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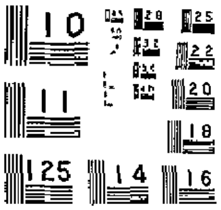

MICROCOPY RESOLUTION TEST CHART

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UNCLASSIFIED NERVA RESEARCH
AND DEVELOPMENT REPORT

NERVA DEVELOPMENT STATUS

by

W H Esselman
Deputy Manager, NERVA Project
Westinghouse Astronuclear Laboratory

Presented to the American Nuclear Society and Professional Engineers Society
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It is my intent today to review some aspects of the NERVA nuclear rocket development program and, by this means, point out the readiness of the reactor technology for flight engine development   NERVA is a part of the ROVER nuclear rocket engine program which was initiated at the Los Alamos Scientific Laboratory in 1955

Significant accomplishments have been made in nuclear rocket development during the last few years   The initial progress achieved by Los Alamos on the conceptual reactor design and fuel element development was rapid and, by 1960, the KIWI series of reactor tests had demonstrated the significant performance and potential of the nuclear rocket engine   The NERVA (Nuclear Engine for Rocket Vehicle Applications) Program was initiated in 1961   This effort, under the direction of the Space Nuclear Propulsion Office of NASA and the AEC, is being performed by the Aerojet-General Corporation as the prime contractor and the Westinghouse Electric Corporation as the principal subcontractor for the nuclear subsystem development   The NERVA Program is intended to extend the heat transfer reactor principles to practical application in the development of a system that will withstand the loads, environment, and operating requirements of flight   The KIWI and NERVA reactor programs have been closely coordinated to provide a continuing, logical development, and the progress clearly highlights the noteworthy advance that has been achieved in our basic technological understanding of the operating potentials and characteristics of the nuclear rocket engine

In the way of background, I will briefly review the basic operation of a nuclear rocket system   Figure 1 shows a simplified sketch of a nuclear rocket engine attached to a flight tank   We have recently established a new size for the NERVA system   The engine

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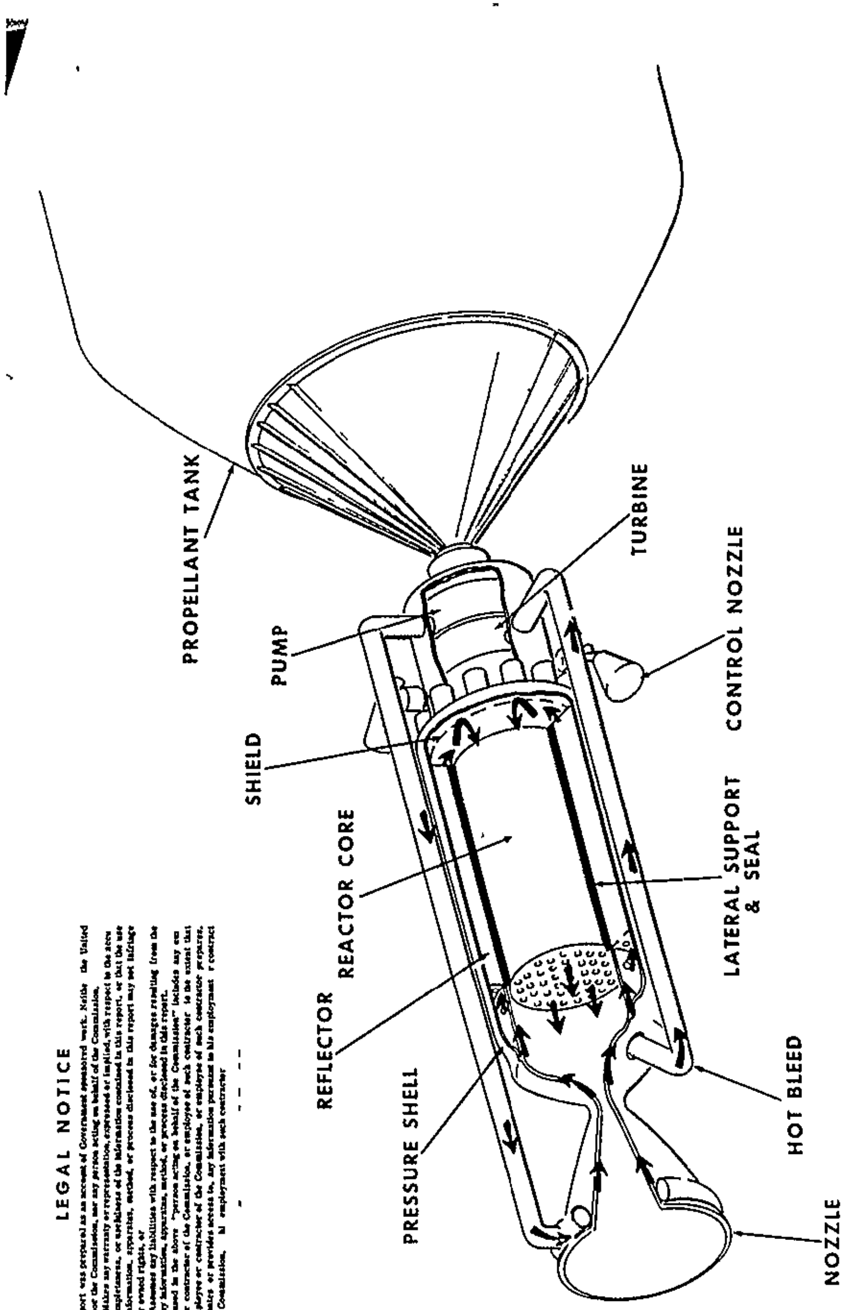


