure, if the conditions permit. All auxiliary-equipment support structures and thrust-transmitting members will be subjected to simulated load conditions and accelerated tests to destruction. Propellant handling equipment will be tested for its capability of transporting propellant with a minimum of loss and hazard. No testing of the ground handling equipment of the missile is anticipated during this year.

c. Controls

The design and fabrication program for the full-scale components will be similar to the small-scale program. Since the components developed here are to be used in the next four phases, the degree of detailed design will be increased. The objective of this program is to develop components that may be used in the preliminary prototype propulsion system, or that the information and data which is obtained by development may be used to produce prototype components. Besides obtaining functional and operational characteristics of control components by the means listed in paragraph B,4,c, data must be compiled to include problems of ground servicing, launching procedure, and improved operating procedure. It is in this phase that a major effort must be made to design and evaluate flight controls.

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A full-scale support or backup program must be established. This program must continue after completion of component reliability testing. The subsequent designs will be considered as advanced models. These designs may be adapted to the prototype nuclear rocket.

d. Thrust Chambers

It is anticipated that sufficient progress will have been made in the small-scale-nozzle, cooling test program to begin fabrication and testing of the full-scale nozzle. As in the small-scale testing, only a partially plugged segment of the nozzle will be flowed with the working fluid. Experience gained in using the porous-graphite heat source in small-scale testing will be applied to full-scale testing.

7. Full-Scale Subsystem Development

In support of the full-scale-component development phase, it is planned to combine the components into subsystems to evaluate possible interactions by cold-flow testing. It is not considered practical, however, to conduct complete system tests with a nonreactive heat source because the development of the heat source alone would be a major development program. The full-scale subsystem development phase will be initiated during the third year by design improvement of the full-scale components and initiation of fabrication of subsystem elements.

8. Prototype Reactor

a. It is anticipated that the prototype reactor will be based on designs developed by the National Laboratories. However, since some investigation into novel and unique systems is to be carried out, the possibility of such a system showing great promise should not be neglected.

b. During this period, detailed design of the prototype reactor components will be continued and design of the reactor itself will be initiated. Early stages will deal primarily with fuel and control elements, with adequate attention being given to structural members and methods of mounting the core in its shell. Remote techniques for handling the prototype

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after test firings must be considered and the necessary equipment designed. Also, at this time, the design of a reactor mockup, complete with natural or depleted uranium in the fuel elements, for engineering test purposes, should be accomplished.

c. The fabrication of reactor components for test purposes will continue and component proof testing will get under way. A mockup of the remote-handling equipment will be fabricated and tested, and fabrication of the reactor mockup will be initiated.

E. FOURTH- AND FIFTH-YEAR PROGRAMS

1. The fourth- and fifth-year programs will be characterized by increased activity in nearly all of the phases of endeavor which have been inaugurated during the earlier years. They will also produce the fruition of much of the development work in terms of test results. During these years, the larger part of the work will be in active development tests, and the most significant of the mileposts established for the 5-year program will be achieved. For example, during the fourth year it is anticipated that the component development work will result in the demonstration of satisfactory performance of all of the major components, both small-scale and full-scale. Moreover, the small-scale propulsion system without reactor will be operated, and this is considered to be a key achievement in providing confidence in the future efforts of the full-scale system. At the present time it is not possible to define the exact test operation because the design specifications related to specific selected missions are not now defined, but will be defined in the course of the first year's program. It is intended, however, that the development-test plans will include sufficient testing, particularly of the individual components, to provide, by the end of the fourth year, adequate indication of performance, reliability, and operational life. It does not follow that the attainment of the mileposts shown in Figure 1 will mean the stoppage of test work. Continued testing will be necessary, although perhaps on an intermittent basis, to evaluate design improvements which will be made continually throughout the program.

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2. During the fifth year, additional achievements may be anticipated. The operation of the small-scale system with reactor and the operation of the first of the full-scale experimental reactors are most significant mileposts, and the completion of the installation of the full-scale propulsion system with reactor is the primary objective of the 5-year program. At this point the full-scale system with reactor will be ready to test in a ground installation. The components of this system are expected to be essentially prototype from the standpoint of functional performance, although not in terms of weight or optimum packaging. After considered study it has been concluded that the 5-year program was too short a period in which to achieve operation of a full prototype system. In fact, it is considered that such an achievement is well beyond the scope of the 5-year program, even though preliminary design of the prototype has been initiated.

