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CONTRIBUTION TO NUCLEAR ROCKET PROPOSAL
Section 1 - Preliminary Design

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PRELIMINARY REPORT

This report is preliminary and informal in nature and was prepared for use at the Aircraft Nuclear Propulsion Department, General Electric Company in the course of work under AEC contract AT (11-1)-171, U.S. Air Force contract AF 33(038)-21102, or U.S. Air Force contract AF 33(600)-38062. Views, opinions, conclusions or proposals expressed in the report are those of the author(s) only. This report is subject to revision upon further evaluation or availability of additional data.

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1.2 SUMMARY

1.2.1 OBJECTIVES

For the preliminary design of the Nerva engine the proposer adopted the following objectives:

Safety and reliability are the overriding considerations.

The costs of the Nerva program should be kept to a minimum.

The design should incorporate operational capabilities beyond the flight test missions.

1.2.2 DESCRIPTION OF DESIGN

The nuclear rocket engine consists of the following major components: reactor with pressure shell, shield assembly, propellant feed system, thrust nozzle, thrust structure and control system.

The reactor used is the KIWI-B1 reactor in accordance with the requirements of the request for proposal. The pressure shell is designed to satisfactorily carry the flight loadings to which the reactor will be exposed.

A shield is proposed for installation in the dome of the pressure shell to reduce the heating rate of structure components located between reactor and vehicle tank.

The propellant feed system consists of the turbopump (s), turbine (s), pipes and valves, and tank pressurization equipment. It is of the hot gas bleed type. The turbopump under development at the Rocketdyne Division of the

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1.2 SUMMARY

1.2.2 DESCRIPTION OF DESIGN (cont.)

North American Aviation Company will be used if upon evaluation it is found to be satisfactory for the application. A preliminary design is presented for dual pumps which could be developed by the proposer if this would be of a decisive advantage to the Nerva program.

The nozzle is of the regenerative cooled type. The nozzle under development by the Rocketdyne Division of the North American Aviation Company will be used if upon evaluation it is found to be satisfactory for the application. The proposer has included the design of a nozzle which could be developed if this would be of decisive advantage to the program.

The thrust structure connects all structural parts with the vehicle and incorporates provisions for gimbaling the entire engine at a point immediately on top of the reactor pressure shell. The structure is uncooled.

The control system presented considers start-up of the reactor after launch when the vehicle is at safe distance from the launching pad and populated areas. Hydrogen flow is initiated at the time of separation from the previous stage. On the ground and during the initial phase^{of} launching the reactor is highly poisoned to prevent criticality under any conceivable abnormal situation. Although the preliminary design of a control system has been presented, the proposer intends to utilize the accumulated experience of the ^{Los Alamos Scientific Laboratories} ~~LLNL~~ to the greatest

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1.2 SUMMARY

1.2.2 DESCRIPTION OF DESIGN (cont.)

extent for the final design of the control system.

1.2.³~~2~~ COMPARISON WITH OBJECTIVES

The approach to safety used in the preliminary design is reflected particularly in the control system and the operational procedures for ground test and flight test. Reliability is emphasized by simplicity of the design. Where weight savings would have resulted in a substantial complication of the design, reasonable increases in weight have been accepted and simple designs selected.

In order to keep the costs of the Nerva program to a minimum, it is the contention of the proposer to evaluate all components under development in connection with the Rover program, to make full use of the state of the art applicable to the Nerva engine, and to arrive at an optimum utilization of them in the design. The approach will avoid unnecessary re-development of available components which are satisfactory for the intended application.

Since sufficient details with respect to the components under development are not available to the proposer at the present time, the proposer has prepared a preliminary design incorporating components which are believed suited for the Nerva application. Where ever practical, these components have been designed for the growth power rating of 1500 MW. These components will also operate satisfactorily at the "derated" condition of 1130 MW.

1.2 SUMMARY

1.2.4 LIMITATIONS

The suggested approaches to safety, ~~and~~ especially for flight testing, cannot be considered as complete in this preliminary design. The entire question of start-up during the booster phase of the mission as compared to reaching criticality on the launch pad must receive considerably more attention. The final design recommendation must be based on an extremely critical review of this problem.

The possible desirability of recovering the nuclear rocket is recognized. No attempt, however, has been made in the present preliminary design to implement recovery. A separate study of this problem with respect to practicability and economic feasibility is proposed.

The shield and control system cannot be considered as final since neither the requirements of the missile frame manufacturer nor the previous design work of ~~the~~ ^{the Los Alamos Scientific Laboratories} has been incorporated.

1.2.6) ALTERNATE DESIGNS

No alternate designs are being proposed at this time. The proposer, however, has included several ideas for solutions of possible design problems which he hopes will be of value to the Nerva program.

