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NUCLEAR PROPULSION - AN EMERGING TECHNOLOGY

by

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INTRODUCTION

Although I am sure that the events that took place beneath the West Stands at Stagg Field here in Chicago on December 2, 1942 have been referred to on at least several occasions during this Midwest Space Month, I believe that the subject of my talk gives me a particularly proprietary right to refer to that first controlled, self-sustaining nuclear chain reaction. It is, I believe, also proper that since this is next to the last discussion to be presented in this Third Conference on the Peaceful Uses of Space, I remind you of that first self-sustained nuclear reaction and the nuclear physics and chemistry work that preceded and followed it as an example of the unforeseen uses that scientific discoveries may eventually have. Although the general potential of a new source of energy could be postulated at that time, the impact on medicine, in industrial uses, in agriculture, in ship propulsion, in large power generation systems could be only generally considered but not specifically anticipated at that time. Although we do not anticipate so

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fundamental a discovery in our space science and exploration program, we still anticipate major effects that will be felt in all fields as a result of the scientific and technological discoveries and procedures and manpower that are developed.

I would like today to present to you a discussion of how nuclear energy, to a major extent, made possible by the scientific discoveries of those pioneers at Stagg Field in 1942, is being applied for use in the space program. Certainly those scientists and engineers could not have anticipated these areas of current interest. Although this is still a comparatively new area of development in our space program, equipment has been tested and technology development programs are directed toward developing this whole new area of rocketry and power.

The early and practical utilization of nuclear energy in space is a major goal of this country's advanced propulsion and power generation program. To this end, we have adopted the program philosophy shown on the first figure (R63-809). Essentially, we utilize the closest available technology in order to provide early hardware developments which are aimed at determining the feasibility of systems and at evaluating the flight problems that we will encounter when we start operating systems in the flight environment. These early developments are so designed that they will provide a growth capability for early application in operational missions. While we proceed with this early development program, we consider that a major and essential part of the program is a parallel and continuing advanced research and technology effort. This effort will provide the technology in support of the early development program and of advanced high power systems, and it will also evaluate the feasibility of new ideas that are proposed.

Our program is composed of two major parts, nuclear rocket systems and nuclear electric power and propulsion systems. As you might expect, a large portion of these programs is a combined effort between AEC and NASA. Responsibility for providing the required reactor research and development rests with the Atomic Energy Commission. NASA assumes responsibility for the non-nuclear component research and development programs, as well as for the integration of the reactor into operational systems and application of these systems in flight missions.

NUCLEAR ROCKETS

The nuclear rocket program is composed of several major hardware elements. The relationship of three of these elements, KIWI, NERVA, and RIFT, is illustrated in the next figure (R63-336). The reactor technology obtained from the KIWI project will be used in the development of a flight propulsion system in the NERVA project. The NERVA propulsion system will be flight tested in the RIFT stage. The RIFT stage will be designed to fit the Saturn V launch vehicle in such a way that with continued development, an early operational capability will be realized.

KIWI Project

Progress made in the KIWI and NERVA reactor portion of the project sets the pace for the NERVA engine and RIFT vehicle projects. Three KIWI-A research reactor tests were run in 1959 and 1960, followed by three KIWI-B experiments in 1961 and 1962. In the KIWI-B series of reactors, the Los Alamos Scientific Laboratory established several designs which represented different approaches to the solution of problems associated with the use of the brittle graphite materials in the environment of a nuclear rocket reactor. In the conduct of this phase of the program, Los Alamos has worked with ACF Industries, Inc.; Air Products and Chemicals, Inc.; Egerton, Germeshausen and Grier, Inc.; Bendix; Rocketdyne, and other groups. Armour Research Institute here in Chicago has performed certain materials evaluation work for us and the Argonne National Laboratory has performed safety testing for us.

The first of the KIWI-B designs, the KIWI-B1A reactor, was tested with gaseous hydrogen coolant flow in December 1961. A similar reactor, KIWI-B1B, was then tested with liquid hydrogen flow, as is required in a flight rocket engine, in September 1962. A photograph of that reactor at the test cell is shown on the next figure (R63-355). This is the general configuration of the test setup of all reactors run to date. They have been fired with the exhaust jet pointing upward to simplify the facility installation. The nozzle in this test was regeneratively cooled with liquid hydrogen. The results of this test indicated that the reactor could be started stably with liquid hydrogen. However, in this KIWI-B1B design, damage occurred in the reactor core similar to damage that had occurred in certain of the KIWI-A tests. The fact that this damage has not been explained through extensive laboratory tests and analyses has made us discard the KIWI-B1 design, for the present, as a candidate for the NERVA engine.

The most recent reactor test, the KIWI-B4A, was conducted by Los Alamos in November 1962. A photograph of that reactor is shown in the next figure (RN63-739A). Although this reactor is, externally, very similar to the KIWI-B1 reactor, the core design is substantially different. Almost as soon as the test of the KIWI-B4A reactor was started, flashes of light were noted in the exhaust jet. The test was continued until the flashes of light occurred so frequently that it was determined more could be learned by shutting down than by continuing. After disassembly of the reactor, it was found that there was extensive damage, probably due to vibrations that originated in the reactor. Work is now actively under way by Los Alamos and Westinghouse to modify the mechanical design so as to reduce the possibility of a recurrence of such vibrations to a minimum. Before the next reactor full power tests are run, component, subassembly, and full-scale mechanical and cold-flow testing will be conducted to evaluate the failure mode hypothesis and to check the suitability of redesigns.

NERVA Project

The next element of our program is the NERVA development. This development is being conducted by Aerojet General Corporation, with Westinghouse Electric Company as the principal subcontractor for reactor development. In addition, Bendix and American Machine and Foundry are subcontractors to Aerojet. A full-scale mock-up of the NERVA engine is shown on the next figure (R63-1094). The engine stands 22 feet high. Shown in the figure are the reactor, the regeneratively cooled nozzle, the control drum actuators, and the thrust structure at the top of the engine. The turbopump, the tank shut-off valve, and gimbal bearing about which the entire engine may be swiveled for thrust vector adjustment are mounted within the upper thrust structure section. The large spheres at the top of the engine are pressurized gas bottles used as a drive source for the pneumatic actuators in the system.

In the near future, our major emphasis will continue to be on the reactor of this engine. We are, however, proceeding with non-nuclear component work in both the engine and the flight test stage programs aimed at evaluating the critical long lead time design and operating problems. While we will be pursuing work in these critical non-nuclear areas, the procurement of large numbers of flight components aimed at developing those components to high reliability will not be conducted until successful reactor operation is achieved.

RIFT Project

As mentioned previously, the primary purpose of the RIFT project is to flight test the NERVA propulsion system. However, its design will consider its eventual development to operational status as a third stage on the Saturn V vehicle. This stage is being developed by the Lockheed Missiles and Space Company.

The next figure (R63-587) shows a drawing of the RIFT stage. It will be 33 feet in diameter, the same diameter as the Saturn V vehicle. From the exit of the NERVA jet nozzle to the top of the stage, it will stand approximately 126 feet.

Several unique problem areas are associated with the development of this RIFT stage. It will require the largest flight tank ever constructed for liquid hydrogen. The combined effects of low temperatures, resulting from the use of liquid hydrogen, and the nuclear radiation generated by the reactor in the NERVA engine on the materials, structures, insulations, propellants, etc., represent problem areas where research is now beginning. The nuclear flight safety requirements will require the development of new techniques for check-out, launch operations and destruct systems in addition to those that are already provided for range and flight safety in non-nuclear applications. The combination of the comparatively heavy gimballed nuclear engine and the large, but relatively light weight, tank of liquid hydrogen presents unique aerodynamic and structural loadings and thrust vector requirements. Finally, the requirements for engine restart and reactor cool-down after power cycles will impose additional factors that must be considered in design of the tank pressurization, venting, and particularly the guidance and control. Four flight tests are planned on a trajectory, as indicated on the next slide (R62-342, Rev. 3-63), utilizing the Saturn V launch complex at the Atlantic Missile Range. These flights will be conducted with the RIFT stage mounted on top of the Saturn V first stage using water ballast in a dummy second stage to obtain the proper stage acceleration conditions.