NUCLEAR ROCKET ENGINE

FIGURE 1

delivers approximately 75,000 lb of thrust at a specific impulse of 825 lb_f-sec/lb_m The reactor produces 1575 Mw of power and the core consists of clusters of graphite fuel elements surrounded by a beryllium reflector The pump, which is driven by a turbine, increases the pressure of the liquid hydrogen to 1000 psia and provides approximately 91 lb/sec through the pump discharge line to the nozzle inlet plenum The liquid hydrogen then flows through the regeneratively cooled nozzle tubes into the reflector of the reactor After passing through the reflector and removing the radiation-deposited energy, the hydrogen enters the shield region at the forward end of the dome The purpose of the shield is to decrease the radiation levels on the engine parts and to reduce the heating of the hydrogen propellant stored in the tank The hydrogen passes through the reactor-fueled section and is heated to above 4000°R when it enters the thrust chamber formed by the convergent section of the nozzle The hot hydrogen from the thrust chamber is expanded and accelerated by the nozzle, thereby producing the required thrust A small portion of the core exit hot gas is extracted at the hot bleed port located in the nozzle to supply the gas needed to drive the turbine The temperature of this gas is reduced to a suitable level by mixing with cold diluent extracted from the shield end of the pressure vessel

The nuclear rocket engine derives its primary advantage over chemical rocket engines from its use of the hydrogen as a propellant which results in very high specific impulse Specific impulse (I_{sp}), which is the ratio of thrust produced to propellant flow rate, is a prime measure of a rocket engine's performance since it relates directly to the amount of propellant which must be carried to perform a mission Since specific impulse is a function of the inverse of the square root of the molecular weight of the propellant, hydrogen with a molecular weight of two is an ideal propellant All chemical rocket engines combine fuel and oxidize with resulting higher molecular weights Thus, the nuclear rocket engine develops a specific impulse approximately double that of the best chemical rocket engine

At this point it is appropriate to show a short movie on how the reactor tests are performed

With this background we can proceed with an assessment of the status of the development program For the purpose of comparison, a period of early 1964 has been chosen as a base point At that time, three basic feasibility questions existed as shown on slide 1-a The doubts raised by these problems were the key ones addressed during these most recent years of the program At this point, it is my purpose to present the technical accomplishments which have been achieved to resolve these doubts and to highlight some plans for proceeding on future tests

The first question, that of suitable structural integrity and proven performance, is amply covered by Figure 2, which lists the key tests that have been conducted since 1964, the cumulative test time at nominal full power is shown as the ordinate. The KIWI and Phoebus reactor tests were conducted by Los Alamos, while the NRX tests are part of the NERVA program By early 1964, the structural integrity of the reactor had not been demonstrated The core vibration questions introduced by the KIWI B4A test were not completely resolved Cold flow tests on KIWI and NRX-A1 were designed and performed to demonstrate that the problem was understood and corrected At that time, no power test had been conducted on the reactor design principle selected for the NERVA development

However, by late 1964, the power tests conducted on KIWI B4D, NRX-A2 and KIWI B4E showed that the structural problem with the reactor had been corrected and operation was achievable at high chamber temperatures for significant periods of time It then became necessary to demonstrate that the system would operate for useful mission times

Early estimates of required engine operating times for useful missions varied up to 20 min Later mission studies indicate times up to 40 min for the more ambitious missions, however, the nominal operating time for a favorable Mars mission is in the 20 - 30 min range and the operating time for a very useful lunar mission is 10 min for the large size (200-250K thrust) NERVA engine and 20 min for a 55,000 lb thrust engine

These operating times should be compared with the endurance test times actually achieved in the NRX-A3, NRX/EST, NRX-A5 and NRX-A6 tests. The NRX-A3 reactor