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III. FACILITIES

A. TESTING AND FACILITY STUDIES

1. Introduction

One of the most difficult problems in the development of a nuclear rocket is to devise techniques and equipment for performing the necessary test work safely and at a cost within reasonable proportion to other costs of development and production. Among the critical problems, in addition to those presented by chemical rockets, are exhaust-product radioactivity and its control and/or containment, and operation of equipment in the presence of highly radioactive and toxic materials of the reactor.

The discussion below, taken in part from Report No. 1157, includes these and related problems. They are presented, together with the planned approach to these major technical problems and the nature and magnitude of the necessary testing and facility engineering effort. This study, as specified in the contract work statement, is to be conducted "to establish the design criteria and detail requirements for the optimum design of a nuclear rocket test facility from the standpoint of cost, technical desirability, and safety."

It is to be noted that the continuity of the entire development program for the nuclear rocket is dependent on thorough planning of facilities, which must be initiated concurrently with the system studies and in close cooperation with them.

2. Scope of Program

The study program as presented herein is for a continuing and expanding program, during which all phases of testing from small-scale component tests to flight testing will be considered.

The first year will be a basic study of the total program, intended primarily to determine areas for extensive study during the appropriate subsequent years. The level of effort in the study will be doubled during the second year, as more detailed problems become evident, and tripled at the beginning of the third year.

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3. Problem Areas

The program for the development and testing of a nuclear rocket will involve many unique facility aspects. As has been found to be the case in previous rocket programs, facility problems can be the limiting factor, either from the standpoint of construction cost or practicability. It is necessary, therefore, that an engineering study covering all tests and the facilities for such tests continuously parallel the development of any new rocket program in order to avoid such an eventuality. Advanced planning and engineering foresight resulting from studies of testing problems and facilities may make this possible. Accordingly, the proposed study covers all engineering necessary to furnish a continuous, comprehensive analysis of the implications of the rocket development program in terms of facilities.

A portion of this study will be devoted to problems and solutions associated with these special circumstances:

- a. Delay of scheduled tests during the radioactive decay period which prevents disassembly, removal, or modification of test equipment.
- b. Condemnation and abandonment of a facility in the event of a serious malfunction which would contaminate the locale to intolerable levels. Economic considerations in facility design will be considered. These considerations will include potential equipment and test area loss, as well as operational safety measures such as shielding, remote-controlled handling equipment, and environmental radiation-level detection.
- c. Area contamination problems associated with fallout in the proximity of the test facility. Meteorological and health physics aspects associated with contamination to preclude any compromise of personnel safety.
- d. Containment or dispersal of reactor and test-equipment gaseous waste, containing radioactive fission products. The discharge of large quantities of gaseous hydrogen or other working fluids volatilized during test operations and containing radioactive fission products will

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require a thorough evaluation for the study. This problem is fundamentally similar to that associated with a large-chemical-rocket test facility (as well as that of a chemical separation plant) in that the compromise of personnel or test-area safety cannot be permitted.

A survey and evaluation will be made of present well-established techniques for the handling of both non-nuclear and reactor waste products as an aid in establishing design criteria for test programs.

4. Site Location

In arriving at recommendations for the site location of the various test facilities, the usual factors evaluated by architect-engineers will be applied, together with the application of the unique requirements of this program as established under other topics of study. In the event that considerations of waste disposal or dissemination require a test site remote from populated areas, the location study must establish: (a) the relative feasibility of alternative plans (for example, testing in Nevada versus the Pacific), (b) the excess cost required for supporting facilities and transportation to support the more remote operation, and (c) the loss of convenience and operational effectiveness resulting from transport and communications time, and numerous related factors. These engineering considerations must be applied to each of the facilities and each test phase on a uniform and consistent basis. The results of this study are contingent upon the results of other sections of the study, and vice versa; e.g., the cost of liquid-hydrogen manufacturing plants, in the event that "on site" manufacturing is required, is determined by the number and location of test sites.