Nuclear Rocket Development Station

The Nuclear Rocket Development Station (NRDS) is an area located approximately 90 miles northwest of Las Vegas, Nevada, in which facilities are being provided for all power testing of reactors, engines, and stages required in the nuclear rocket program. The large distance between NRDS and Las Vegas has made it necessary for the AEC, with NASA participation, to comprehensively study the means by which a community could be established near the test facilities so that recruitment and retention of the large number of high caliber people required in the program can be encouraged.

The general layout of the test facilities that are being established at the NRDS is shown on the next slide (RN62-882). These facilities can be divided into reactor facilities, NERVA engine facilities, and RIFT stage facilities. Some of the reactor facilities have, of course, been in operation for several years. An additional reactor test cell, Test Cell C, is now nearing completion, some of the NERVA facilities are under construction, and others are under design. In addition, support facilities will be designed and built during this year and next year. None of the RIFT facilities have been funded for construction as yet, although design work will proceed in a limited way on certain of these facilities. It is important to emphasize that the facilities being built at the Nuclear Rocket Development Station in Nevada provide a national development capability for nuclear rockets that will not be duplicated anywhere else. This site could, therefore, be considered as the National Nuclear Rocket Development Station.

Nuclear Rocket Advanced Research and Technology

The last major element of the nuclear rocket program is the Advanced Research and Technology program which is aimed at providing technical support for our hardware development projects and also for providing the capability to build reactors and propulsion systems having performance characteristics well beyond those now under development. The principal work areas as shown on the next figure (R63-811) include reactors, nozzles, controls and instrumentation, turbopump and flow systems, system studies and mission analysis, and advanced concepts. Under the reactor area, the AEC and NASA are looking at concepts other than the graphite systems being used in KIWI-NERVA. The Argonne National Laboratory is one of several groups participating in this effort. We are evaluating materials properties for such systems. We are working toward high specific impulse and long life systems over a wide range of power. This reactor area is the key to future advanced systems. However, much remains to be done in nozzle, pump, and control technology before we can develop reliable, high-performance systems.

NUCLEAR ELECTRIC PROPULSION AND POWER GENERATION

In addition to nuclear energy for nuclear rocket propulsion, nuclear energy for electric power and electric propulsion will be required. In the range of hundreds of kilowatts to many megawatts, the only practical source of long-life electrical power is nuclear energy. Applications representative of such power levels include orbiting manned space platforms, manned interplanetary spacecraft, communications satellites, and unmanned planetary probes. These applications can generally be divided into the needs for on-board power for communications, life support, data acquisition, etc., and the power required for electric propulsion. A propulsion application, in the more distant future, is the manned interplanetary spacecraft. Such a vehicle would weigh a million pounds or more, might require orbital assembly, and would utilize a large electric rocket propulsion system requiring tens of megawatts of electrical power.

The next figure (R63-341) lists the program goals and major program elements of our nuclear electric power and electric propulsion programs. Several of the goals of both the power and propulsion subprograms are similar. Maintenance-free life of years will be required. Low weight is essential for propulsion systems, hence the power program goal of 10 pounds per kilowatt of electricity produced. It is important to note that for on-board power systems, such low weight is desirable but not essential because of the large vehicles now being developed. With regard to the electric propulsion program, high thrustor or engine efficiency is of major importance rather than engine weight, since the weight of the electric rocket engine itself is small (10 percent or less) in comparison with the electric power generation system needed to drive the rocket engine. The major electric propulsion and power generation program elements are listed in the right-hand portion of the figure. Let us turn our attention to the first four elements, the SNAP-8 Development, the SNAP-8 Flight Evaluation the Advanced Research and Technology, and the MECA Project.

Electric Power Generation

SNAP-8 Development Project

The SNAP-8 is a 30 kilowatt, reactor-powered, electric power generation system suitable for space flight applications. As shown in the figure (R63-310), it is composed of two major components, the nuclear sybsystem and the power conversion subsystem. The nuclear subsystem is composed of a nuclear reactor, shielding, and the associated pumps, tubing, and working fluid necessary to transfer the heat generated in the reactor to the boiler. The working fluid, a mixture of sodium and potassium (NaK), is heated in the reactor and pumped to the boiler where its heat energy is transferred to the mercury in the boiler. It is then pumped back to the reactor and is reheated.

The heat energy transferred to the boiler causes liquid mercury in the second loop to boil. The resulting mercury vapor passes through a turbine which extracts enough energy to drive the generator. The mercury vapor is then cooled in the condenser and the resulting liquid pumped back to the boiler for reheating. The heat energy released by the mercury in the condenser is removed by a single-phase cooling fluid which is pumped to the radiator. Here, the excess heat energy is radiated to space and the cooled fluid is returned to the condenser. Not shown on the figure is a small fourth loop needed to provide cooling for the bearing lubrication system and various electrical components. In simpler terms, heat energy produced in the reactor is transferred to the turbine section where approximately 10 percent is extracted in the form of electricity. The unused heat energy is then rejected to space by the radiator.

Cycle temperatures range from 1300° F in the reactor to 180°F in the generator. These temperatures coupled with the 10,000 hour, maintenance-free lifetime requirement are presenting difficult problems in materials selection and bearing and seal design.

<u>SNAP-8 Flight Evaluation Project</u>

The objective of the SNAP-8 Flight Evaluation Project is to evaluate the problems of starting and operating a SNAP-8 Electrical Generating System in the space environment and to demonstrate such operation. The spacecraft is estimated to weigh as much as ten tons including an electric propulsion system and will be launched by a Saturn IB launch vehicle. It is important to note that no major hardware commitments will be undertaken until SNAP-8 Development Project progress warrants such action. Preliminary studies of spacecraft, design, operational safety problems, etc., are planned for initiation during this Fiscal Year.

Advanced Research and Technology

The Advanced Research and Technology Project is aimed at acquiring the technology on which to base the development of future systems and is shown in the next two slides (R63-1086). The 2100°F, Rankine cycle, turbo-electric system utilizes lithium and potassium as working fluids and a segmented radiator to minimize radiator weight. The next slide (R63-1087) shows a thermionic direct conversion system which appears to be a simpler system than the turbogenerator system in that it has fewer moving parts. However, it required a maximum temperature of approximately 3000°F. Both systems have design weights on the order of 10 - 20 pounds per kilowatt and are technologically far beyond current ground-based power generating devices. The uncertain micrometeoroid environment, and the lack of basic and engineering knowledge on materials, heat transfer, flow processes, etc., pose serious obstacles to be overcome before hardware development of such advanced systems can be undertaken. We,therefore,attach much importance to this area and, under the direction of the Lewis Research Center, are conducting a vigorous program with approximately 25 industrial, research, and university contractors, as well as within NASA, to provide the necessary data. This program includes such items as the experimental evaluation of viscosity, specific heats, thermal conductivity, etc., of liquid metals and metal vapors of interest; the emissivity of radiator materials over a wide range of temperatures for space use; the boiling heat transfer coefficients of the metal working fluids at the high temperatures required; and, the compatibility of the metal working fluids with the containment materials and the components used in the system. This area of work also includes analysis and experiments on such system components as bearings, turbines, generators, pumps, thermionic emitters, etc.

MECA Project

The MECA Project is aimed at determining the effects of relatively long-time zero-gravity exposure on liquid metal boiling and condensing heat transfer. The eight or ten minutes of zero gravity exposure needed to establish equilibrium conditions will be obtained in freely falling vehicles at high altitudes. Experiments weighing up to 1000 pounds will be launched by small (110,000 pounds of thrust) solid rocket-powered vehicles shown in the next figure (R63-374). Composed of available motors, vehicles will be launched from Wallops Island at a rate of two to three per year. The first experiments are in direct support of SNAP-8 and will utilize mercury fluid and SNAP-8 boiler and condenser component configurations. Data will be telemetered to the ground and also recorded on film. The camera package will be recovered using techniques already developed.