1.5.1 KIWI-B1 REACTOR

The reactor used for the preliminary design of the Nerva engine was the Kiwi-B1 reactor. Since the Kiwi-B1 reactor was designed for ground test, the proposer believes it may be desirable to make some design changes to the reactor pressure shell prior to flight testing. As a result this section will be devoted to a description of the Kiwi-B1 reactor, obtained from current literature, followed by some proposed changes to the reactor pressure shell which would be needed for a flight type engine.

The literature available to the proposer on the Kiwi-B1 reactor was fragmentary. As a result, most of the data for this reactor was obtained from paragraphs two and three on page 1 of Attachment A of the Request for Proposal, Report LAMS-2502, and Report LAMS-2422. The proposer's concept of the Kiwi-B1 based on this data is shown in Figure 1-1.

1.5.1.1 CORE

The core is made up of approximately 160 graphite modules 52 inches long. The modules have the same geometry as a bundle of seven hexagonal tubes; each bundle measures slightly less than three inches across the flats. Each hexagon has a 3/4 inch diameter hole drilled through it longitudinally.

The cylindrical fuel elements fit in these holes with sufficient clearance to accommodate the differential thermal expansion. Each module is supported by a stainless steel tube threaded into the upper end of the center hole of the graphite module. The tubes in turn project through and are attached to a

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1.5.1.1

suitably designed perforated plate (tube sheet) which is supported in the forward end of the pressure shell. The inertia, thrust, and pressure forces on the core are carried by this arrangement into the pressure shell.

The fuel elements are extrusions of a graphite-flour uranium-oxide binder mixture in the form of $3/4$ inch O.D. rods which have *seven* holes of approximately $3/16$ inch diameter drilled in them longitudinally for passage of coolant-propellant. Each fuel element is in two sections, that is, there are fourteen fuel elements in each module. The fuel elements passages are protected from the hydrogen-graphite reaction which occurs at high temperatures by thin niobium metal sleeves which have been carbided in place in the gas passages.

The active core has a nominal outside diameter of 35 inches and is 47.50 inches in length. At the upper or inlet ends of the modules where the supporting tubes are threaded into the graphite there is a 4.00 inch length which contains no fuel elements. At the opposite or exhaust ends there is also one-half inch of module which contains no fuel elements. The fuel elements are prevented from blowing out of the modules by shoulders extending into the $3/4$ inch diameter holes at the exhaust end of the modules.

1.5.1.2 RADIAL REFLECTOR

The radial reflector consists of an inner graphite cylinder and an outer beryllium cylinder which surround the reactor core. The inner reflector is a hollow cylinder 52 inches long having an inside diameter of 36 inches and an outside diameter of 40 inches

1.5.1.2

for nominal wall thickness of 2 inches. The 36 inch I.D. provides a one-half inch space between the inner surface of the graphite reflector and the outside surface of the active core to allow for the differential thermal expansion of the core and reflector. This space is stuffed with graphite wool.

The outer beryllium reflector has an inside diameter of 40.25 inches and an outside diameter of 49.25 inches. There is a .125 void between the inner surface of the beryllium and the outer surface of the inner graphite reflector to allow for thermal expansion. The reflectors are laterally supported inside the pressure shell. Forward support is provided by the front tube sheet and aft support is provided by an internal flange or shelf which is a part of the pressure shell. The outer reflector contains twelve longitudinal cylindrical openings dimensioned to accommodate the reactor control drums.

1.5.1.3 PRESSURE SHELL

The pressure shell is a .75 inch-thick aluminum cylinder, 50.875 inches O.D., with an oblate ellipsoidal shaped pressure dome at the inlet end of the reactor. At the exhaust end of the reactor the shell incorporates an integral toroidal manifold and terminates in a flange designed to mate with a similar flange on the inlet end of the nozzle assembly.

The pressure dome is attached to the side pressure shell by means of a flange and clamp. A cylindrical skirt of one-half inch thick aluminum alloy plate is welded to the outer surface of the dome and located concentric with the center-line of the

1.5.1.3

reactor-pressure-shell assembly. This skirt provides support for the twelve actuators which operate the reactor control drums.

The tube sheet which supports the reactor core is located inside the pressure dome and is in turn supported by a cylindrical groove around the inner surface of the shell. This groove is defined by a shoulder formed by a portion of the side shell which projects above the side shell flange and an upper shoulder machined in the inner surface of the dome. Removal of the clamp from around the front flange permits lifting the dome away from the side shell and thus exposes the tube sheet for disassembly of the reactor.

Since the Kiwi-B1 is designed for operation with the exhaust nozzle pointed upward, the toroidal manifold on the pressure shell serves as a reservoir to trap any liquid propellant that might flow over from the nozzle manifold. The toroidal manifold on the pressure shell is internally baffled in a manner that prevents any liquid propellant from entering the reactor, an occurrence which could cause a nuclear perturbation in the reactor or which could produce thermal shock to the hot parts of the reflectors and core.

