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# NERVA DEVELOPMENT STATUS

by

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## INTRODUCTION

During the past few years significant accomplishments have been made in nuclear rocket development. It is the purpose of this paper to review this progress and to highlight the present status of the NERVA engine development. NERVA is part of the ROVER nuclear rocket engine program which was initiated at the Los Alamos Scientific Laboratory in 1955. Figure 1 traces the key accomplishments of this development program from the beginning through the demonstration of feasibility, to the present phase of advancing the technology and extending performance.

The initial progress achieved by Los Alamos on the conceptual reactor design and fuel element development was rapid and, by 1959, the KIWI series of reactor tests demonstrated the significant performance and potential of nuclear rocket engines and stimulated interest in the development of a flight-type 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 KIWI development program demonstrated feasibility and proof-of-principle of the nuclear rocket reactor. The NERVA Program is intended to extend these principles to practical application in the development of a system that would 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 chronology of 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.

Figure 2 shows a schematic of the technology engine which is designed as a ground test system that delivers approximately 55,000 pounds of thrust. Liquid hydrogen ($LH_2$) is delivered to the turbopump by dewar pressure. The turbopump increases the $LH_2$ pressure to 940 psia and provides approximately 75 pounds/second through the pump discharge line to the nozzle inlet torus. At this point a small fraction of the $LH_2$ is by-passed around the nozzle coolant tubes to cool the nozzle to pressure vessel closure bolts. The remainder of the $LH_2$ flows through the nozzle U-tubes, through the outer reflector of the reactor core and into the dome end plenum of the pressure vessel. Here the hydrogen is reversed in direction and passed through the reactor fueled section where it is heated and into the thrust chamber formed by the convergent section of the nozzle. The hot hydrogen from the thrust chamber accelerates through the nozzle throat thereby producing the required engine thrust.

A small portion of the core exit hot gas is drawn off at the hot bleed port located in the convergent section of the nozzle and mixed with cold diluent extracted from the dome end of the pressure vessel. This fluid is used to power the turbine that drives the turbopump. The hydrogen mass flow rate to the turbine is controlled by the turbine power control valve. Turbine flow is exhausted through the two exhaust lines.

Under operating conditions, the temperature of the hydrogen entering the reflector is approximately 130°R. The reflector consists of 12 beryllium sectors, each containing a control drum. Boral plates in these drums supply the poison for reactor control. The hydrogen cools the various parts of the reflector, and the gas temperature reaches approximately 220°R before passing through the core. The NRX-A reactors are right circular cylinders and produce 1120 Mw of power at nominal full power. In the core, nuclear energy increases the gas temperature by more than 4000°R. The core consists of graphite fuel elements combined into clusters.

The NRX reactor tests and the first engine system test (NRX/EST) were performed at the Nuclear Rocket Development Station (NRDS) with the system in the upfiring position shown in Figure 3. The test assembly is mounted on the test car as shown and is connected to the test cell. For the NRX tests the turbopump is auxiliary gas driven by a facility installed turbopump and for the NRX/EST, the turbopump was mounted on the test car and was driven by the hot bleed gas from the nozzle.

All future engine system tests starting with the testing of the first experimental engine (XE-1) in the fall of 1967 will have their components in flight oriented configuration and will be tested in the down-fired position in the Engine Test Stand at NRDS. An important capability of this test stand is altitude simulation and consequently a significant step forward in the knowledge of nuclear rocket engine operation in space will be achieved in this testing. Performance margin evaluations will be conducted with the two experimental engines presently scheduled in the NERVA technology development program.

Any appraisal of progress implies a comparison with the developmental status at some previous key date. The period of early 1964 has been selected as a base point for this paper. Reflecting back to this date we can recall a great many feasibility questions. Some of these were of second order, but a number of key questions existed. These are:

1) Can a reactor be constructed that will produce optimum propellant temperatures and maintain structural integrity and reliability for useful operating periods?

2) Will the reactor have multiple restart capability?