Electric Propulsion

Referring again to the right-hand column of a previous figure (R63-341) the propulsion subprogram is composed of an Advanced Research and Technology Project, and Engine Development Project, and a Flight Evaluation Project called SERT.

Advanced Research and Technology Project

With regard to the Advanced Research and Technology Project, our efforts are directed toward providing the basic information necessary for the development of systems. The next figure (R63-730) lists the three main types of electric rocket engine we are investigating, the arc jet, the ion engine and the plasma jet. The arc jet develops thrust by heating a working fluid such as hydrogen or ammonia and expanding it through a nozzle. The ion engine depends upon electrostatic forces and reactions to accelerate a working fluid such as cesium or mercury, thereby developing thrust. The plasma engine utilizes electromagnetic forces to accelerate plasmas, thereby developing thrust. As can be seen in the left-hand column of the figure, the arc jet has a specific impulse range of 700 - 1500 pounds of thrust per pound per second of propellant flow. The ion engine develops impulses in the 3500 - 10,000 seconds range. The plasma jet offers the potential of covering the whole range of the other two.

Another Advanced Research and Technology area that has been somewhat neglected in favor of work on thrustors is the power conditioning and control system. A program in these areas has been initiated this year and will be increased in 1964. Approximately 26 industrial and university contractors are involved in the various portions of this project.

Engine Development Project

The Engine Development Project consists of a number of development contracts for arc jet and ion engines aimed at providing hardware for ground and flight test purposes. Hopefully, the engines developed as part of this project will be suitable for early applications. An example of this philosophy is the 3 KW ion engine module, under development by the Hughes Aircraft Company, and the concept of clustering the basic 3 KW unit into megawatt-size systems.

The next figure (R63-322) shows the basic engine module. You will note that it is a strip or rectangular engine rather than the circular or ring engine discussed in prior years. Its dimensions are approximately 3X6 inches. The next figure (R63-320) illustrates the clustering concept. The power levels have been selected so that each development would be suitable for the potential applications listed across the bottom of the figure.

SERT Project (Space Electric Rocket Test)

The SERT Project is composed of a series of electric rocket engine tests that, in general, cannot be performed meaningfully in ground facilities alone. By comparing flight test results with data obtained in ground facilities, we will determine the limitations and accuracy of our ground tests. Because we can never expect to simulate the space environment completely, flight tests such as these are also necessary to prove or qualify specific engine developments for future mission applications.

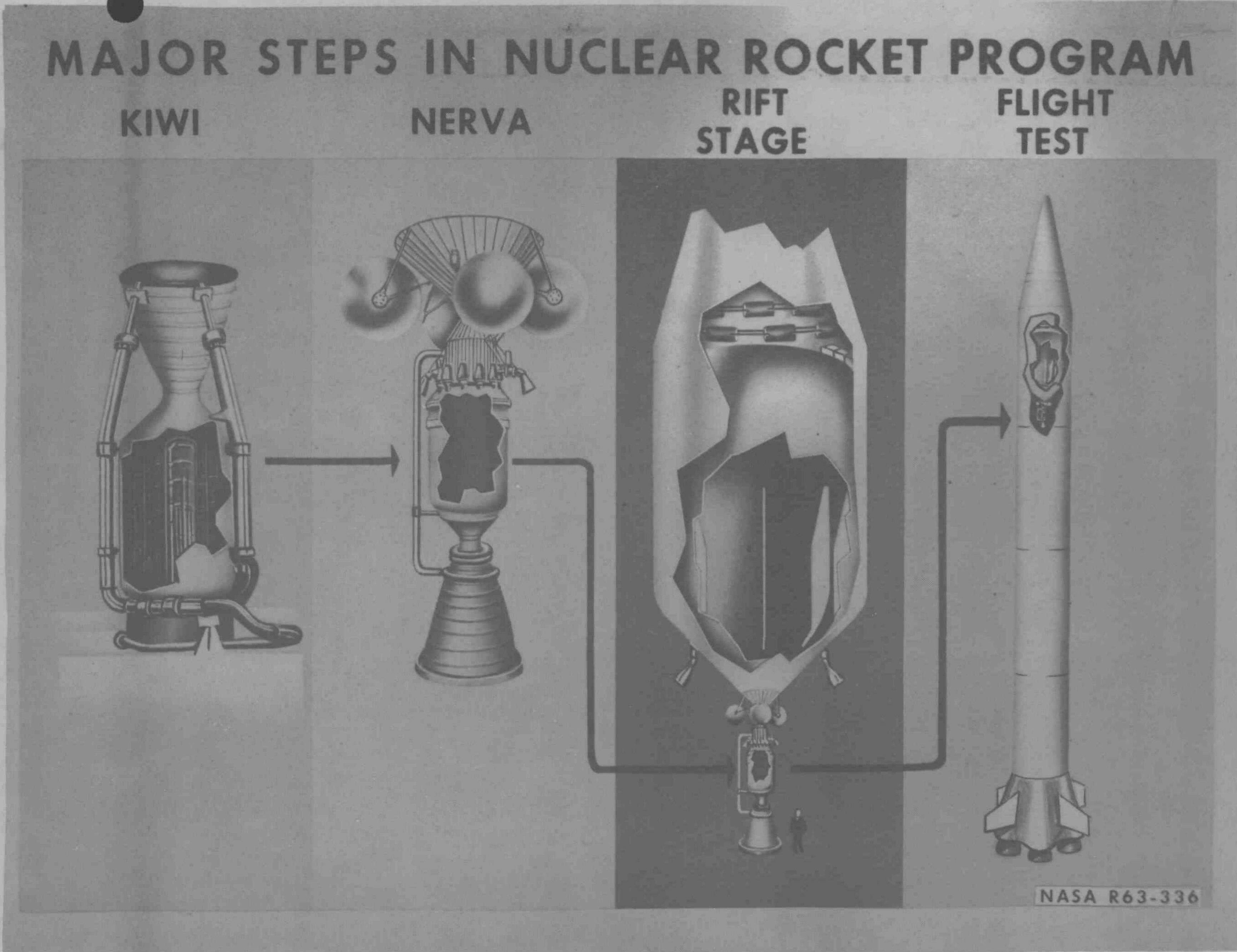
The first SERT flight to be run later this year will consist of an ion beam neutralization experiment. A 350-pound, spin-stabilized capsule, built by RCA, will be launched from Wallops Island, Virginia, by Scout launch vehicle on the trajectory shown on the next figure (R63-728). This trajectory will give up to 55 minutes of free fall above the Earth's atmosphere. During this time, two ion engines will be operated in such a manner as to change the capsule spin rate. The amount of change in spin rate will be a measure of the thrust developed, which in turn is a measure of the degree of neutralization achieved. Succeeding SERT flights will involve orbital trajectories as well as the ballistic type shown here.

In summary, I want to emphasize that the door that was opened here in Chicago in December 1942 has in less than 20 years led us to concepts and hardware for the utilization of that new energy source in space missions that could not be generally anticipated at that time. As a result of that dramatic scientific effort, we have established major goals aimed at the early and practical utilization of nuclear energy in space. We are convinced that a substantial effort is justified by the potential performance advantages and the many applications of these systems for difficult space missions. This work will lead us not only to the development of particular hardware items, but will open new fields of rocket propulsion and power to permit us to travel freely in space.