1.5.1.4 MODIFIED PRESSURE SHELL

In designing the flight vehicle a structure is needed between the engine and the vehicle structure capable of taking the thrust and inertia forces from the rocket engine, and which will incorporate some type of gimbal mechanism for directional control of the vehicle. In addition, it would be desirable to provide a shadow shield at the forward face of the active core sufficient to

1.5.1.4

eliminate any need to cool the structure that is located between the front of the engine and the vehicle.

A convenient method of providing for attachment of a gimbaling mechanism to the engine would consist of designing the pressure-shell dome to take the thrust and inertia forces directly. This may be done by making the dome terminate in a conical shape as illustrated in Figure 1-2. This constitutes a simple and structurally efficient method of transferring the gimbal forces to the rocket engine assembly.

Studies have shown that the structural integrity of the pressure vessel may be increased by moving the upper flange, which attaches the pressure dome to the side pressure shell as shown in Figure 1-2, some distance down the side of the pressure vessel. This moves it away from the vicinity of the bending moments induced in the shell at the point of discontinuity where the pressure dome is tangent to the shell. These ^{bending} moments result because the pressure dome does not deflect radially as much under the internal pressure as does the side shell and, therefore, the dome produces an inward restraining force on the side shell. Also, it appears advantageous to make the flange connection with bolts which would improve the pressure tightness and allow for increased strength as the power plant development progresses to greater power levels. It may eventually prove necessary to install self-pressurizing metallic "O" rings between the flanges to insure complete pressure sealing rather than depend upon a ground surface fit. The "O" ring seals can be accommodated by the flange design. Remote

Fig. 1-2 - Pressure shell modifications (207R341)

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1.5.1.4

handling procedures would also be facilitated by use of the type of flanges and bolts shown.

The collector manifold at the aft end of the side pressure shell may be changed from an oval to a triangular cross-section and the flange that attaches the nozzle assembly to the pressure shell moved upward to the point where the conical nozzle shell intersects the side shell as shown in Figure . This arrangement should improve the structural stiffness in this region, and would permit bringing the nozzle coolant flow directly into the collector manifold without the need for external piping to get the flow past the flanges. The passages for the coolant flow into and out of the triangular manifold may be located to minimize the possibility of liquid propellant entering the reflector region when the engine is operated in the flight attitude. Further study may indicate a need to cool the pressure shell to nozzle flange connection which might prove to be easier to accomplish with the suggested arrangement.

Shield studies, which are outlined in Section 1.5.2, have indicated that approximately 1300 pounds of shielding are necessary for reactor operation at 1130 MW for 10 minutes to reduce the radiation level around the thrust structure sufficiently so that cooling will not be necessary. The preliminary design of a shield that could fulfill this requirement is shown in Figure 1-3 . The specific details of this shield will be discussed more completely in Section 2.1.1.4.²

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Fig. 1-3 - Preliminary design of shadow shield (737D736)

1.5.1.4

The following table presents estimated weights for the Kiwi-B1 reactor with modified pressure shell.

~~TABLE 1~~ - KIWI-B1 REACTOR WEIGHTS
Weights (pounds)

Pressure Vessel	1015
Front Plate	220
Control Actuators	210
Graphite Side Reflector	790
Be Reflector Plus Control Drums	2240
Core Plus Forward Graphite Reflector	3000
Shadow Shield	<u>1300</u>
Total Weight	8775

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1.5.2 SHIELD

Preliminary calculations were performed to determine the shield weight necessary for a flight type nuclear rocket incorporating the KIWI B-1 reactor. This shield was designed to overcome the following problems which are caused by the nuclear radiation field around a reactor.

1. Radiation damage to engine components.
2. Vaporization of the hydrogen propellant in the fuel tanks.
3. Excessive radiation heating of engine components.

In order to determine the magnitude of these problems and the amount of shielding possibly required on the flight version of the nuclear rocket engine, which incorporates the KIWI B-1 reactor, preliminary shielding calculations were made.

The calculations that were made supplemented the calculations provided by Los Alamos.* At the points where the calculations overlapped they were compared and found to be in good agreement.

The calculations indicated a 700 pound ^{Hevimet} shadow shield, located in the pressure shell in front of the reactor, ~~that~~ could be designed which would eliminate the propellant temperature rise and the propellant vaporization problem, but engine component cooling would be required. To eliminate the need for cooling, it was calculated that the shield weight would have to be increased to 1300 pounds of Hevimet for a ground test version of the

* "Miscellaneous Data in Support of LASL Presentation Before Engine Contract Bidders Briefing," LAMS-2502, January 1961, pg. 15-16.

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1.5.2

flight engine operating at 1130 megawatts for 10 minutes. For the flight engine itself, 1800 pounds of Hevimet would be required for the 1500 megawatt operation for 20 minutes.

From the standpoint of reliability it would be preferable to provide enough shielding to eliminate component cooling. Since the proposer believes that reliability is one of the principal criteria of a rocket engine, the heavier shields were chosen.

A more detailed discussion of shield problem is contained in section 2.1.1.4.