5. Reactor Testing

The study will include detailed investigations of required reactor facilities. Both fractional-scale and full-scale testing of the reactor itself will demand imagination and ingenuity. Basic requirements will clearly include "cold" assembly, "hot" testing, and "hot" disassembly facilities, together with numerous and complex supporting facilities, such

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as remote instrumentation and observation, propellant supply system, equipment for handling heavy loads, atmospheric contamination control, etc.

6. Laboratory Facilities

In addition to facilities for tests of materials and components which are necessary for the rocket aspects of the present program, extensive needs for many types of laboratories must be studied and evaluated. In the case of very low-level or "cold" laboratory requirements, the possibility of making use of existing laboratories at such sites as Sacramento or Azusa will be evaluated. It is anticipated, however, that similar laboratories will be needed in close proximity to the "hot" test site. In addition to the relatively modest "hot" facilities needed at the research and development laboratories of the project, it is evident that extensive "hot" laboratory facilities will be essential for support of "hot" test-site operations. Among these, must be included laboratories for radiochemistry, radiophysics, and reactor technology, high-level and low-level cells for metallurgy and material studies, and health investigations.

7. Supporting Facilities

Particularly in view of the additional personnel required for handling problems introduced by radioactivity, supporting facilities may represent a relatively significant application of engineering effort during the study. However, from experience with previous rocket programs, "rule of thumb" bases for determining test-operation support requirements will be useful in many phases of the study. Construction cost estimates for such facilities will be prepared. The cost of such facilities, especially for operation at remote locations, is usually a very significant portion of the total facilities costs and will be carefully considered in the determination of the test sites.

8. Survey of Existing Facilities

Concurrently with the preparation of other sections of the study, a comprehensive survey of existing facilities which are adaptable and would be usable for the program will be accomplished. To this end, the

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Facility Requirements study information will be compared with the capacities and characteristics of existing installations to permit their use, especially in early program phases, wherever possible. Major facilities to be considered would be those owned by the Government or that could be made available to the Government, such as hydrogen manufacturing plants, storage facilities, materials and engineering testing reactors, pump and turbine test laboratories of large capacity, and rocket static-test stands. Screening of existing installations will be accomplished first on a technical basis for applicability and, secondly, on the basis of their availability and convenience to the program.

9. Supply, Storage, and Handling of Working Fluids

Liquid hydrogen and ammonia are being evaluated as possible working fluids for a nuclear propulsion system. Inasmuch as these two fluids are currently the most promising, it is planned to include consideration of both in the study of facilities.

A systems study of liquid hydrogen, related to overall safety, liquid handling, and control of the flight vehicle during ground operation and flight, will be coordinated in the overall systems evaluation.

Evolution of propellant requirements during this study will permit a more complete evaluation of liquid hydrogen and other cryogenic facility requirements necessary for the following years of research, development, and testing. Facilities studies will be initiated to expedite successful experimental studies following the feasibility study. Production capacities, storage requirements, supply distribution, and recovery or disposal evaluations will provide data for recommendations for small-scale prototype testing and associated problems of heat transfer, fluid flow, tank design, thrust-chamber development, and reactor use. These considerations of economic supply, storage, and handling of fuels required for the rocket program will be carried through, in the study program, from the first experimental work on materials to the total requirements for rocket launching.

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10. Testing in a Radiation Environment

The need for an extensive study into the effects of radiation upon materials, and various phenomena, such as the pumping of liquid hydrogen, is recognized. Because of the urgency of resolution of some of these problems, adequate facilities must be provided at a very early stage. Planning must be accomplished with respect to the construction of reactor facilities. Owing to the long lead time involved for such construction, this problem will receive early attention in the study program.

A broad study will be conducted into the adaptability of existing reactors for use on material and component in-pile experiments. Particular attention will be directed toward research and training reactors. This is especially significant since materials-testing reactors may not be available to the extent necessary in the early phases of the program. To produce interpretable data, it is believed that a relatively high-intensity reactor is required to closely simulate actual operating conditions. Evaluation of existing reactor facilities will be conducted through an intensive literature survey and by direct contact with operating personnel.