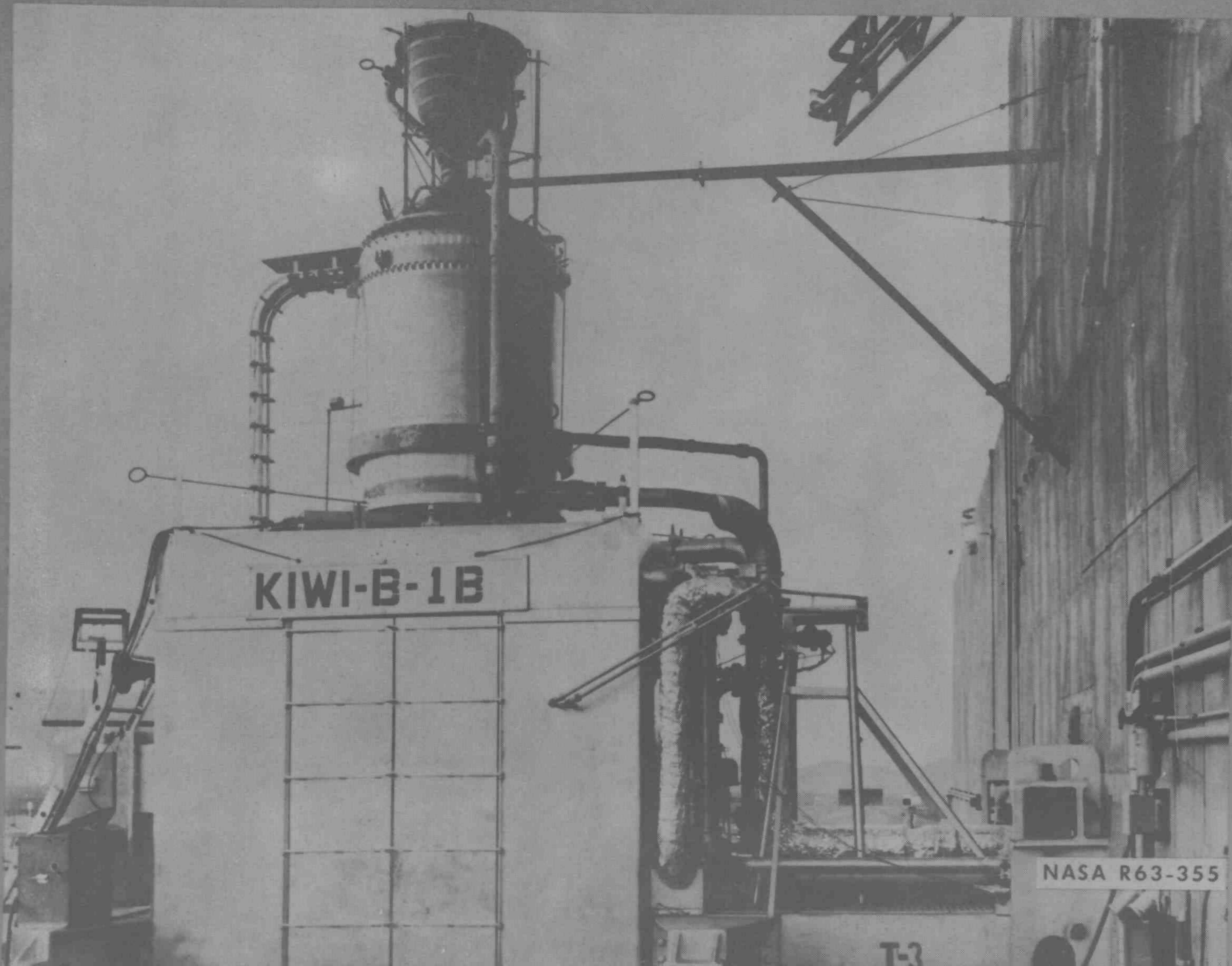
PROGRAM PHILOSOPHY

- EARLY DEVELOPMENT
  - * USE CLOSEST AVAILABLE TECHNOLOGY
  - * DETERMINE FEASIBILITY
  - * EVALUATE FLIGHT PROBLEMS
  - * PROVIDE EARLY APPLICATION OF CONCEPTS

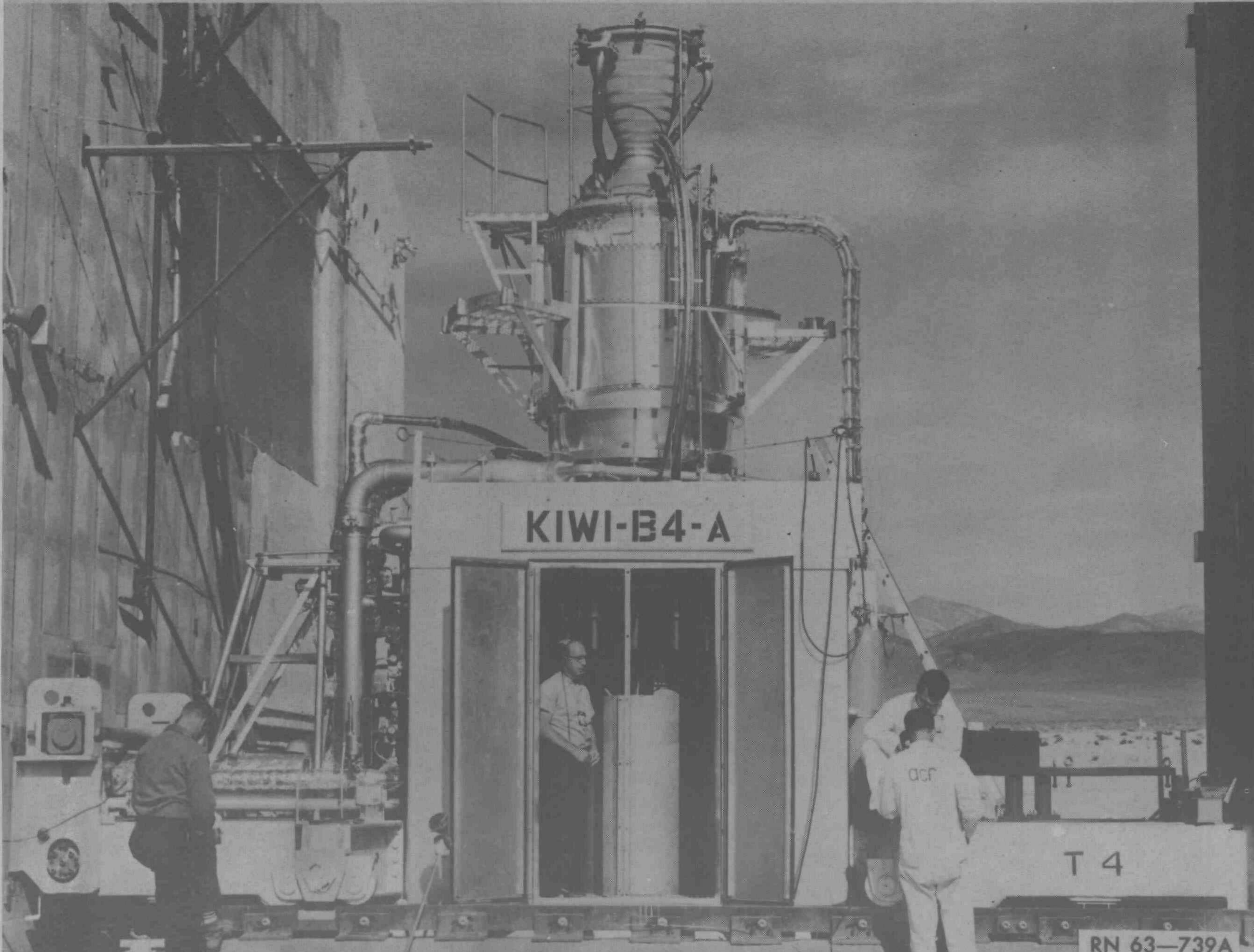
- ADVANCED RESEARCH AND TECHNOLOGY
  - * PROVIDE TECHNOLOGY FOR ADVANCED SYSTEMS
  - * EVALUATE FEASIBILITY OF NEW CONCEPTS
  - * SOLVE DEVELOPMENT PROBLEMS