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1.5.7.1 Controls Requirements

Described in this section is an integrated control system for the flight test engine, excluding the thrust vector control

(Section). Phases of control operation are:

1. Pre-launch checkout at remote site
2. Pre-launch checkout at launch pad
3. Startup
4. Power operation
5. Shutdown
6. Multiple restarts
7. Aborted missions and destruct

An objective has been to provide operation of the engine at maximum average specific impulse; maximum utilization of propellant during both the startup and shutdown phases is, therefore, required. Great attention has been given to reliability, particularly through simplification. Safety has been given very great attention, not only in the airborne regime, but also in the launch pad operation, and pre-launch operation, and during the ground based reactor tests in which the control system would be given its first tryout. The design takes into account the structural requirements of the fuel elements, the pressure shell, the inlet header, reflector and other reactor components. Two items of particular concern were that provisions be made so that there would be no excursion on the launch pad, and secondly that the reactor, in the event of failure of the boost phase, would be returned to the earth in such a highly

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poisoned conditions, that it would not go critical when falling on the ground or into water.

The control system described herein is included to indicate one possible approach to a challenging problem. The final control system must, of course, incorporate all the available experience and know-how of the Los Alamos Scientific Laboratories.

For a flight test mission as described in Section the Saturn C-1 configuration has been assumed for the booster of the flight test vehicle. The booster burnout is at 127 seconds at an altitude of 191,000 feet and at a distance of 53 nautical miles from the launch pad. The nuclear stage attains fuel thrust in 15 seconds and operates for 100 seconds; the position is 250 miles horizontal from launch pad and 500,000 feet altitude. This is followed by a coast period of 300 seconds and finally a retro-thrust operation by the nuclear stage for 200 seconds.

In addition, for subsequent phases, an escape mission was contemplated using a nuclear third stage on a Saturn vehicle. This assumed mission had the following specifications:

Time from earth launch to separation of nuclear stage	- 273 seconds
Time to attain full thrust after separation	- 15 seconds
Total initial operating time	-1000 seconds

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1.5.7.1

Power operation is followed by 47 hours coast time and 97 seconds of retro-thrust. The above two missions fulfill the needs as expressed in the request for proposal relative to restart.

A launch site such as the Cape Canaveral was assumed which emphasizes the requirement for safety in the initial launching phases. This assumption was based on the likelihood that a new nuclear rocket tracking system will not be required for a nuclear rocket.

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1.5.7.2 Description of System

1.5.7.2.1 Introduction

The control system for flight testing and operational rockets requires a minimum amount of hardware and possesses the attendant reliability which can be achieved with simplicity. The simplicity of the control system is achieved by designing the reactivity worth of the control drums to be a specific amount and the use of a cold critical experiment to verify and trim the reactivity to the desired value. The system is characterized by its ability to accomplish rapid startups.

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1.5.7.2.2 Location of Control Components. The proposed locations for components on the rocket-reactor assembly are shown in Figure ~~1-5-7-2-2-1~~ ¹⁻⁴.

This sketch is presented in order to provide a quick graphical reference to the location of the important control components or assemblies. It is particularly useful in pointing to the possible component environmental conditions.

Electronic components are shown above the hydrogen tank in an area partially protected from thermal transients and extreme nuclear radiation.

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LOCATION OF CONTROL COMPONENTS

FIGURE 1-4

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1.5.7.2.3 Description of System

The control system consists of **four** major elements; a control unit which schedules neutron flux level and propellant flow as predetermined functions of time; a neutron flux loop which regulates the neutron flux, i.e., power level; a propellant flow loop which regulates the propellant flow; and a trip circuit used for aftercooling that senses the temperature of the pressure shell or other suitable component.

A block diagram of the control system is shown in Figure 1-5
~~1-5~~.

The control unit schedules flux and flow demands according to preset schedules but receives its commands to initiate hold, and stop these scheduled demands from the guidance control system. It also is capable of initiating reactor scram and stopcocking of propellant flow upon command of the guidance control. It does not receive radio commands directly from ground based control but could be made to do so if desired.

The flux loop consists of an error amplifier with control stabilization elements which compares the flux demand with the existing flux level to generate a flux error signal. The flux error signal is divided by the demanded flux level to provide gain compensation and the resultant signal is used as the common demand for the control actuator position loops.

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1.5.7.2.3 Description of System (continued)

The position loops are operated in parallel to achieve steady state synchronization of the control drums. There are twelve position loops, each consisting of a position error amplifier, actuator and position feedback sensor. Two actuators are regulating actuators and the remaining actuators are shims. All actuators have fast insert rates (negative reactivity), but the regulating actuators have a much faster withdraw rate capability than do the shims. The position loops withdraw or insert reactivity to increase or decrease the flux level, respectively, in response to the manipulated flux error signal so that the sensed flux level corresponds to the flux demand and the error is reduced to zero. The flux loop regulates power level from 0.1% full power to 120% full power.