B. SCHEDULED FACILITIES

The 5-year program plan for the development of a nuclear rocket (Figure 1) has broadly outlined the anticipated testing and experimental work. A test facilities plan corresponding to the project outline has been prepared (Figure 2) which indicates the approximate schedule covering design and construction of facilities for each general testing category, together with milestone completion dates for some of the major facilities.

Early planning of test facilities, and the meeting of design and construction schedules is of paramount importance in the success of the overall development program. The milestone schedule must be met in order to complete the development through construction of a full-scale system ready for test at the end of the fifth year.

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1. First Year

The facility construction program during this year will be devoted to acquisition of basic research equipment, "hot" labs, and small-scale-component test installations, as follows:

a. Radiation Laboratory

Irradiation evaluation of materials and small components is a requisite to properly evaluate the feasibility of various designs. This laboratory, scheduled for completion by the end of the first year, will provide the equipment necessary for post-radiation evaluation of materials. Speciment irradiation will be conducted as in-pile loop experiments in one of the national reactors.

b. Hydrogen Liquefier

A small-scale cryostat will be provided during this year to support the low-quantity research requirements for liquid hydrogen and helium.

c. Turbopump Test Facilities

A component-test installation for cryogenic temperature testing of conventional bearings and seals will be completed at the end of the year.

2. Second Year

A significant increase in the facilities program will occur in the second year. Included will be the construction of facilities needed for research, component testing, and small-scale systems tests. Specifically, the following facilities will be in process during this period.

a. Basic research facilities will be completed for heat-transfer and fluid-flow experiments and materials testing. Intermediate research facilities, required for larger-scale experiments in the third year, will be designed and major procurements made.

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b. A component "hot" laboratory will be constructed for use during the year, and the design will be completed for the core disassembly and examination "hot" lab, which will be required at the test site the following year.

c. The design and major construction of full-scale pumps and turbine test facilities will be completed by the end of the second year.

Both of the installations are planned to be integral facilities, each a complete unit consisting of multiple test positions served by a central control area. These units will involve motivating power for the pump testing and steam- and gas-turbine generating plants in the 50,000-hp class. Liquid-hydrogen closed circulation systems and major tank-farm facilities will be part of the pump test installation.

As a supplement to these facilities and for the large-scale heat-transfer and fluid-flow testing required in the third year, a 2-ton per day hydrogen liquefaction plant will be designed and constructed. The liquefier facilities will be needed because the anticipated propellant requirements are far greater than will be commercially available.

d. An instrument and electrical controls laboratory will be constructed in order to provide the equipment necessary for development testing and evaluation of all small-scale and full-scale components of the control elements of the mechanical and electrical systems. Supporting facilities will include hydraulics laboratories and assembly shops.

e. The facilities required for testing a small-scale functional system having a simulated reactor will be in the design and early construction stage during the second year. Heating equipment is planned for supplying heated gas for short-duration testing of the complete system.

f. Construction of a small-scale components-test reactor facility must begin early in the second year and be carried out as rapidly as possible in order to be available early in the third year. This facility is anticipated to be of a design which will be available from prior work.

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g. A test reactor for full-scale components testing, which is scheduled to be available in the fourth year, will be designed during the second year.

h. Design work will begin late in the second year on facilities for small-scale systems testing which are to include utilization of a reactor. Designs will be initiated also on the major facilities required in the fourth and fifth years for testing full-scale systems. These are planned to be separate installations, one which will handle the propulsion system without reactor and a remote installation with all supporting facilities for testing the complete system with full-scale reactor.

3. Third Year

A major portion of the small-scale facility programs will be completed, and planning and design of the large-scale test stands will be inaugurated during the year. This will require a continued increase in the level of effort and may be significantly affected by the results of the first-year study.

a. An intermediate research laboratory will be completed. Intermediate or pilot-scale, heat-transfer, nozzle-flow, and materials evaluation experiments will be provided among these facilities.

b. A "hot" laboratory for core disassembly and examination will be carried to the construction phase. Utilizing the equipment of this laboratory, the operating personnel will be able to safely remove and examine portions of spent reactor cores. Remotely controlled and shielded devices will disassemble the core and transport it from the test bay to the "hot" laboratory. This is an extensive installation incorporating all existing practical features to preclude any compromise of personnel safety.

c. The test laboratories for full-scale components will contain test bays for full-scale pumps, turbines, and thrust chambers. These laboratories, with required instrumentation, will be completed during the first half of the third year. This will permit the testing of full-scale items prior to assembling and testing as a system.