3) Will the control of the engine be inherently stable, simple and reliable?

4) Will engine performance be predictable by use of analog and digital models?

5) Will non-nuclear hardware such as the turbopump, nozzle, valves, lines, instrumentation, etc., be reliable for useful operating periods?

## REACTOR ENDURANCE

In 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 eliminated. The cold flow tests on KIWI and NRX-A1 were designed 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.

Figure 4 lists the key tests that have been conducted since that period and the cumulative time at nominal full power. In 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 show that the system would operate for useful mission times.

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

These operating times should be compared with the endurance test times actually achieved in the NRX-A3, NRX/EST, and NRX-A5 tests. The NRX-A3 reactor was operated in its first run for 3.5 minutes and was inadvertently (scram from full power) shutdown due to a facility circuitry malfunction. It was restarted and operated at full power for a period equivalent to the test cell propellant capacity for a total operating time of 16.3 minutes 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 and the planned reactor objectives were combined with a series of key engine system objectives. This system was started ten times to power and the total operating time at power conditions was 116 minutes. The time at full power was approximately 28 minutes. The NRX-A5 reactor was operated for two periods for a total of thirty minutes 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 minutes. This test was the first of the Phoebus series of tests directed toward a higher thrust and performance reactor. At the present time, the experience on ROVER systems tested since 1964 includes over 100 minutes of operation at or near full operating power and temperature.

## RESTART CAPABILITY

In addition to the endurance tests which were conducted, the table in Figure 4 shows starts to power conditions that have been achieved. The first restart was achieved on KIWI B4E and, since that time, experience has been gained on 21 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 and 2 on NRX-A5.

The prime purpose of the restart capability requirement was for ground testing so that extended endurance data could be obtained with limited facility hydrogen supplies. In addition, various engine system tests were required and it was essential that a single reactor be used for those experiments.

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 temperature transient to which the test article was subjected was very large. 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.

A restart of interest is Run 2 of EP-IIB 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 subjected to an excessive temperature transient similar to that expected 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 using nuclear rather than stored energy.

## ENGINE CONTROL

A major part of the early control efforts was applied to the development of an adequate understanding of the reactor dynamics under various power and flow conditions. Initial concerns included uncertainties in the temperature coefficient of reactivity and the reactivity effects of the gaseous and liquid hydrogen. Analytical studies indicated that the temperature coefficient of reactivity was negative; that is, a temperature increase results in a negative reactivity insertion and a consequent power decrease. 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 analog 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 with 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. On NRX-A3 a fixed drum startup was made from 1 Mw to 35Mw. This startup 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. For the first time chamber pressure was controlled. 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 in order to develop an understanding of system dynamics. One of the NRX/EST experiments was a fixed drum startup to a higher power level of 250 Mw as indicated by the second curve in Figure 5. 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. The original control system depended on a neutron feedback loop with temperature feedback as a trim to the power loop. The output of the neutron feedback error signal was used to vary the control drum position. The first tests made with the neutron feedback loop removed were conducted on NRX/EST. The neutron feedback loop was removed when the reactor was operating at stable power conditions. Examination of the test results indicated the adequacy of this type of control allowing the simplification of the NRX-A5 control system. The two power runs made on the NRX-A5 reactor test were made without the neutron feedback loop.

Additional tests were conducted on an on-off type temperature control system during the NRX/EST tests. This type control could replace the proportional temperature control feedback loop which has been used and is presently being studied for future systems application.

The control test results to date indicate the wide latitude in control system design. The inherent stability of the engine system affords many opportunities of simplified and highly reliable control system design.

## ENGINE COMPONENT RELIABILITY

During the NRX-A program, two major components of the technology engine were tested and their designs verified. These were the pressure vessel assembly including the forward closure and the stainless steel U-tube nozzle. NRX/EST allowed for extended duration testing of the engine turbopump assembly, the hot bleed port, the turbine power control valve and miscellaneous engine lines and valves. Development of diagnostic and control instrumentation for use in a combined cryogenic and nuclear radiation environment has successfully continued throughout the NERVA Program.