MAJOR STEPS IN NUCLEAR ROCKET PROGRAM
KIWI
NERVA
RIFT STAGE
FLIGHT TEST
NASA R63-336

KIWI-B-1B REACTOR

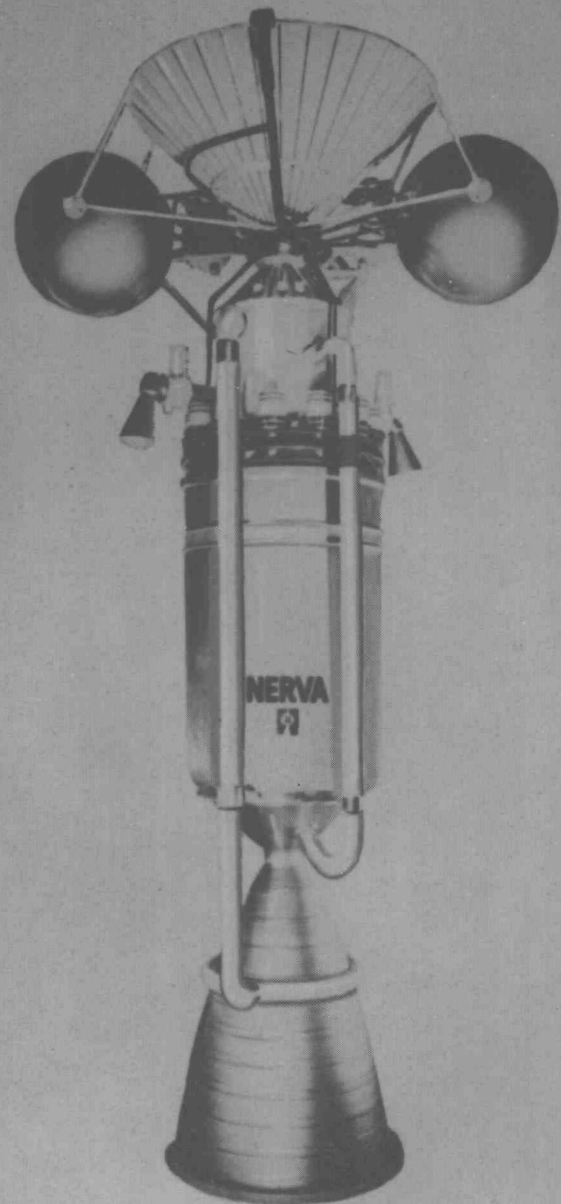


KIWI-B4-A REACTOR



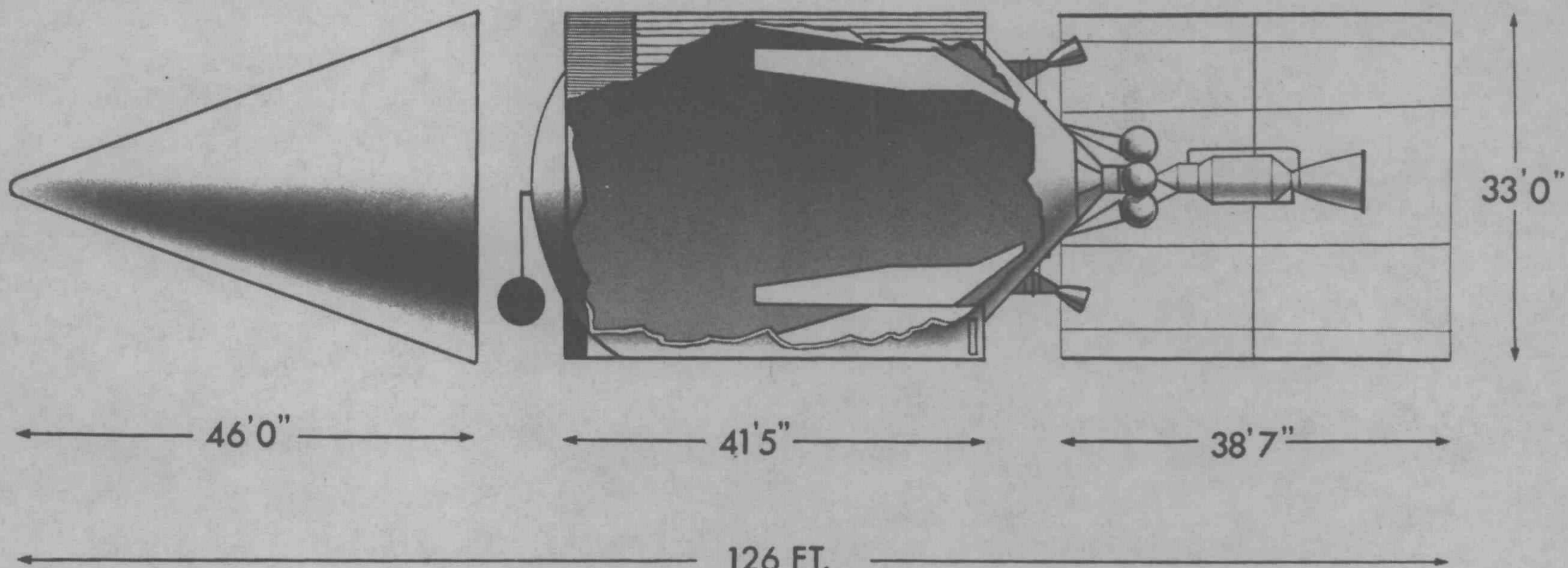
RN 63—739A

NERVA MOCKUP