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III Facilities, B (cont.)

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d. A testing laboratory for flight control systems will be completed during the latter quarter of the third year, thus providing a small-scale facility for control-system testing. Provisions will be made to accommodate a complete control system, including the simulation of most components.

e. The component-test reactor facility will be partially completed by the middle of the third year. The engineering development will have proceeded to such an extent that a reactor will be ready for criticality tests and could be operated at a very low power level. A low-power test does not require extensive facilities for cooling nor does it require extensive radioactive shielding from the coolant stream. All necessary equipment will be incorporated into an irradiation laboratory to conduct materials evaluation and pumping experiments in the radiation environment provided by the small-scale components-test reactor, which is scheduled for completion early in the third year.

f. The design of facilities for use in the small-scale-system tests, the full-scale-system (cold) test, and the full-scale-system tests with the reactor will be completed by mid-year, and construction will be initiated.

4. Fourth and Fifth Years

Facilities constructed during this period are extremely large and complex, requiring extensive planning to insure the optimum in economic design. It is expected that full-scale static testing can be accomplished safely at a Nevada test site. The results of tests planned to be made by the National Laboratories prior to the fourth year will aid in determining the hazards involved. Testing in the Pacific proving ground, if found necessary, will increase the major facility costs during the fourth and fifth years of the schedule presented.

To meet the continued demand for increased research facilities and for the resolution of critical problem areas which may have resulted from previous study phases and advanced-systems testing, an advanced research laboratory is planned. It is scheduled for completion early in the fourth year.

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III Facilities, B (cont.)

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Complete full-scale system testing, as scheduled for the fifth year, will require very large and complex installations, accounting for a substantial portion of the total facilities expenditures. Elaborate remote handling and transportation systems are required.

To meet the unusually large requirements for cryogenic fluids, created by systems testing, a 25-ton/day hydrogen liquefier will be completed during the fourth year.

Although no actual construction work is planned on the prototype static test stand, it is anticipated that the preliminary planning and basic design will be completed by the end of the 5-year program.

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IV. MANPOWER AND COSTS

A. MANPOWER

The manpower estimates are based on the 5-year program described in Section II and Figure 1. It is believed that in order to achieve a uniform and reasonable growth rate in manpower available to the second-year program, the first-year effort must be somewhat more intensive and extensive than that described in the Work Program Report of 31 July 1956. Consequently, the present plan, as shown in Figure 3, calls for approximately a 50% increase in manpower in the first year. The extension of work in the first-year program is described in Section II, B, 4, i, j, k, l, and m.

The manpower distributed by work classes is shown in Table I, for the first 2 years of the program, with totals given for the remaining 3 years.

B. COSTS

The costs which are presented in Table II, and Figures 4 and 5, are based on the best estimates to date. Since neither the size of the nuclear rocket nor its mission have yet been determined, these estimates are subject to wide variations, particularly in the last 3 years of the program. Table II, which shows the costs by work classes, does not include the cost of facilities. The latter cost is shown in Figure 4.

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TABLE I

5-YEAR NUCLEAR ROCKET PROGRAM
MANPOWER REQUIRED, BY WORK CLASSES

Year	1	2	3	4	5
1. Power-Plant Performance Analysis	15	20			
2. Engine and Engine Components					
a. Design	66	265			
b. Fabrication	10	260			
c. Testing	50	115			
3. Heat Transfer	16	45			
4. Materials Study	16	45			
5. Liquid-System Components	-	-			
6. Instrumentation and Controls	12	30			
7. Ground Handling and Servicing					
8. General Planning, Administrative and Training	15	20			
TOTAL	200	800	2061	2606	3051