## ENGINE PERFORMANCE PREDICTABILITY

The NRX/EST test demonstrated the functioning of the engine system during bootstrap startups. During this test series the engine system was subjected to ten startups to power, of which eight were to high temperature conditions. Figure 6 shows a comparison of some calculated and measured engine parameters during such a startup. Prior to testing NRX/EST, engine cold flow start transients were investigated in the cold flow development test system (CFDTS). The results of these tests were duplicated during the cold flow tests on NRX/EST. The predicted calculated test parameters in all cases closely matched the actual test results.

## FUTURE

The test results described indicate the progress that has been achieved in the nuclear rocket development since early 1964. The basic questions of feasibility have been answered and a firm technological base has been established.

The nuclear subsystem tests now planned include NRX tests to explore longer duration operation and Phoebus reactor testing by the Los Alamos Scientific Laboratory to explore higher temperature and power operation. Mission studies have indicated that a single size engine of about 200,000 pounds thrust would be close to optimum for all the missions being considered in the late 1970's or 1980's. The Los Alamos Scientific Laboratory will test a reactor of this rating in their Phoebus 2A test.

Initial studies are underway to determine the optimum configuration for a NERVA engine (NE) which will develop approximately 200,000 pounds thrust rather than the 55,000 pound size on which tests have been conducted to date. This engine will be developed and demonstrated through preliminary flight rating tests and available for use in manned planetary missions after 1975.

## FIGURE 1. PROJECT ROVER REACTOR DEVELOPMENT CHRONOLOGY

| | |
|---|---|
| 1955 to 1961 | Research phase of the program conducted by the Los Alamos Scientific Laboratory. General design methods were established, controls data and materials information were accumulated, fuel element fabrication methods were developed and an initial reactor test was conducted. |
| 1961 | NERVA development team of Aerojet-General Corporation and Westinghouse Electric Corporation selected. |
| 1962 to 1963 | KIWI power test series demonstrated successful reactor startup with liquid hydrogen. In November 1962 tests of the KIWI B4A, which was the favored design for the NERVA engine, led to the identification of fuel element vibration and structural problems. Year of redesign, analysis, component and subsystem testing, and cold flow tests of KIWI B4A and KIWI B4B reactors that demonstrated cause of vibration and indicated that revised design approaches of Los Alamos and Westinghouse would lead to a stable design. KIWI B4D and NRX-A1 cold flow tests indicated that the redesigns avoided the vibration problems. |
| 1964 | KIWI B4D and KIWI B4E successfully operated at full power and temperature, restart was included. NRX-A2 reactor operated at full power and temperature conditions. Restart tests were also conducted. |
| 1964 to 1966 | NRX-A3 operated successfully for over sixteen minutes at full power and temperature conditions. Three restarts demonstrated and fixed drum reactor transient test completed. Phoebus 1B reactor tested. The NRX/EST, the first breadboard engine system demonstrated bootstrap (self-starting) capability over a wide range of conditions; stability and predictability of engine performance over the full operating regime; and operated for a total of 29.5 minutes nominal full power. NRX-A5 operated for 29.4 minutes nominal full power. |