ROVER

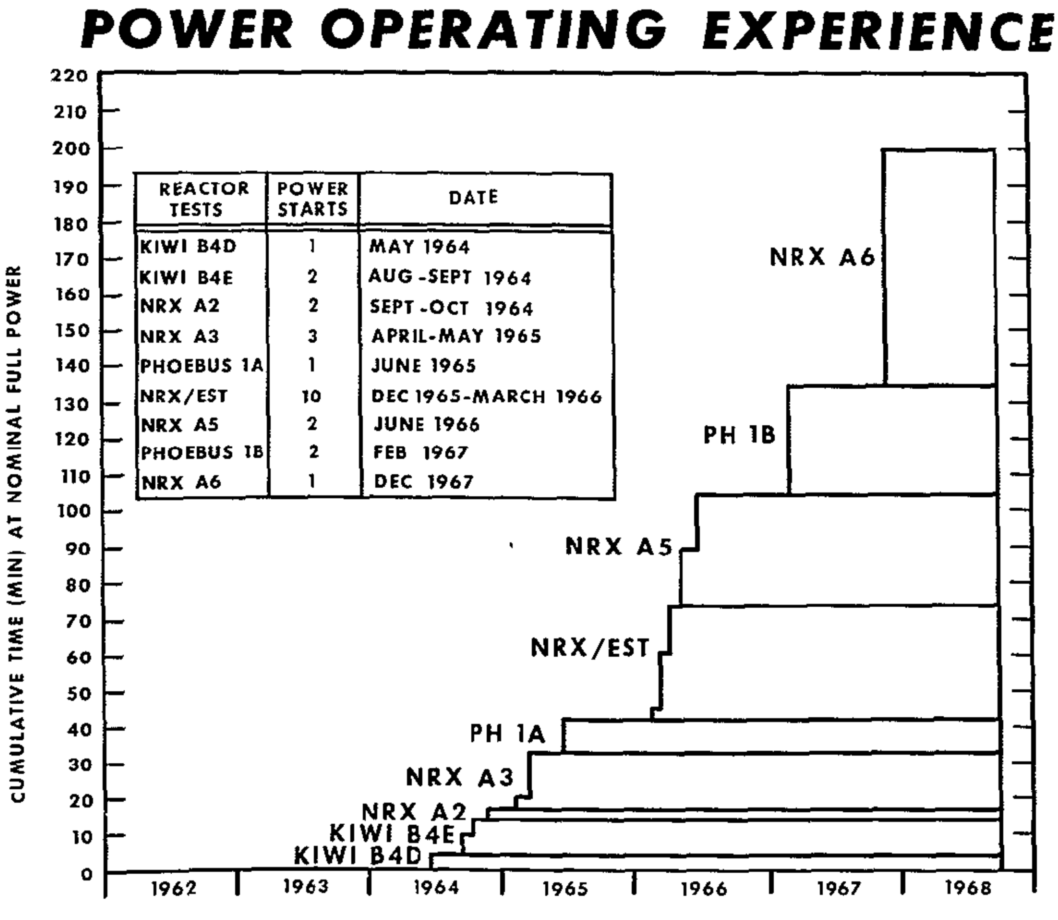
FEASIBILITY QUESTIONS OF 1964

1 STRUCTURAL INTEGRITY

2 RESTART CAPABILITY

3 PREDICTABILITY, CONTROLLABILITY, RELIABILITY

Figure 1-a



REACTOR TESTS	POWER STARTS	DATE
KIWI B4D	1	MAY 1964
KIWI B4E	2	AUG-SEPT 1964
NRX A2	2	SEPT-OCT 1964
NRX A3	3	APRIL-MAY 1965
PHOEBUS 1A	1	JUNE 1965
NRX/EST	10	DEC 1965-MARCH 1966
NRX A5	2	JUNE 1966
PHOEBUS 1B	2	FEB 1967
NRX A6	1	DEC 1967

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FIGURE 2

was operated in its first run for 3 5 min and was inadvertently shut down from full power by a scram caused by a facility circuitry malfunction It was restarted and operated for a total operating time of 16 3 min at or near full power and temperature

At this point in the program, it was determined that an early engine system test was feasible Therefore, the planned NRX-A4 reactor test was changed to the NRX/EST Engine System Test and the planned reactor objectives were combined with a series of key engine system objectives This breadboard engine system was started ten times to power and the total operating time at power conditions was 116 min The time at full power was approximately 28 min The NRX-A5 reactor was operated for two periods for a total of 30 min at full power operation

The Phoebus 1A test by Los Alamos Scientific Laboratory was conducted on 25 June 1965 for a period of 10.5 min This test was the first of the Phoebus series of tests directed toward a higher thrust and performance reactor Phoebus 1B test was conducted in February, 1967, and achieved 30 min of operating at a nominal 1500 Mw

The most recent reactor test was the NRX-A6 which was successfully completed on December 15, 1967 by operating at rated conditions for 60 min in one run The test was ended as planned when the endurance objective was achieved, not because of any reactor difficulties In fact, operation could have continued for a significant time but it had been planned to shut down at the end of the desired 60 min to preserve post-operative examination data In one run the NRX-A6 operated for twice the endurance of any previous reactor Total operating time at power conditions was over 70 min, of which 60 min were within design tolerances of rated temperature and power of 4090°R and 1120 Mw

Adding this operating experience to that which has been previously attained, we now have about 195 min of cumulative time at full power This experience is graphically shown in the attached figure This test again points out the high performance capabilities of the NERVA system, and the achievement of the longer run time without taxing the design indicates that further performance improvements can be anticipated in nuclear rocket systems