The propellant flow control system, assuming the use of dual pumps, consists of two independent flow control systems operating from a common demand. Each control system regulates one of the dual pumping system by sensing the mass flow with a mass flowmeter, comparing this signal with the flow demand and generating an error signal that acts on the turbine regulating valve to control the turbopump speed. If a single pump is used an additional simplification can be accomplished.

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1.5.7.2.3 Description of System (continued)

During full power operation, the control unit schedules the flux demand to 120% full power and after a brief period, reduces the net flux demand so that the design temperatures of the fuel elements are maintained but not exceeded. It would be a design and development objective to provide flux and flow sensors with accuracy capabilities such that 100% power and flow could be scheduled with assurance that design temperatures were achieved without the necessity of a temperature override. This requires also that the power plant be accurately predictable.

The pressure shell temperature trip circuit consists of a temperature sensor and trip circuit. As the temperature rises during the aftercooling phase, it is sensed and when it exceeds a preset value, the trip circuit provides a signal to the control unit which initiates an aftercooling pulse of propellant.

The method of control is described with reference to time sequence of events that occur during the lifetime of the system. The sequence of events is divided into five distinct phases:

- I. Prelaunch checkout while on the launch pad.
- II. Post launch reactor startup and rise to power range.

1.5.7.2.3 Description of System (continued)

- III. Separation, acceleration to full power and full power run.
- IV. Shutdown and aftercooling.
- V. Restart.

1.5.7.2.4 Startup

Prior to Phase I before mounting on the launch pad, poison, in addition to the fully inserted control actuator poison, is inserted into the core to insure against achieving criticality in the event of accidents on the launch pad; typical accidents being fire, explosion, or hydrogen leakage into the core. The neutron source is not inserted into the reactor until as late as possible before launching. The reactor control system is first checked out in a cold critical experiment at a remote site and then moved to the launch pad without interrupting cable connections. It is desirable, while the rocket is on the pad, to test every component whose test does not require the reactor to be made critical to insure that no damage has been incurred since the earlier checkout. In this second check there must be an absolute minimum of procedures that open signal lines or otherwise disrupt the control hardware for such tests depreciate the integrity of the control system. A detailed checkout procedure would be determined during design and development of the system, but would roughly consist of functional checkout of control unit, actuators, and electrical components. The highly poisoned condition of the core would permit considerable latitude in actuator checkout without danger of achieving criticality. A discussion of the factors involved is presented in Section 2.1.1.5.2.1.

1.5.7.2.4 Startup (continued)

After the pre-launch checkout and other activities have been completed, the neutron source is inserted into the reactor. This act is delayed as long as possible to permit access to the nuclear stage for as long a time as possible prior to launch. The source will not significantly increase the neutron flux level in the highly poisoned core, but its own radiation level will require special handling and care. At this point the nuclear stage is ready and the final count-down is commenced and the booster is fired.

Phase II covers the period of time elapsing between the firing of the booster and the separation of the nuclear stage. For the Flight Test Mission, which is the one used as a basis for discussion, this period of time lasts 127 seconds, using the Saturn C1 booster. In the following discussion, the times indicated, while given precise values for illustrative purposes, ~~are to be~~ regarded as only typical of those which might be determined in a detailed design.

Just prior to the reactor startup, the additional poison inserted into the core for ground protection is removed and jettisoned. The source flux level is now governed by the sub-critical multiplication factor of the scrammed reactor and the strength of the source and is estimated as $10^{-9}\%$ full power with a 10 to 100 curie source. At 40 seconds after launch, the

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1.5.7.2.4 Startup (continued)

control system is activated and the flux demand is set at 0.1% full power by the control unit. The flux loop withdraws 11¹ of the actuators at their maximum withdraw rate in the attempt to satisfy this demand. Complete withdrawal requires 10 seconds, based upon the velocity capability of the actuator currently being developed by the Aircraft Accessory Turbine Department of General Electric for LASL. The remaining actuator is prevented from withdrawing at this time by not providing it with actuator power. The net positive reactivity worth of the 11 drums completely withdrawn against their suitably adjusted mechanical stops is that amount required to establish a one to two second stable reactor period. This net worth was previously verified and trimmed to the required value during the cold critical experiment. The reactor becomes supercritical as the drums withdraw and the stable period is rapidly achieved. The flux level increases on the stable period until 0.1% full power is reached and the flux loop inserts reactivity to level and regulate the power level at 0.1% full power in response to the flux demand. This rise to power requires approximately 32 seconds using a 1.7 second period as an example. During this

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A nominal number. Further investigation may show that 10, 9, or even 8 drums would be desirable for initial withdrawal.