Table I

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TABLE II

5-YEAR NUCLEAR ROCKET PROGRAM
COSTS BY WORK CLASSES (MILLIONS OF DOLLARS)

Year	1	2	3	4	5
1. Power-Plant Performance Analysis	.374	.500			
2. Engine and Engine Components					
a. Design	1.462	4.380			
b. Fabrication	.148	3.400			
c. Testing	.643	2.000			
3. Heat Transfer	.608	1.400			
4. Materials Study	.415	1.600			
5. Liquid-System Components					
6. Instrumentation and Controls	.340	1.100			
7. Ground Handling and Servicing					
8. General Planning, Administrative and Training	.335	.500			
TOTAL	4.325	14.880	44.11	48.88	53.3

Table II

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FIGURE 1. PROJECT SCHEDULE WITH MILEPOSTS

1. CONCLUSION OF COMPARATIVE STUDY
2. SELECTION OF SPECIFIC SYSTEMS FOR PARTICULAR MISSIONS
3. ESTABLISHMENT OF DESIGN SPECIFICATIONS
4. COMPLETION OF PRELIMINARY DESIGN LAYOUTS - COMPONENTS AND SYSTEMS
5. DEMONSTRATION OF SATISFACTORY COMPONENT PERFORMANCE
6. COMPLETION OF DETAIL DESIGN OF SMALL-SCALE PROPULSION SYSTEM

7. DEMONSTRATION OF SATISFACTORY SYSTEM OPERATION WITHOUT REACTOR
8. DEMONSTRATION OF SATISFACTORY SYSTEM OPERATION WITH REACTOR
9. DEMONSTRATION OF SATISFACTORY PERFORMANCE OF FULL-SCALE COMPONENTS
10. COMPLETION OF DETAIL DESIGN OF FULL-SCALE SYSTEM
11. CRITICALITY OF FIRST REACTOR, OPERATION AT LOW POWER
12. CRITICALITY OF SECOND REACTOR
13. COMPLETION OF INSTALLATION OF FULL-SCALE PROPULSION SYSTEM WITH REACTOR, INITIATION OF TESTS

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FIVE-YEAR PROGRAM LEADING TO THE DEVELOPMENT OF A NUCLEAR ROCKET

FACILITIES SCHEDULE

PLANNING, DESIGN & CONSTRUCTION

1ST YEAR

2ND YEAR

3RD YEAR

4TH YEAR

5TH YEAR

1. BASIC RESEARCH FACILITIES
2. INTERMEDIATE RESEARCH FACILITIES
3. ADVANCED RESEARCH FACILITIES
4. MATERIALS TEST HOT LAB.
5. COMPONENTS TESTING HOT LAB.
6. CORE DISASSEMBLY AND EXAMINATION HOT LAB.
7. BEARING & SEAL TEST FACILITY
8. SMALL-SCALE PUMP & TURBINE TEST FACILITIES
9. CONTROLS LAB.
10. INSTRUMENT & ELECTRICAL CONTROLS LAB.
11. LARGE-SCALE PUMP & TURBINE TEST FACILITIES
12. FULL-SCALE THRUST-CHAMBER TEST FACILITIES
13. FLIGHT CONTROLS SYSTEMS TESTING LAB.
14. REACTOR CRITICAL - SMALL SCALE
15. REACTOR CRITICAL - FULL SCALE
16. FACILITY READY FOR CRITICAL REACTOR
17. FACILITY READY FOR FULL-SCALE CRITICAL REACTOR
18. PRELIMINARY DESIGN & PLANNING COMPLETION

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Figure 2

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FIVE-YEAR PROGRAM LEADING TO THE DEVELOPMENT OF A NUCLEAR ROCKET
RESEARCH AND DEVELOPMENT MANPOWER

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FIVE-YEAR PROGRAM LEADING TO THE DEVELOPMENT OF A NUCLEAR ROCKET

DEVELOPMENT AND FACILITY ANNUAL COSTS

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FIVE-YEAR PROGRAM LEADING TO THE DEVELOPMENT OF A NUCLEAR ROCKET
DEVELOPMENT AND FACILITY COSTS

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Figure 5