RESTART CAPABILITY

In addition to the endurance tests which were conducted, the table in Figure 2 shows the starts to power conditions that have been accomplished The first restart was made on KIWI B4E and experience has been gained on 25 starts - 1 on KIWI B4D, 2 on KIWI B4E, 2 on NRX-A2, 3 on NRX-A3, 1 on Phoebus 1A, 10 on NRX/EST, 2 on NRX-A5, 2 on Phoebus 1B and 2 on NRX-A6

A number of these restarts were made under conditions worthy of particular note The shutdown on NRX-A3 was very severe, because flow to the reactor was inadvertently lost while the reactor was at full power The reactor was scrammed and the test article was subjected to a very large temperature transient A thorough analysis indicated that the reactor integrity, while somewhat impaired, was capable of a restart and that no impairment to the nozzle or other system components was detected Restart was demonstrated on 20 May 1965

Another restart of interest occurred on NRX/EST During previous restarts, the engine component material temperatures were ambient and the hydrogen was heated by the stored energy in these components prior to entering the core The question arose, could the engine system be started from conditions similar to those which might be expected immediately after a shutdown in space? To investigate this point, the outer reflector was cooled to 60°R prior to the restart No severe system transient occurred and the system started up satisfactorily by using nuclear, rather than stored energy, to heat the hydrogen

REACTOR CONTROL

The third significant unknown which existed in 1964 was an assessment of the ability of the system to reliably achieve the necessary control requirements for rocket propulsion A rocket engine requires fast startups and achievement of full power in a relatively few seconds This type of transient performance is contrary to the experience in normal power reactor technology It was necessary to mate the reactor control and operating technology with the requirements of rocket propulsion. The achieving of a suitable control system involved the assessment of the reactor kinetics during rapid temperature increases, plus the significant reactivity changes caused by the propellant density variations At full power operation, the hydrogen is liquid at the inlet to the nozzle and is gaseous at temperatures of about 100°R at the inlet to the reflector During startup, however, liquid hydrogen enters the reflector and two-phase flow exists until the pressure rises above 187 psia, at these pressures, a supercritical fluid exists In addition, for space application, the initial temperatures of the reactor vary considerably For example, the reflector temperature could be as low as 200°R, at which point minor temperature variations can influence the hydrogen density strongly and change the flow conditions It was these complex problems which were of concern during the early parts of the development Today, we have much experience in these areas and are able to cope confidently with these problems

Reliable computation techniques have been developed which predict the responses under these various transient conditions Both analytical and digital models have been developed (and are now available) which precisely represent the nuclear, thermal and flow parameters throughout the NERVA system These analytical simulations and digital codes are used extensively in the design of the various steady-state and transient aspects of the system One of the principal tools used in system design and control analysis is a NERVA systems model, named the Common Analog Model, which can be used on either an analog or digital computer This model was developed jointly with the Aerojet-General Corporation Westinghouse provided the nuclear subsystem portion of the model, while Aerojet developed the engine system and nozzle aspects. This common model is the main tool for system development and is reasonably complex, involving the solution of some 145 to 190 simultaneous equations, and the use of 500 to 650 amplifier analog computations The adequacy of this model was improved with each of the various tests It is the normal practice to precisely predict the transient magnitudes of the many variables during each of the test operations Subsequent to each test series, the data is carefully analyzed and computer model deficiencies are corrected so that a more reliable prediction is assured This philosophy of predicting the test variables, determining the cause of differences, and then improving the analytical models has proven extremely successful in the NERVA program

To illustrate the techniques used to improve our understanding of the system dynamics, a number of aspects of the control system will be described and, where appropriate, the system transient performance will be compared with the analytical results Figure 3 shows a typical operating cycle for the NRX/EST test series. The parameters shown are the thrust chamber temperature and pressure The abscissa shows the control room time in seconds A startup from source level to approximately 0 1% power is made with essentially no hydrogen flow through the system From 0 1% to full power, the reactor temperature, reactor power and flow are increased simultaneously It will be noted that the time of startup from 0 1% power to full power for this particular run is approximately 140 sec The steady-state portion continued for some 800 sec, when the shutdown sequence was initiated The steady-state operating conditions were maintained relatively constant throughout the run

We will now examine each of the phases of the startup, first focusing attention on the source level to the 0 1% power level transient This phase is accomplished by an automatic system which we call nuclear autostart As shown in Figure 4, the control drums are programmed rapidly from their subcritical shutdown condition to a preset drum position near the critical value, and then rotated on the slow outward ramp until a predetermined power level is reached

Figure 5 shows a typical transient from 0 1% power to full power At zero time the turbopump flow and temperature demand is initiated The dashed curve indicates the rise in control temperature demand, while the solid curve gives the actual values of measured control temperature For this particular startup it can be seen that the demand setpoint for the power limiter circuit was set below design power This resulted in this circuit limiting further increase in power or temperature once the setpoint was reached Similar comparisons were made of all the important core parameters It will be noted that this rise from 1 Mw of power to 1100 Mw would require approximately 55 sec