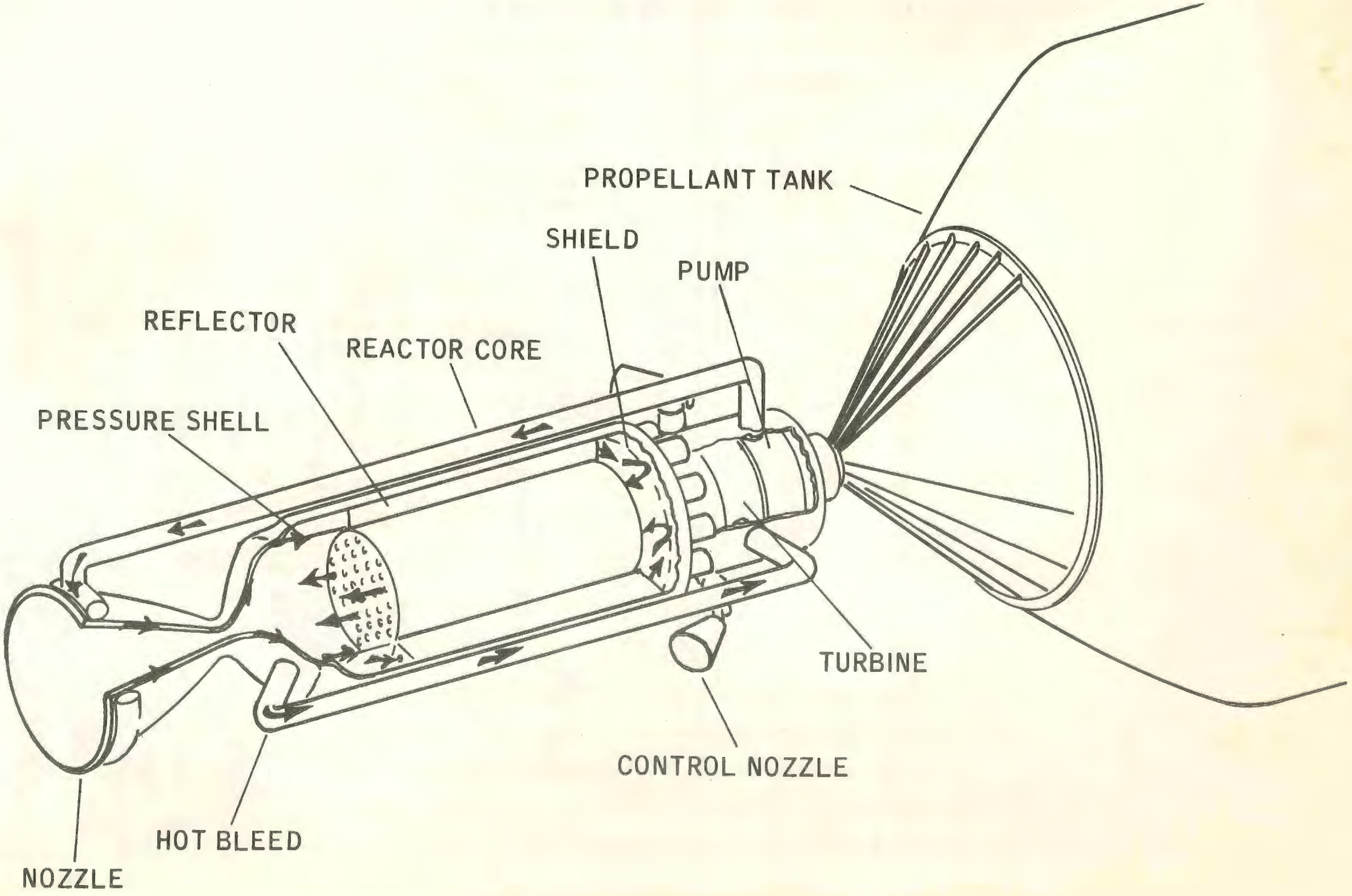

PROPELLANT TANK
SHIELD
PUMP
REFLECTOR
REACTOR CORE
PRESSURE SHELL
TURBINE
CONTROL NOZZLE
HOT BLEED
NOZZLE

Figure 2.