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1.5.7.2.4 Startup (continued)

time there have been no significant temperature changes and no reactivity changes to vary the period. The flux demand is maintained at 0.1% full power for 15 seconds to compensate for the fact that the actual period achieved will vary from the nominally desired period because of tolerances allowed in establishing the drum worth. The holding time insures that the power level is at 0.1% full power for the next control event, even if this level is reached earlier or later than intended. The average core temperature increase at 0.1% full power is estimated to be about 1°F per second. Actuator power is supplied to the remaining twelfth actuator 10 seconds before this holding time is over and as it withdraws toward the position initially held by the first 11, the flux loop causes the insertion of the 11 such that the power level is held at 0.1% full power and the 12 actuators become synchronized in position. At the end of the holding period, the flux demand is increased to 10% full power on a ramp such that this power rise requires 5 seconds. The flux demand is then maintained at 10% full power for 25 seconds, allowing core temperatures to increase at an average rate of 60°F per second. The nuclear stage is separated from the booster at the end of this intermediate holding period.

It is again emphasized that close control of the net positive reactivity worth of the control drums when fully withdrawn is

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1.5.7.2.4 Startup (continued)

required for this proposed startup system to operate properly. If detailed design and test indicate that it is not feasible to trim reactivity to the required tolerances, the contractor would substitute a period controlled startup system of the type designed and developed for the nuclear turbojet power plant. The startup phase is discussed in detail in Section 2.1.1.5.2.1 which includes a description of a startup system which is period controlled. A pre-launch startup system which is period controlled is also described in Section 2.1.1.5.3. If a period controlled startup system were necessary, the rise to power would be made on a constant period with automatic transfer to the flux loop at 10% full power.

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1.5.7.2.5 Power Range Operation

Transition from startup to power range control occurs when reactor power level reaches 10% full power, at which time the control unit holds power level demand at 10% full power. This power level is maintained for the intermediate holding period of predetermined length, allowing core temperatures to increase at an average rate of 60°F/second. The duration of this holding period is such that limiting temperatures in the core, reflector, or structure are not approached. By allowing reactor temperatures to increase in such a manner, sufficient stored thermal energy is insured for vaporization of the initial propellant flow and the attaining of the initial exit gas temperature required for the "bootstrapping" operation of the turbopumps is obtained. In addition, the elevated core temperature lessens the rate of temperature change for a given thrust acceleration to full power.

At the end of the holding period, the program unit calls for 10% propellant flow, and the "bootstrapping" operation begins. Initially, 3% flow is provided utilizing tank pressure only, but 10% flow is rapidly obtained when hot exhaust gas becomes available. Programming up to this point has been such that the initial introduction of propellant occurs simultaneously with stage separation, or shortly thereafter. Upon attainment of 10% propellant flow, the program unit calls for an increase in power level to 120% full power, effected according to a prescribed schedule, simultaneously increasing propellant flow so as to maintain approximately the same power to flow ratio, until 100% propellant flow is obtained. The rate at which this acceleration to full power is effected is limited only by the rate of core temperature rise. The

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1.5.7.2.5 Power Range Operation (cont.)

program unit then maintains 120% full power for a period of time sufficient to completely compensate for reactor thermal lag effects, after which the power level demand is reduced, in a stepwise fashion, to 100%. Operation for the remainder of the full thrust period is accomplished with the program unit scheduling a power level demand signal corresponding to 100% full power. In this manner, attainment of full design point thrust is obtained without the inherent reactor thermal lag effect.

For the Test Flight mission, the operating time at full power is 100 seconds. At the end of this period, the power plant is shut down and phase III is terminated.

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1.5.7.2.6 Shutdown

Phase IV covers the period of time between the termination of the full power run and the initiation of the restart cycle.

Two alternate methods of accomplishing the shutdown have been studied and the choice does not significantly affect the control system. One shutdown scheme consists of scrambling the reactor from the full power level and reducing propellant flow accordingly to provide after cooling. The alternate scheme is to reduce power from 100% to 20% at essentially constant discharge temperature within the last 20 seconds of the full power run and then scram. The sloped power shutdown, as it is called, requires a slightly longer power run to achieve the same integrated thrust obtained from operating at full power until scram, but slightly reduces the aftercooling propellant flow requirements. For simplicity in the following discussion, it is assumed that scram is initiated at full power.

Scram is effected by reducing the flux demand to 0.1% full power. This is an approximate value; detailed transient analysis may show that it needs to be slightly higher.