Prior to achieving startups of this type, there were many items of concern that had to be eliminated Initial uncertainties included the magnitudes of the temperature coefficient of reactivity and the reactivity effects of the gaseous and liquid hydrogen Analytical

EP-IVA ENDURANCE RUN

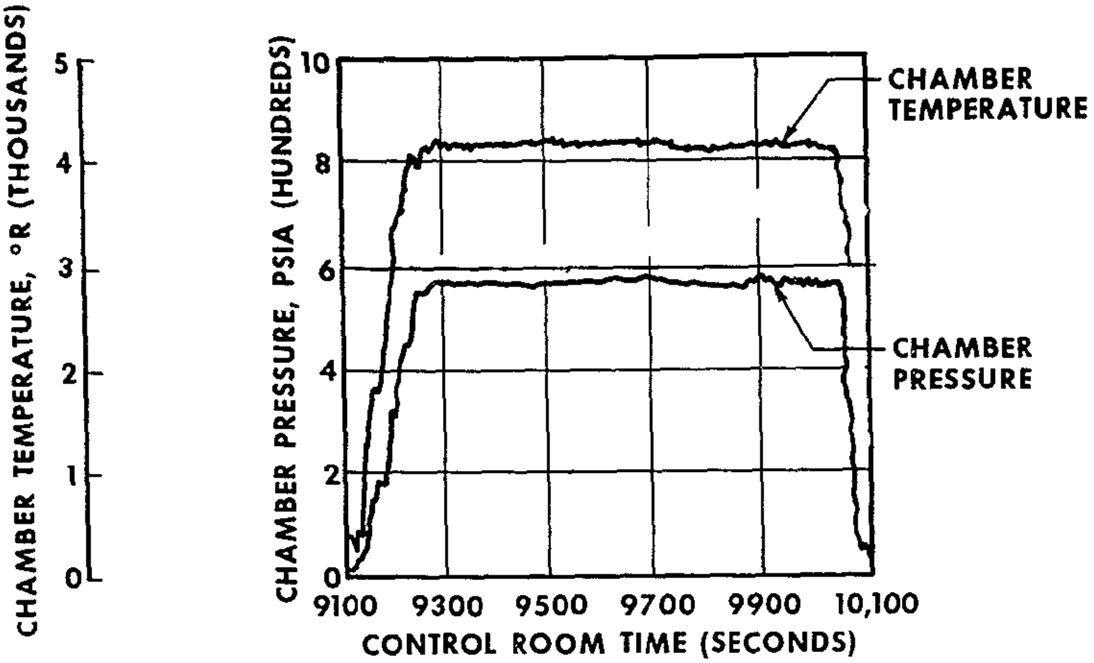
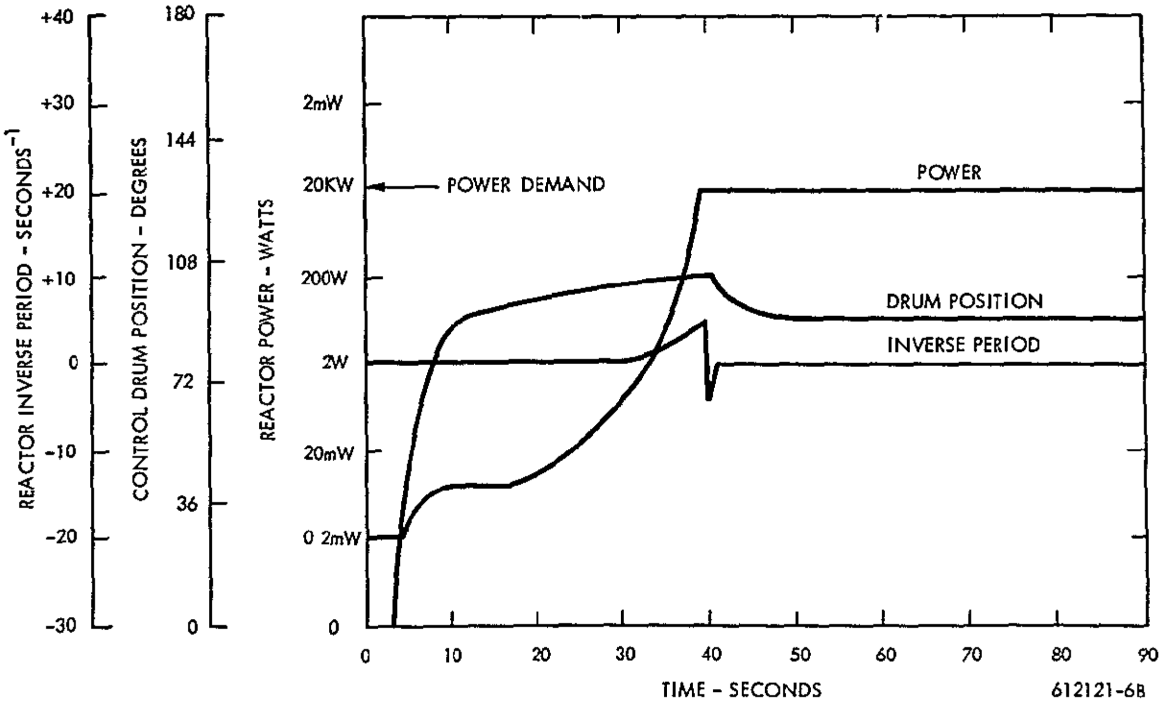
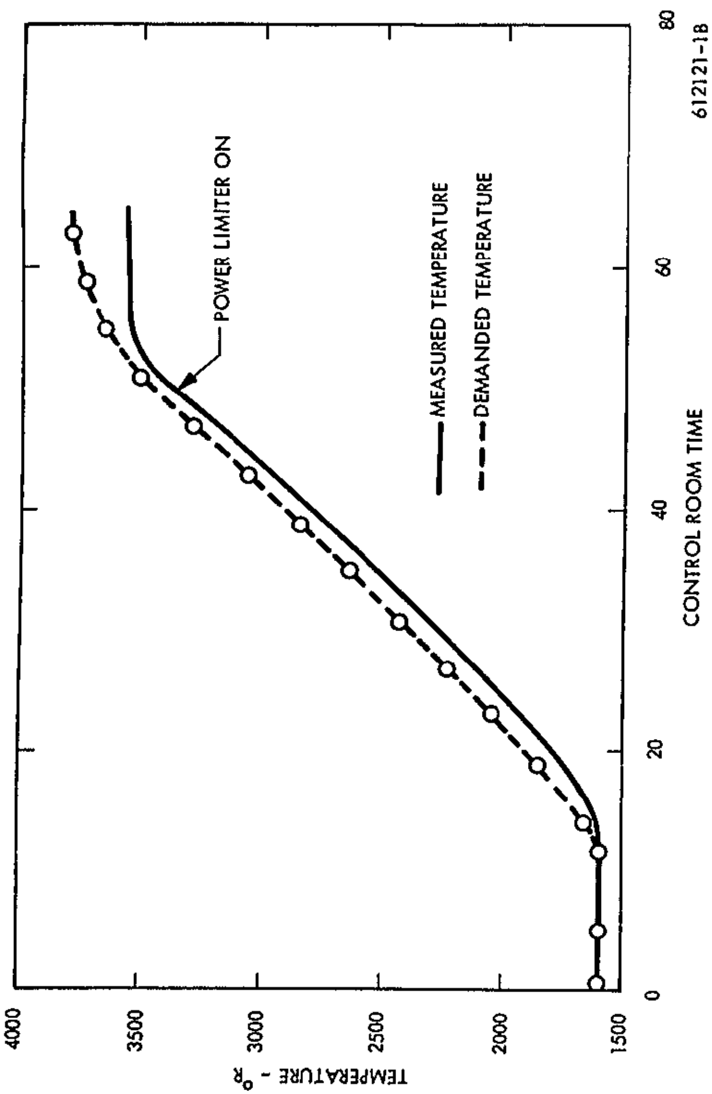