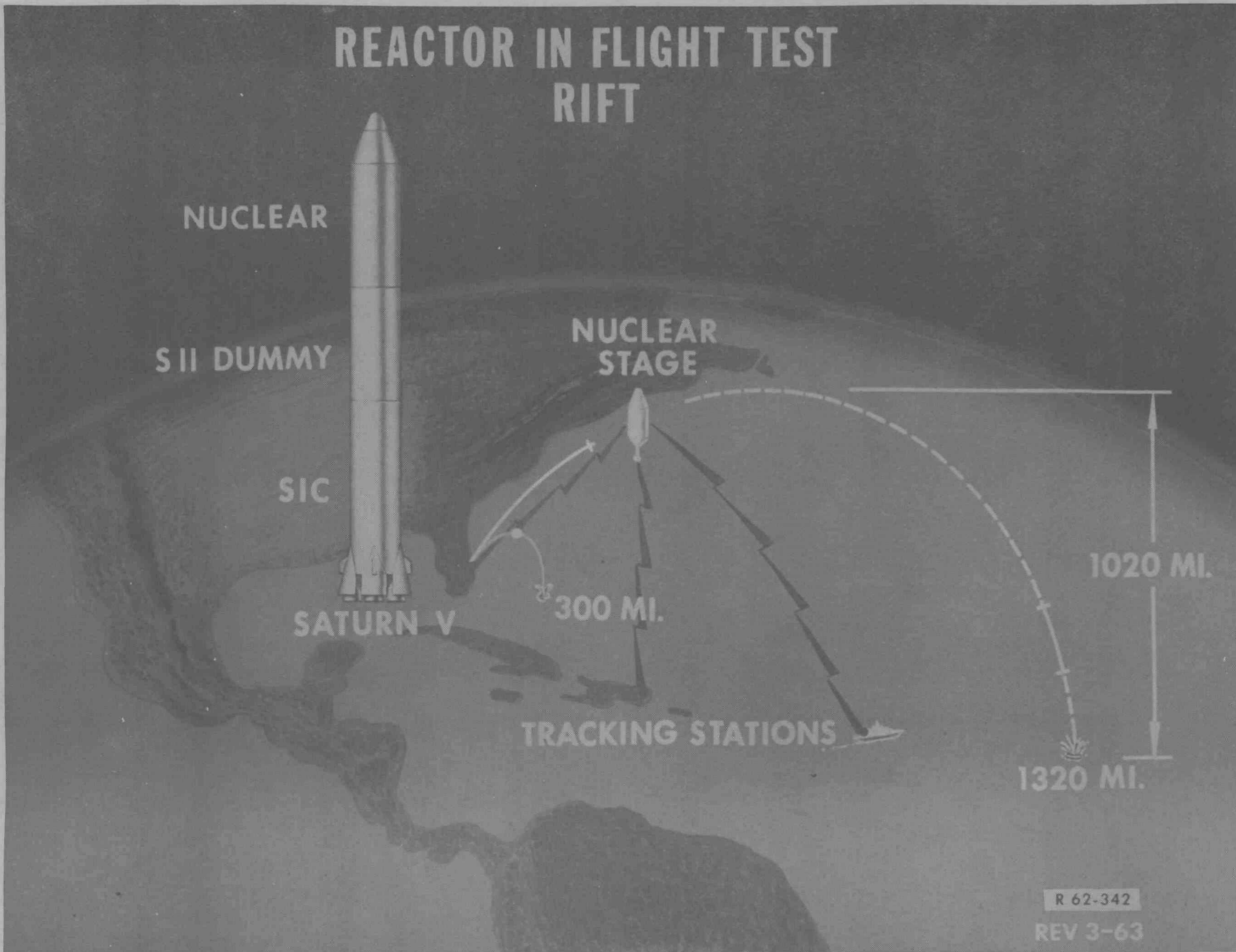


NASA R63-1094

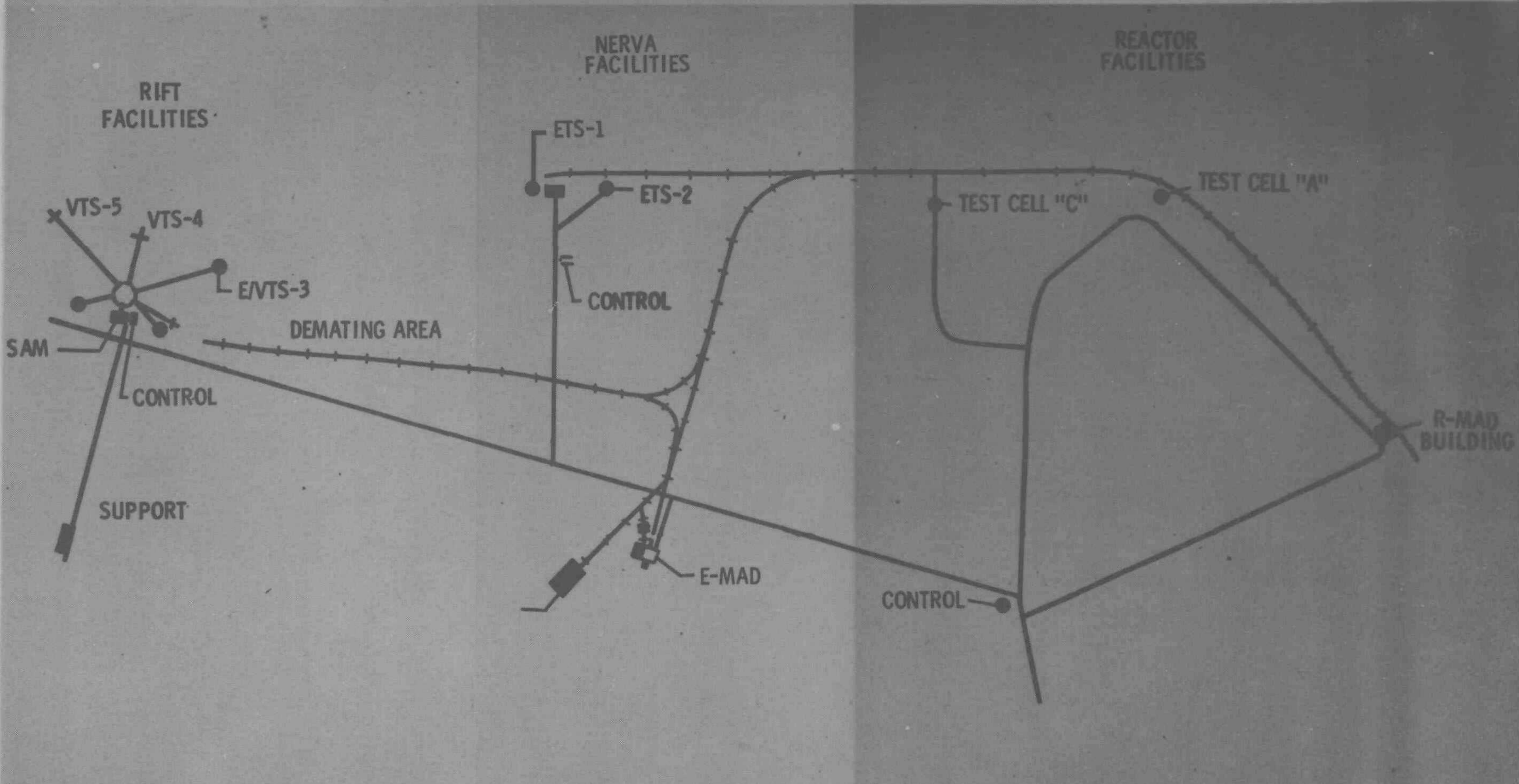
INBOARD PROFILE OF RIFT



NASA R63-587


REACTOR IN FLIGHT TEST
RIFT
NUCLEAR
S II DUMMY
SIC
SATURN V
NUCLEAR
STAGE
300 MI.
TRACKING STATIONS
1020 MI.
1320 MI.
R 62-342
REV 3-63