The three decade reduction in power will require considerable time and the flux loop, in attempting to satisfy the step demand, will cause the control actuators to insert reactivity at the maximum rate. The time required for the

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1.5.7.2.6 Shutdown (continued)

neutron flux level to decay to 0.1% full power is strongly dependent upon the shutdown reactivity available at scram. One percent full power will be reached in the neighborhood of one minute after scram and one to two minutes additional time will be required to reach 0.1% full power. As the 0.1% full power point is reached, the flux loop will withdraw reactivity to make the reactor critical and regulate the power at this level. During the reduction of power, the propellant flow is reduced on a schedule such that limiting materials temperatures are not exceeded but the discharge temperature is as high as possible to provide maximum use of the propellant. When low flows are reached, the flow is held at a fixed value for a short period to undercool the reactor and then cut-off. Temperature immediately begins to rise because of the afterheat and as the limiting temperature is neared, the increasing shell temperature sensor signal causes the trip circuit to operate and indicate to the control unit that cooling is again required. A timed pulse of aftercooling propellant is then provided to reduce the temperature. The reactivity induced by the hydrogen used in pulsing will not cause a significant increase in reactivity because the flux loop is either actively regulating the flux level at 0.1% full power or the reactor is essentially scrammed if the flux

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1.5.7.2.6 Shutdown (continued)

level has not decayed to 0.1% full power. The shell temperature has been indicated as triggering the aftercooling pulses; further analysis may indicate that some other structural component first reaches its limiting temperature. The temperature of that member would be used to trigger aftercooling.

The power level demand is held at 0.1% full power for the period of time between shutdown and restart as a marker point from which to initiate the restart schedule. This is a nominal value for the flight test mission. It cannot be much lower, for in 300 seconds the neutron flux cannot fall much lower. For flight test missions with longer shutdown periods, the flux level would be allowed to decay to a lower residual level; however, since the neutron flux reaches a limiting decay period of approximately 80 seconds (184 seconds per decade), an additional 3 minutes of shutdown time is necessary for each decade that the holding level is reduced, and photoneutron production would limit it even more so.

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1.5.7.2.7 Restart

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This phase includes the second rise to power and a second period of full power operation.

The command from the guidance control to the power plant control unit to initiate restart must precede the time 100% thrust is required by a fixed number of seconds required for the restart operation.

The control unit initiates restart by raising the flux demand from 0.1% full power to 10% full power on a ramp schedule requiring several seconds for completion. The power level is held at 10% full power for a few seconds - less than for the first startup since the reactor is already at an elevated temperature - and then propellant flow is initiated. The remainder of the acceleration to full power and the full power run would be the same as for the first run. At the termination of the full power run, the flux demand is reduced to zero, the reactor is scrammed and the actuator power supply is cut off so that the control actuators must remain in a scram condition. The propellant flow during this shutdown is pulsed in a manner similar to the initial shutdown. Pulsing would continue at continuously slower rates for the remainder of the test flight.

For missions other than the Flight Test mission, the time between the first shutdown and restart may be much longer than the 300 seconds considered in the above discussions. For these missions, the flux level would be allowed to decay to the post-operational level and a restart must be accomplished from this level. New schedules must be provided to cover differences from the initial startup such as core temperature and initial level. Indeed, this mission would have to be fully examined, for a considerably colder reactor at restart would operate on a much faster period than the original start. (PLUS MAT'L FROM MARTA - NOT YET REC'D)

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1.5.7.3 Controls Components

1.5.7.3.1 Actuator Design. A gas powered actuation system appears to be the most logical method for operating the control drums on the nuclear rocket reactor. Selection of the actuator will be based primarily on reliability, quiescent flow requirements, simplicity, and ability to meet the actuator specifications. A vane type actuator comparable to the design submitted to LASL by the Aircraft Accessory Turbine Department of the General Electric Company appears quite satisfactory for this application. The design utilizes a two-stage servo valve which acts as a pressure regulator to balance gas pressure on one side of the vane against the power or scram spring. Limit stops, buffer, and conventional feedback units are also built into the design.

Information is lacking on the actuator proposed by Bendix but the unit is understood to be a gas operated motor which drives through a gear train. Final selection of the actuator would be based on overall performance capabilities.

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1.5.7.3.2 SENSORS, NUCLEAR. "Flight System" Neutron Flux Detection

Since the proposed control system utilizes pre-programmed reactivity to bring the reactor power from source level to 0.1% full power, neutron flux monitoring is necessary from approximately 0.05% full power to 2 full power. This is readily accomplished with D.C. ionization chambers located on the outside pressure shell. Figure 1-6 shows an adequate and existing ionization chamber design. Compensation for gamma radiation can be obtained by using two chambers; one sensitive, the other not sensitive to neutrons. The ionization chamber signal amplitude can be chosen, by suitable detector design, to obtain a high degree of reliability with a minimum weight penalty.

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Fig. 1 The construction of an ionization chamber is shown.

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1.5.7.3.3 Electrical and Electronic Components. The following is a description of the proposed components for the reactor control system shown in Figure ~~1.5.7.3.3.1~~ 1-5 (Page 26)

1.5.7.3.3.1 Flux Error Amplifier and Stabilization. The flux error amplifier could be implemented with a magnetic flux error amplifier being used in the present GE-ANP reactor, using a multistage arrangement of second harmonic and full-wave amplifiers with feedback. This amplifier will meet the requirement of amplifying the input signal with a three decade operating range where linear operation in the lowest decade is not required.