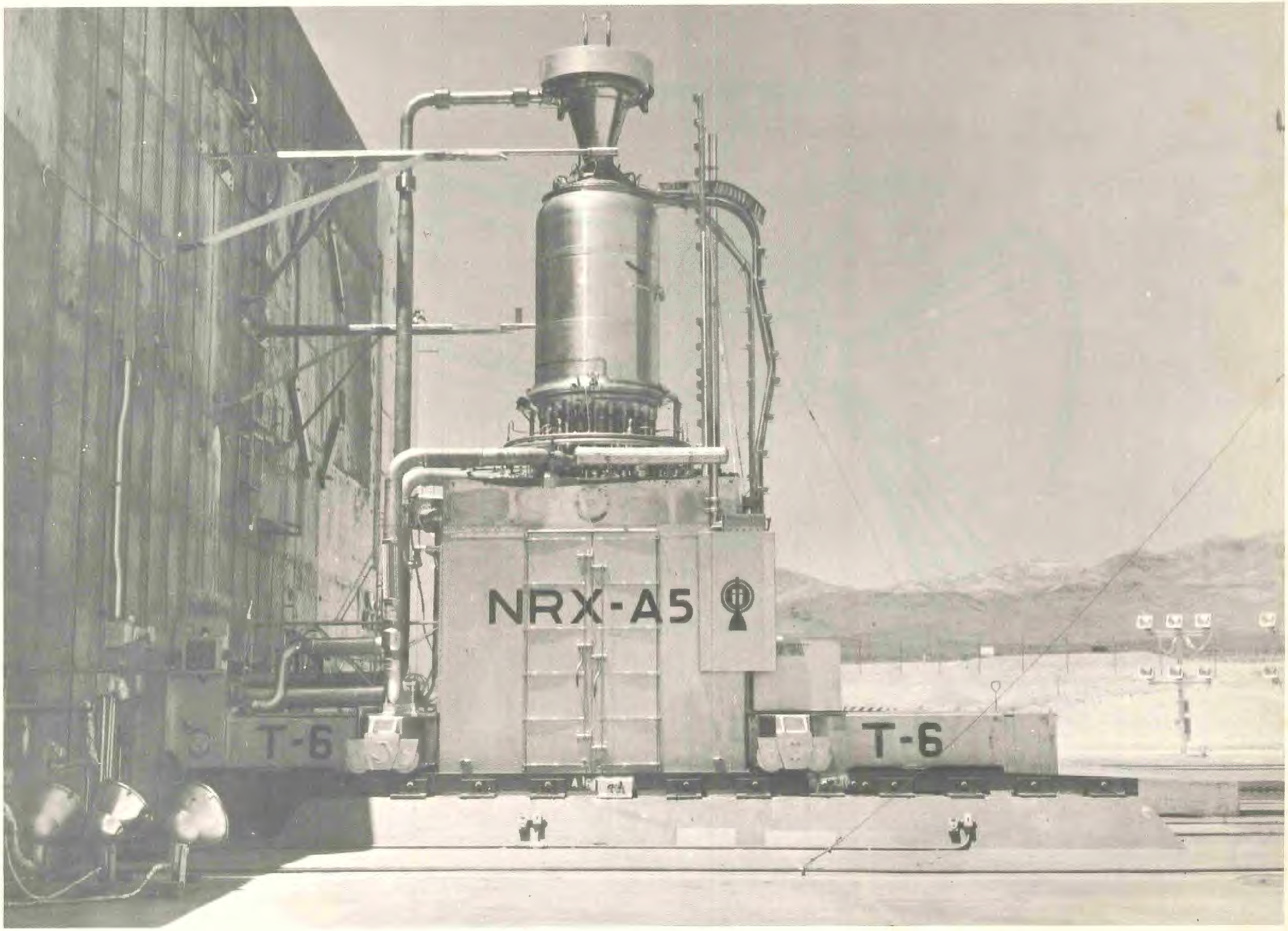