NUCLEAR ROCKET DEVELOPMENT STATION

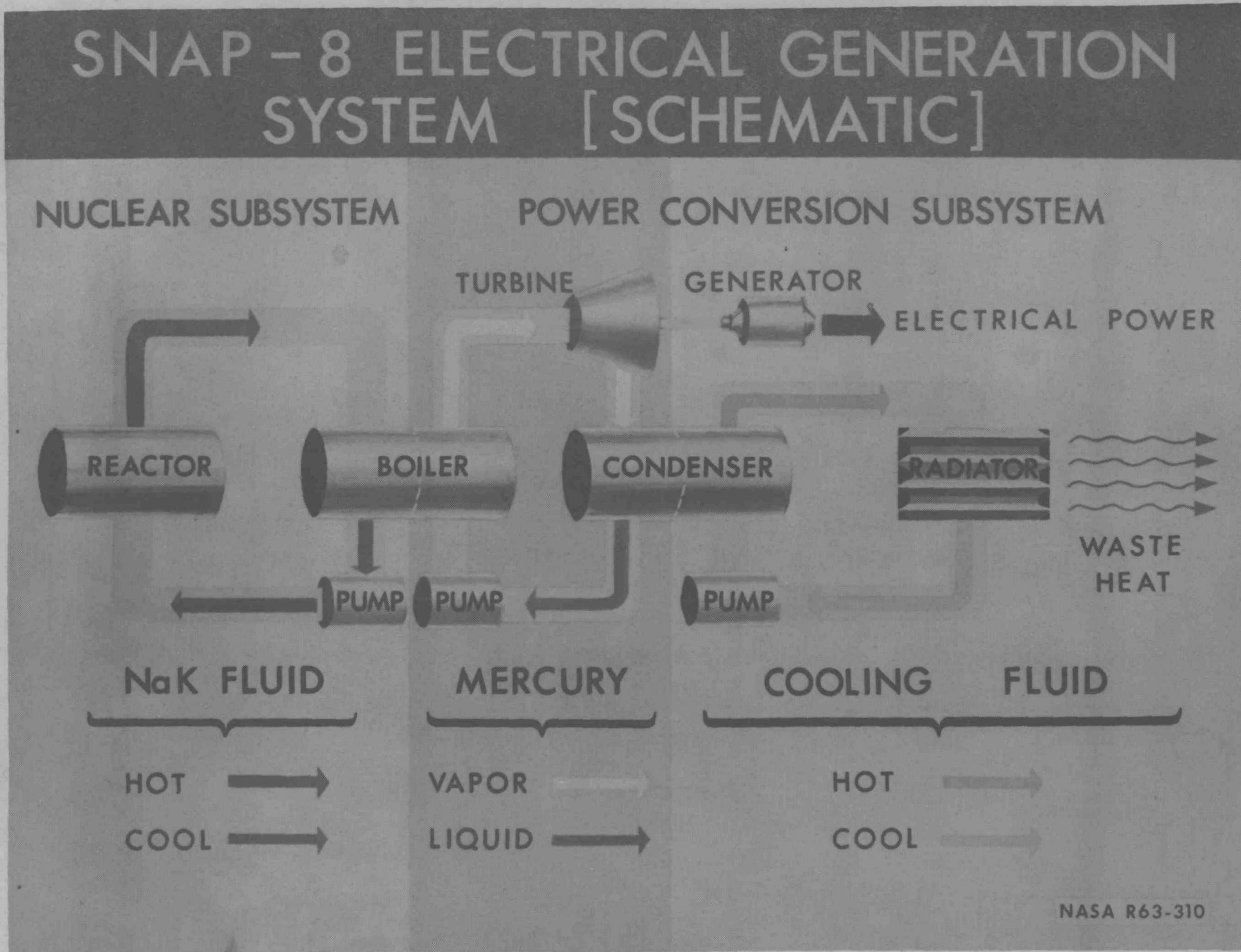


RN62-882

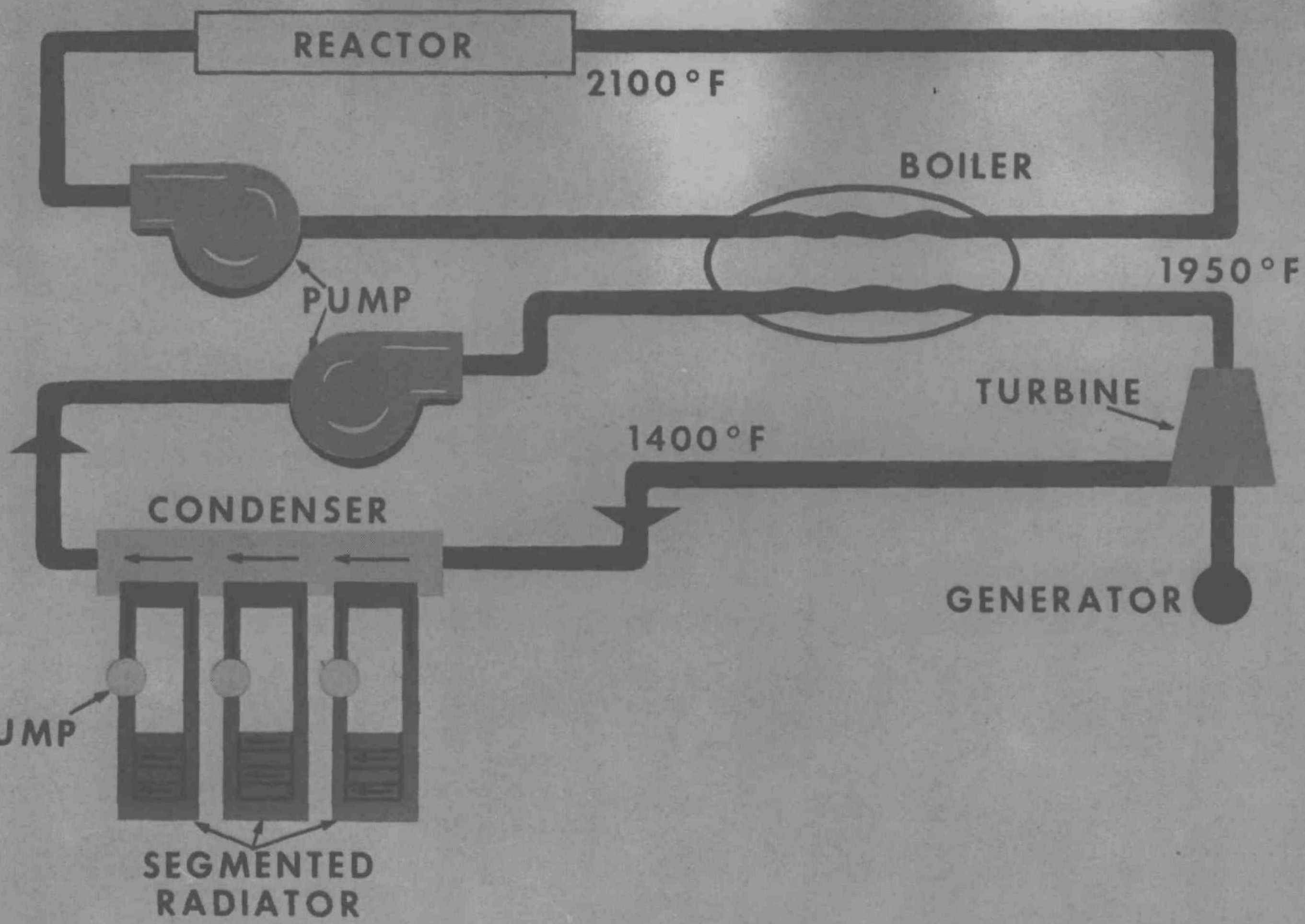
NUCLEAR ELECTRIC SYSTEMS PROGRAM GOALS AND ELEMENTS

PROGRAM	GOALS	ELEMENTS
POWER	• 10 LBS PER KW • WATTS TO MEGAWATTS • LONG LIFE	• SNAP-8 DEVELOPMENT • SNAP-8 FLIGHT EVALUATION • ADVANCED RESEARCH & TECHNOLOGY • MECA (ZERO-G FLIGHT TESTS)
ENGINE	• HI–EFFICIENCY • LONG LIFE • .01 TO 10 POUNDS THRUST	• ENGINE DEVELOPMENT • ADVANCED RESEARCH & TECHNOLOGY • SERT (SPACE ELECTRIC ROCKET TESTS)