1.5.7.3.3.2 Temperature Comparator. The temperature comparator is required to compare a temperature demand or limit with a temperature feedback voltage, provide sufficient amplification of the differential signal with good linearity and very low drift. A magnetic temperature error amplifier system meets these requirements. This amplifier consists of a second harmonic pre-amplifier followed by a full-wave amplifier with negative electrical feedback around the combination. Limiting of the output is accomplished by resistive means.

1.5.7.3.3.3 Drum Position Error Amplifiers. Moderate gain and band pass with sufficient output to drive the servo valves on the drum actuators are required for this function. It must also accept an AC position feedback signal. These requirements are met by position error amplifiers with single stage full-wave amplification and a demodulator for the AC feedback signal.

1.5.7.3.3.4 Amplifier and Stabilization for Propellant Turbine-Pump Controller. The propellant flow meter output acts as a feedback signal through an amplifier to control pump output to the demanded flow. The differential between demanded flow and measured flow is amplifier to a level necessary to operate a servo

1.5.7.3.4.1 diode-saturable reactor oscillator which, when a sufficient signal is introduced, drops in frequency to a low level. This level is discriminated and the resulting DC signal applied to the gate of a silicon controlled rectifier. The controlled rectifier is normally conducting, passing half-wave rectified AC current to the scram valve to hold pressure on. When tripped, the controlled rectifier no longer conducts, dropping out the scram valve and scrambling the reactor.

1.5.7.3.4.2 Single Actuator Hold Control. On the ground, one control actuator is latched in the inserted position to prevent hydrogen leak start up of the reactor. At a command from the receiver, a trip, as described in 1.5.7.3.5.1, will unlatch this actuator and allow it to be operated normally under servo control.

1.5.7.3.4.3 Flow Control Ramp Generator. This generator will be a magnetic integrator circuit. A full-wave magnetic amplifier operating as a computer amplifier with feedback through a capacitor provides integration. The integrator will have its input controlled by a solid state bistable trip. The integrator will give rise to a ramp output with appropriate holding at certain levels controlled by the bistable units, then applied to the flow control system as a demand.

1.5.7.3.4.4 Flux Control Ramp. This circuit will be the same as that described in Section 1.5.7.3.5.3 except for ramp slope and will be initiated from a separate demand signal. It provides a voltage which is the demand for the flux loop.

1.5.7.3.4.5 After Cooling. The after cooling will require pulses of hydrogen to cool the reactor and protect certain elements of the rocket engine. The after cooling is implemented by monitoring the temperature error signal from the temperature comparator. The temperature comparator will compare the

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1.5.7.3.4.5 temperature of the element to be protected with a preset limit.

When the error reaches a set value, it will trip a solid state bistable trip which will initiate hydrogen flow. The hydrogen flow will be stopped with an RC delay initiated, in turn, by the trip. When the RC network reaches a preset value, a second trip will close off the flow and reset the first trip in preparation for further cooling bursts.

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1.5.7.3.5 Propellant Supply System. Valves in the propellant supply system will be pneumatically actuated, the stem of each valve being rotated by means of a crank driven by the piston rod of a double-acting cylinder. The cylinder, in turn, will be controlled by suitable electrically-operated valves. All seals in the actuating cylinders would be made of silver-impregnated graphite to avoid lubrication problems.

The propellant supply valves fall into two categories with respect to mode of operation. The turbine flow valve required proportional operation; all other valves demand on-off actuation with no intermediate positioning.

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1.6 ENGINE GROWTH POTENTIAL

The growth potential of the nuclear rocket engine is primarily dependent upon the growth potential of the reactor and the cooling capability of the nozzle. As indicated by the work of the ^{Los Alamos Scientific Laboratories} ~~ASA~~ on the Phoebus reactor there is substantial growth potential in the reactor with respect to power density. Materials development at ^{the Los Alamos Scientific Laboratories} ~~ASA~~ offer promise of raising the maximum temperature limits of the fuel elements and thereby improving the specific impulse. The proposer believes that improvements in both areas can be realistically expected and that the growth potential of the nuclear rocket reactor is substantial.

The heat flux at the throat of the nozzle may be regarded as another critical problem for growth. Film cooling and utilization of materials with high resistance to heat flow which are under development such as pyrolytic graphite show great promise for application to the nuclear rocket nozzle. Development work performed at the General Electric Company in both areas supports the opinion of the proposer that nozzle cooling will not limit the growth potential of the nuclear heat transfer rocket.

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1.7 SAFETY AND HAZARDS

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Safety becomes primarily a matter of proper controls and operating procedures if the design of the equipment involved is fundamentally sound. Accordingly special emphasis was attached to recommend controls and to describe operating procedures which will provide maximum safety under normal conditions on the ground and in flight. Abnormal conditions which could result in hazards to people or facilities have been anticipated as much as possible at this time and methods and procedures have been discussed which should result in a very high degree of safety. Detailed discussions on ground and flight safety are presented in Sections 2.2.1.5 and 2.4.1 and on controls in Sections 1.5.7 and 2.1.1.5.

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