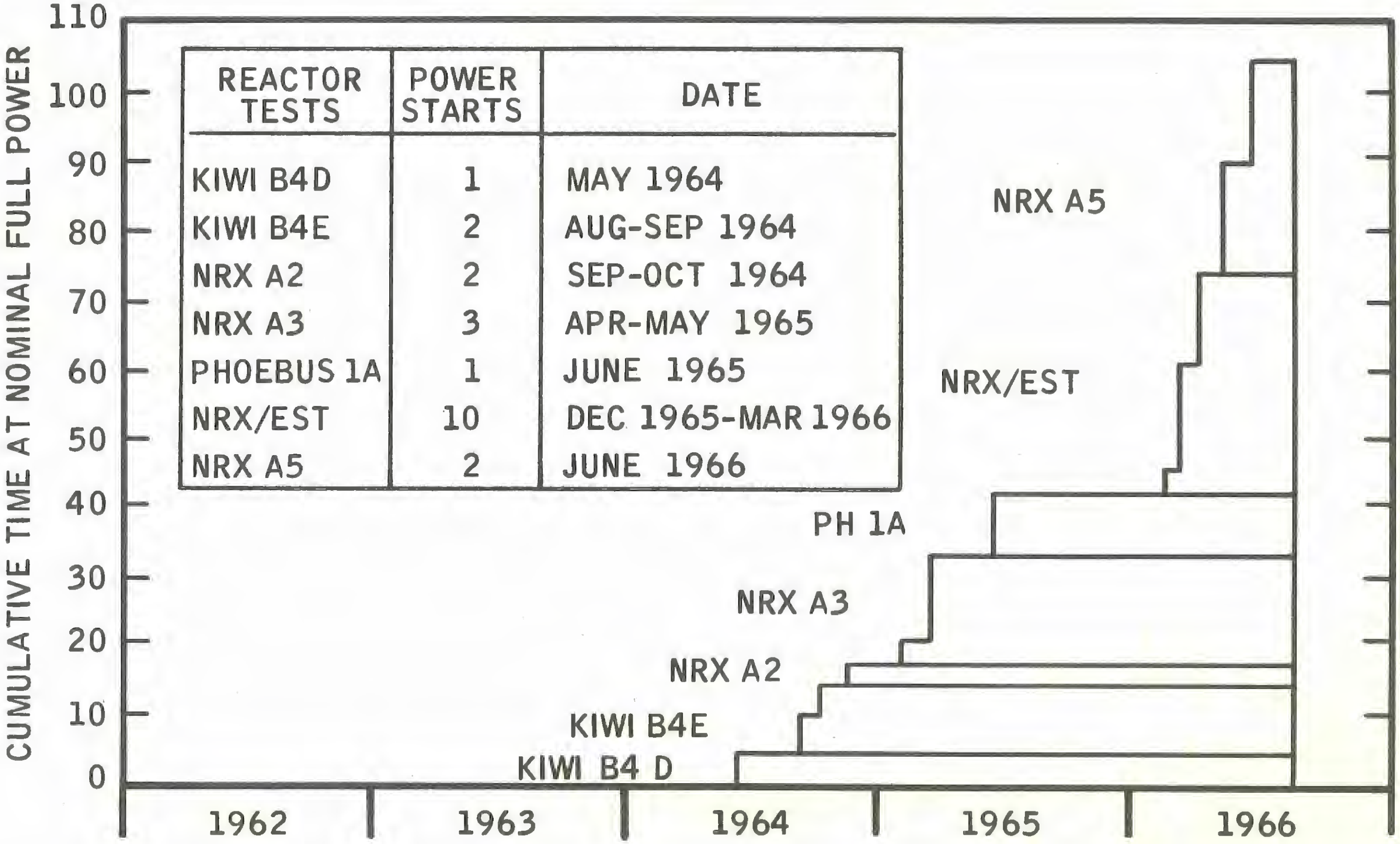