FIGURE 3



REACTOR AUTOMATIC STARTUP TO 20 KW WITH MAXIMUM
VALUE OF EXPONENTIAL SET EQUAL TO DELAYED
CRITICAL 0 3 DEG/SEC RAMP RATE

FIGURE 4



CONTROL TEMPERATURE PROFILE

FIGURE 5

studies indicated that the temperature coefficient of reactivity was negative, that is, a temperature increase results in a negative reactivity insertion Similarly, the hydrogen effect on the reactivity is proportional to its density, that is, a decrease in density reduces the moderating effect of the hydrogen and the reactor power decreases Concern existed with the possibility that the introduction of liquid or high density hydrogen into the core could cause instabilities or would introduce control complexities While computer studies indicated the inherent stability of the reactor system, it was necessary to demonstrate this feature by a series of experiments The first startup of a nuclear reactor to design conditions with liquid hydrogen as a coolant was successfully achieved on KIWI B4D To explore the inherent stable and self-controllable properties of the reactor system, a series of experiments were conducted on NRX-A2 which included operation over a range of 20 to 60 Mw with the control drums fixed This initial attempt at a fixed drum operation is shown in Figure 6 The control drum position was held fixed and the flow was increased from 10 lb/sec to 13 lb/sec It can be seen that the reactor power increased accordingly from 3 5 to 5% When the flow was reduced, the reactor power decreased as shown With this test as background, more ambitious tests were conducted On NRX-A3, a fixed drum startup was made from 1 Mw to 35 Mw This startup, shown in Figure 7, was initiated by moving the control drums a predetermined amount and then maintaining them in a fixed position The liquid hydrogen flow to the system was increased at a linear rate The hydrogen density effect as it passed through the core caused the power to increase A steady-state condition was attained where the hydrogen density and temperature coefficient of reactivity effect balanced the reactivity inserted by the drums Of particular significance was the stability and ease of control of the system during these tests