Figure 3. No Caption.

## POWER OPERATING EXPERIENCE



| REACTOR TESTS | POWER STARTS | DATE |
|---|---|---|
| KIWI B4D | 1 | MAY 1964 |
| KIWI B4E | 2 | AUG-SEP 1964 |
| NRX A2 | 2 | SEP-OCT 1964 |
| NRX A3 | 3 | APR-MAY 1965 |
| PHOEBUS 1A | 1 | JUNE 1965 |
| NRX/EST | 10 | DEC 1965-MAR 1966 |
| NRX A5 | 2 | JUNE 1966 |

Figure 4.

## FIXED CONTROL DRUM STARTUPS

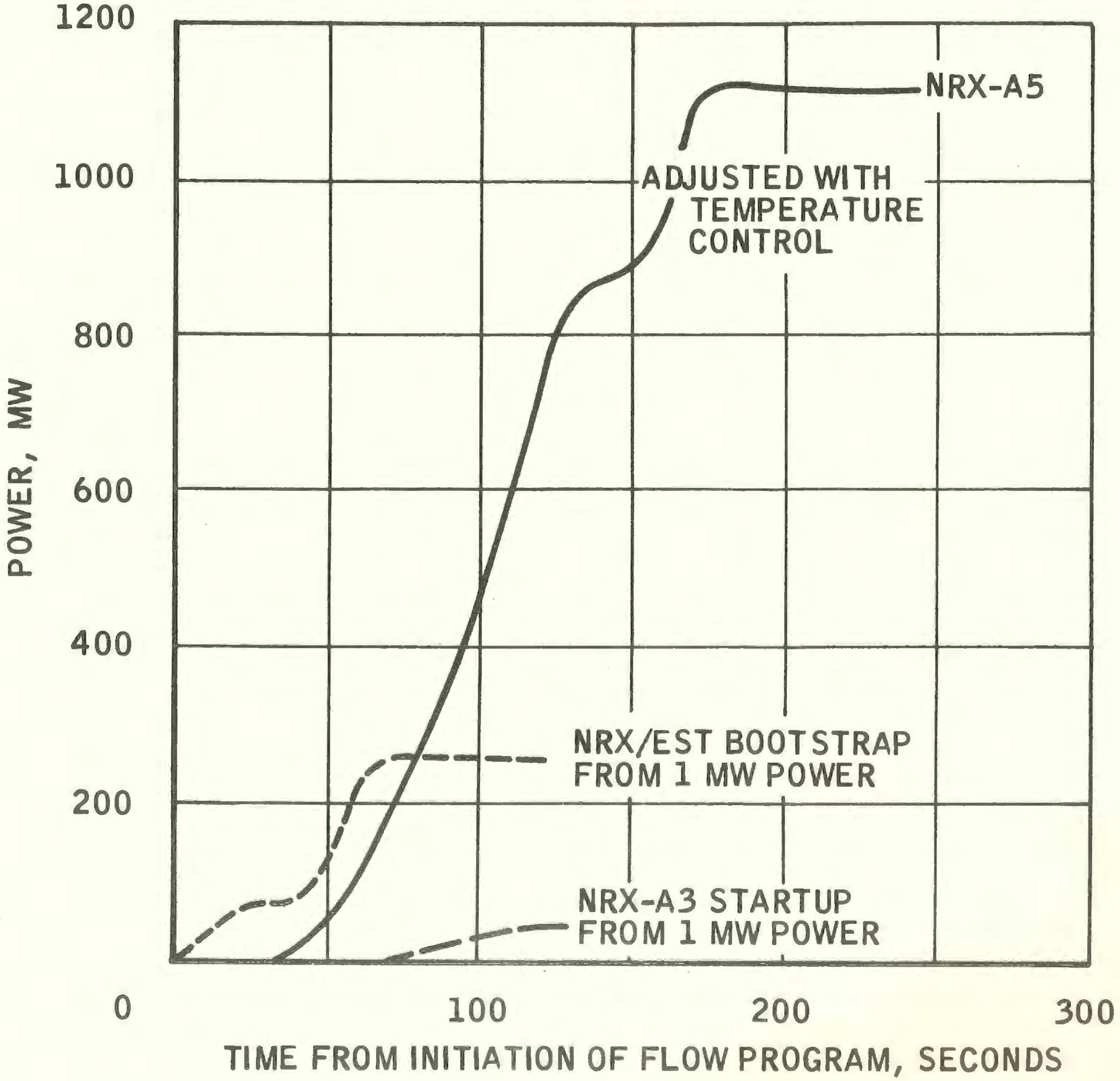


Figure 5.