The encouraging results of these experiments stimulated more ambitious tests on NRX/EST and NRX-A5 NRX/EST was the first time full chamber pressure control was used The chamber pressure demand was slaved to measured chamber temperature and controlled the flow of drive gas to the turbine by properly positioning the turbine power control valve During the NRX/EST tests, the entire operating range of the engine was mapped and transfer functions were made at numerous operating points to develop an understanding of system dynamics One of the NRX/EST experiments was a fixed drum startup

NRX-A2 EP V LOW POWER MAPPING POWER, FLOW VS TIME FOR FIXED DRUM POSTION

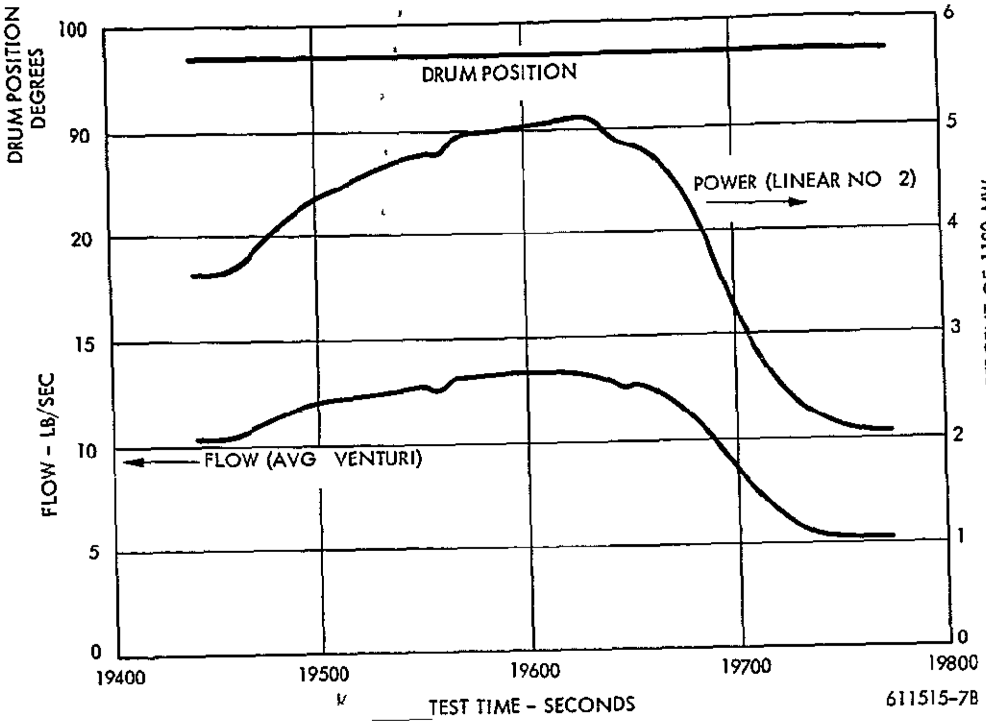


FIGURE 6

FIXED CONTROL DRUM STARTUPS

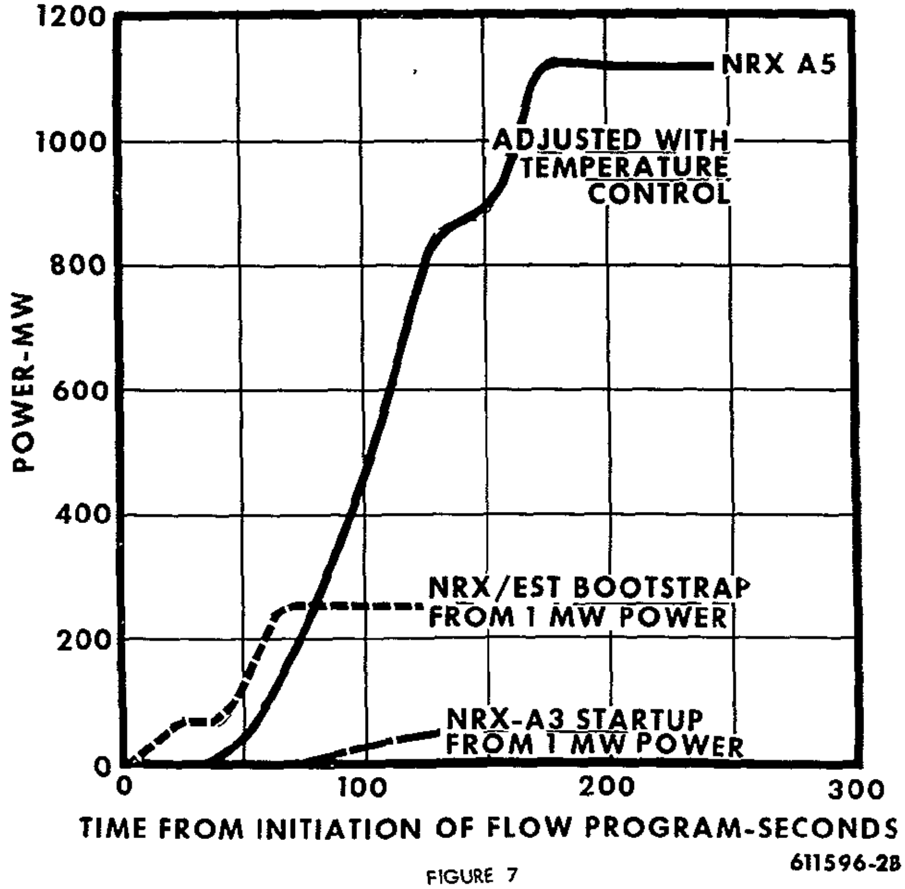


FIGURE 7

to a power level of 250 Mw, as indicated by the second curve in Figure 7 During the NRX-A5 test series, a reactor power level of 870 Mw was reached with the drums fixed, and the power level was then trimmed to full power

SUMMARY

In this paper, I posed three questions of feasibility that existed in the period of early 1964 The question of structural integrity and reactor endurance capability for useful mission times has been answered affirmatively by over three hours of full-power, high temperature operating experience The question of restartability has been answered affirmatively by the many restarts accomplished during the test series At this time, 24 starts to power conditions have been performed successfully The third question of predictability and controllability of the system has been answered affirmatively by the many systems and control tests that have been performed Indications are that the nuclear rocket engine system will be a highly reliable, predictable, and stable means of rocket propulsion Each of the questions has been very adequately answered

While we were achieving our technical objectives we, at the same time, have gained much confidence in the operation of the system In fact, we continue to be impressed by the natural stability and excellent dynamic behavior of this system which,will lead us ultimately to basically simple and reliable control concepts--many of which we have in development at this time We also believe the nuclear system IN SOME RESPECTS to be a simple one compared to a chemical system One handles only one fluid for the propellant, thus simplifying the plumbing We have also found that such early worries as reactivity accidents from malfunctions and instabilities have not materialized and that we can operate a nuclear system with utmost confidence in its safety

The future ROVER program includes engine system testing of the XE-1 and XE-2 engine systems in the ETS-1 test stand, under downfiring conditions, and further tests of NRX reactor endurance The Los Alamos Scientific Laboratory, in their Phoebus program, will be exploring operation of an advanced 5000-Mw system Mission studies have indicated that a single size engine of 200,000 lb thrust would be close to optimum for ~~planetary~~ manned