# EP - IVA ENDURANCE RUN

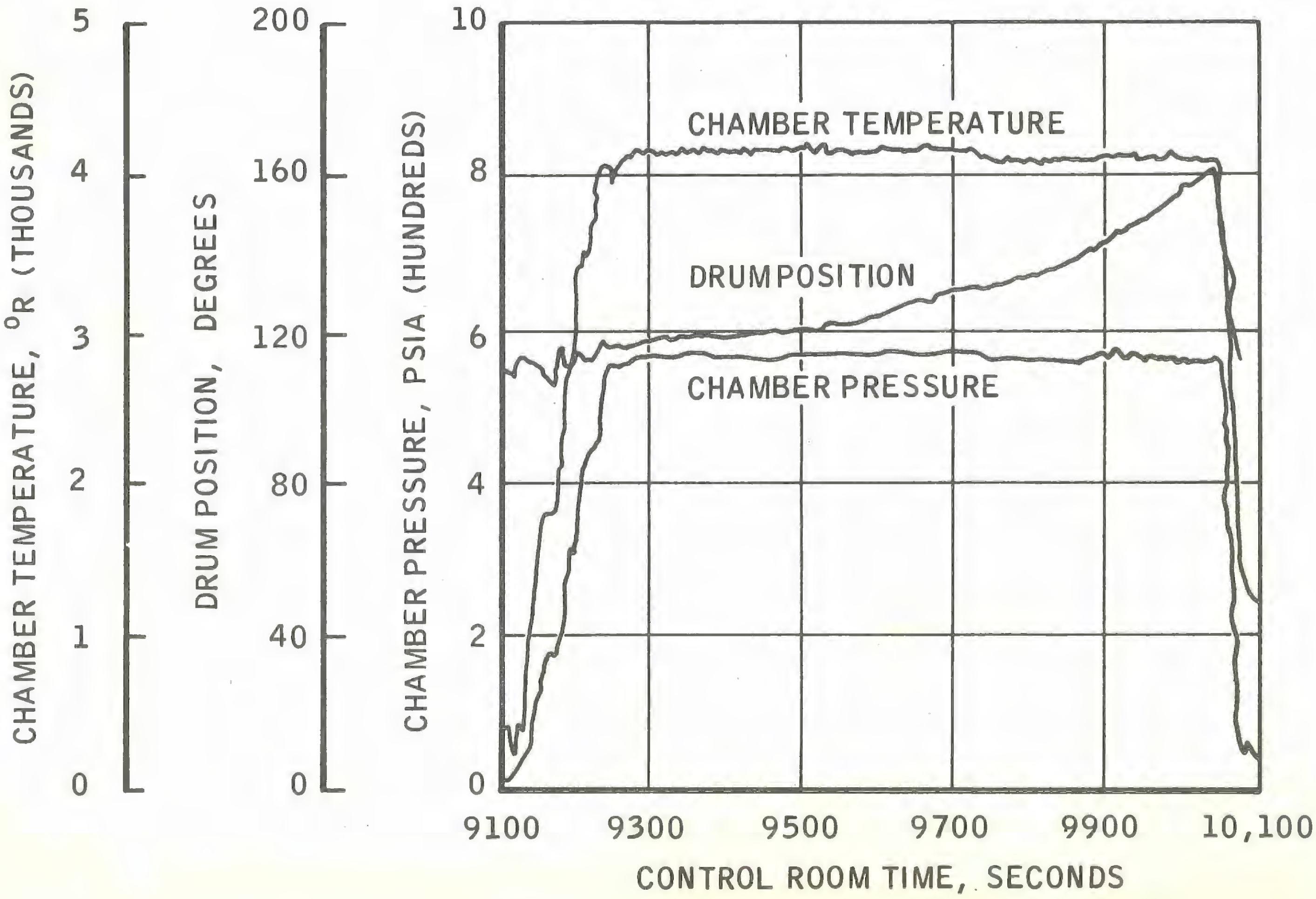


Figure 6.