STATUS OF FEASIBILITY QUESTIONS

1968

	QUESTION	DEMONSTRATED BY
1	STRUCTURAL INTEGRITY	200 MIN OF POWER OPERATION
2	RESTART CAPABILITY	25 STARTS TO POWER
3	PREDICTABILITY, CONTROLLABILITY, RELIABILITY	9 SUCCESSFUL TEST SERIES DEMONSTRATION OF EASE OF CONTROL AND PREDICTABILITY

FIGURE 7-a

missions being considered for the 1980's In the meantime, the NERVA program is pressing forward with the development and testing of reactors and engines of the 75,000 lb thrust system which I have described and which has application to many of the earlier missions in our space program

It is appropriate at this time to also point out the future development potential for nuclear power systems All of the performance demonstrations which I have described to you in this paper were at specific impulses when corrected for vacuum conditions of about 800 sec The NRX-A6 test was terminated as a planned experiment to examine the reactor condition after an extended operating period The condition of the core has shown that either significantly longer time or higher performance would have been possible We are at a very early stage in our knowledge of the potential of nuclear propulsion systems and we must anticipate vast improvements We should expect future increases in temperature of operation, increased thrust, and increased power per unit volume of our present reactors Any of these achievements which will come with normal development progress will improve even further the present payload advantages of the nuclear system over conventional systems We also foresee the possibility of future improvements in concept which can result in reductions in size and weight As we proceed in this program we find that each technical advance opens new possibilities for improvement so that we feel that the ultimate performance potential of NERVA cannot be fully envisioned at this time

In closing, I would like to say a word about the ultimate future of NERVA As you have heard, we believe we have the most difficult questions of technical feasibility well in hand and can look forward confidently to the successful attainment of our technical goals We have mentioned that NERVA has application to lunar and orbital type missions in that it can perform many of these with significantly improved performance over the present chemical systems, and NERVA will more than pay for itself in ~~the~~ these areas of application alone But the ultimate application of NERVA is to the deeper planetary missions where its payload capabilities are many times that achievable from chemical systems For long-range space missions there is no doubt that the nuclear rocket has an inherent superiority over any chemical rocket For deep space missions nuclear powered vehicles appear to be the only practical

approach in the forseeable future The potential is there, in NERVA, to meet these goals--indeed the technology is in hand I am sure that you share with me an interest in the future of nuclear rocket propulsion and the possibility of these future advanced missions

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