NASA R63-341

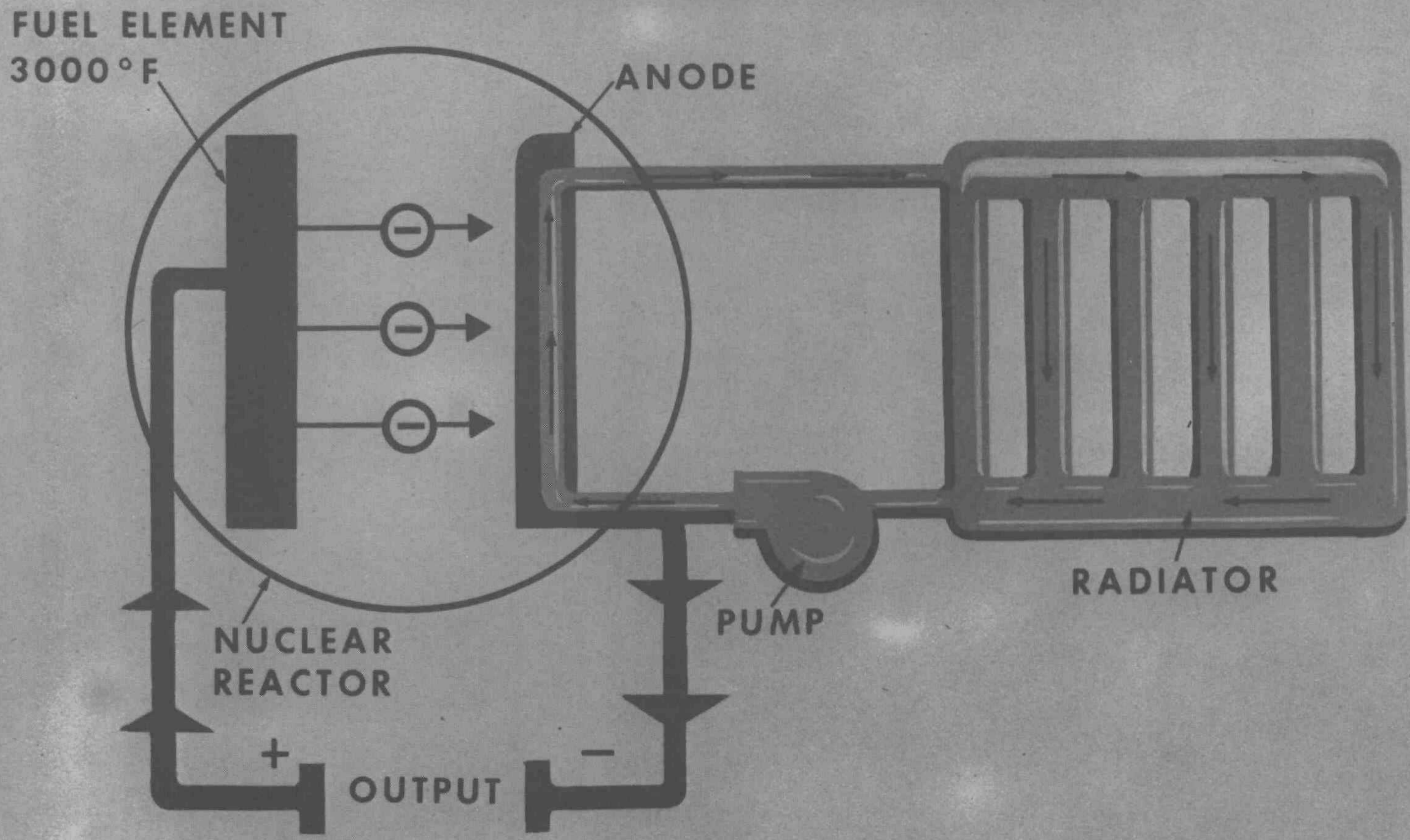

SNAP-8 ELECTRICAL GENERATION SYSTEM [SCHEMATIC]
NUCLEAR SUBSYSTEM
POWER CONVERSION SUBSYSTEM
TURBINE
GENERATOR
ELECTRICAL POWER
REACTOR
BOILER
CONDENSER
RADIATOR
WASTE HEAT
PUMP
PUMP
PUMP
NaK FLUID
MERCURY
COOLING FLUID
HOT
COOL
VAPOR
LIQUID
HOT
COOL
NASA R63-310

ADVANCED SYSTEM
TURBOELECTRIC



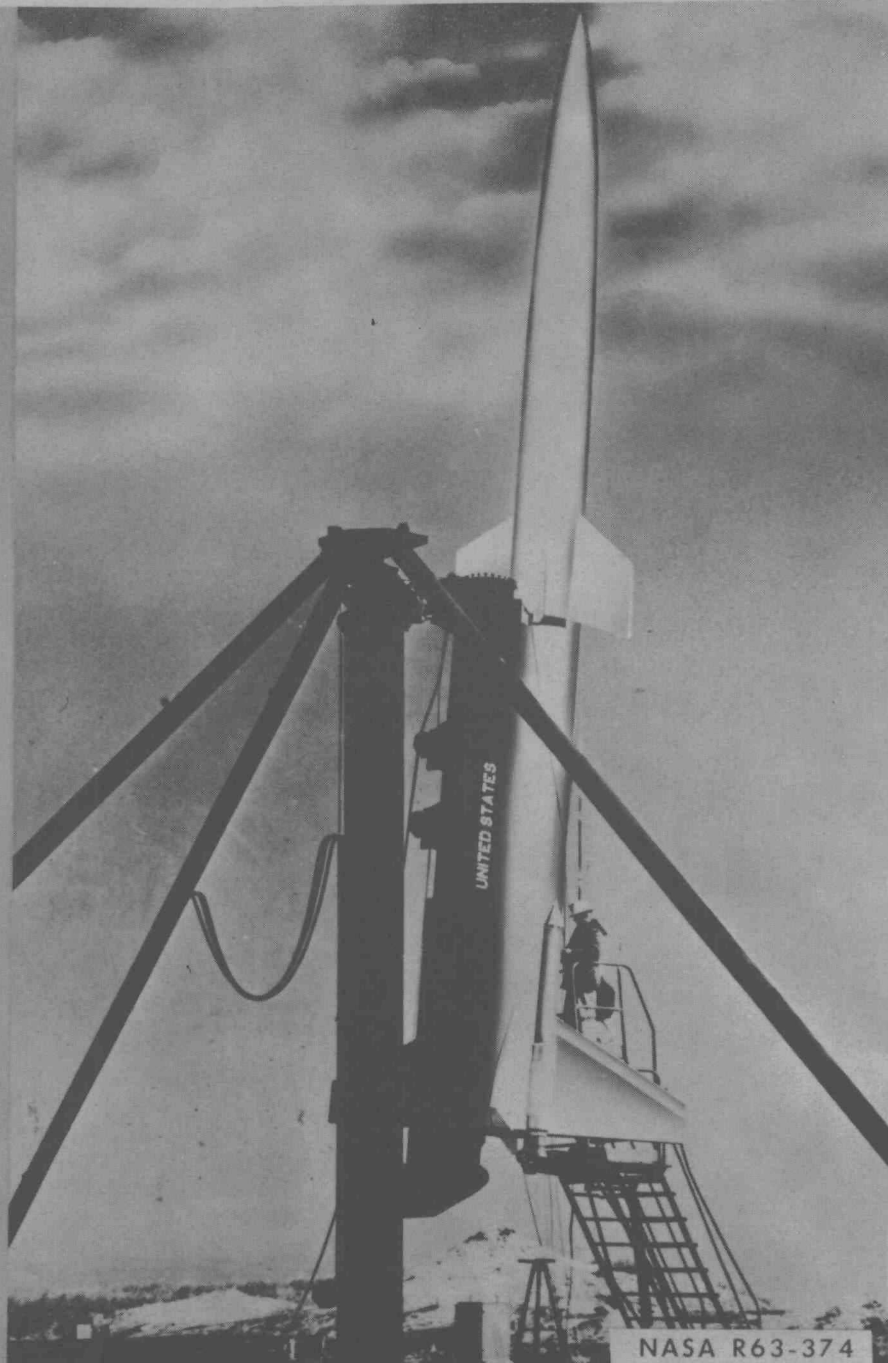
NASA R63-1086

ADVANCED SYSTEM
THERMIONIC DIRECT CONVERSION



NASA R63-1087

MECA VEHICLE ON LAUNCHER



NASA R63-374

NUCLEAR ELECTRIC SYSTEMS PROGRAM GOALS AND ELEMENTS

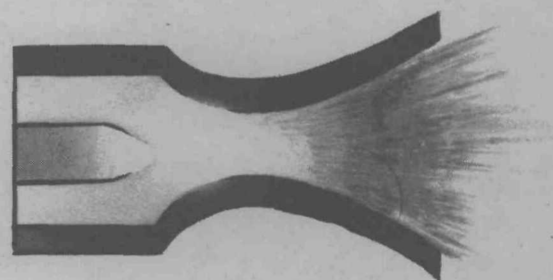
PROGRAM	GOALS	ELEMENTS
POWER	• 10 LBS PER KW • WATTS TO MEGAWATTS • LONG LIFE	• SNAP-8 DEVELOPMENT • SNAP-8 FLIGHT EVALUATION • ADVANCED RESEARCH & TECHNOLOGY • MECA (ZERO-G FLIGHT TESTS)
ENGINE	• HI-EFFICIENCY • LONG LIFE • .01 TO 10 POUNDS THRUST	• ENGINE DEVELOPMENT • ADVANCED RESEARCH & TECHNOLOGY • SERT (SPACE ELECTRIC ROCKET TESTS)

NASA R63-341

ELECTRIC THRUST CHAMBER PROGRAM

MAJOR PROBLEMS

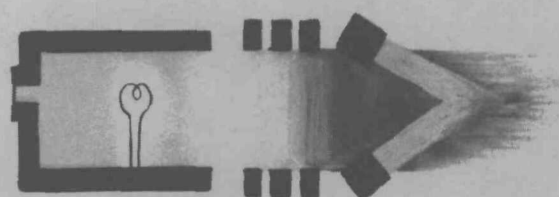
ARC JET
Isp=700-1,500 SECS.



DISSOCIATION LOSSES

ELECTRODE EROSION

ION ENGINE
Isp=3,500-10,000 SECS.

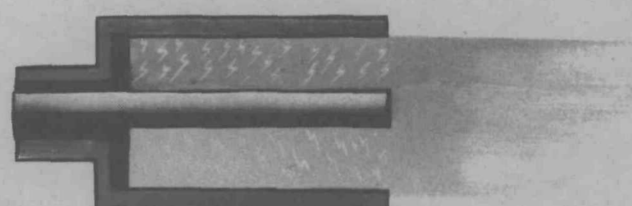


IONIZATION

ACCELERATION

NEUTRALIZATION

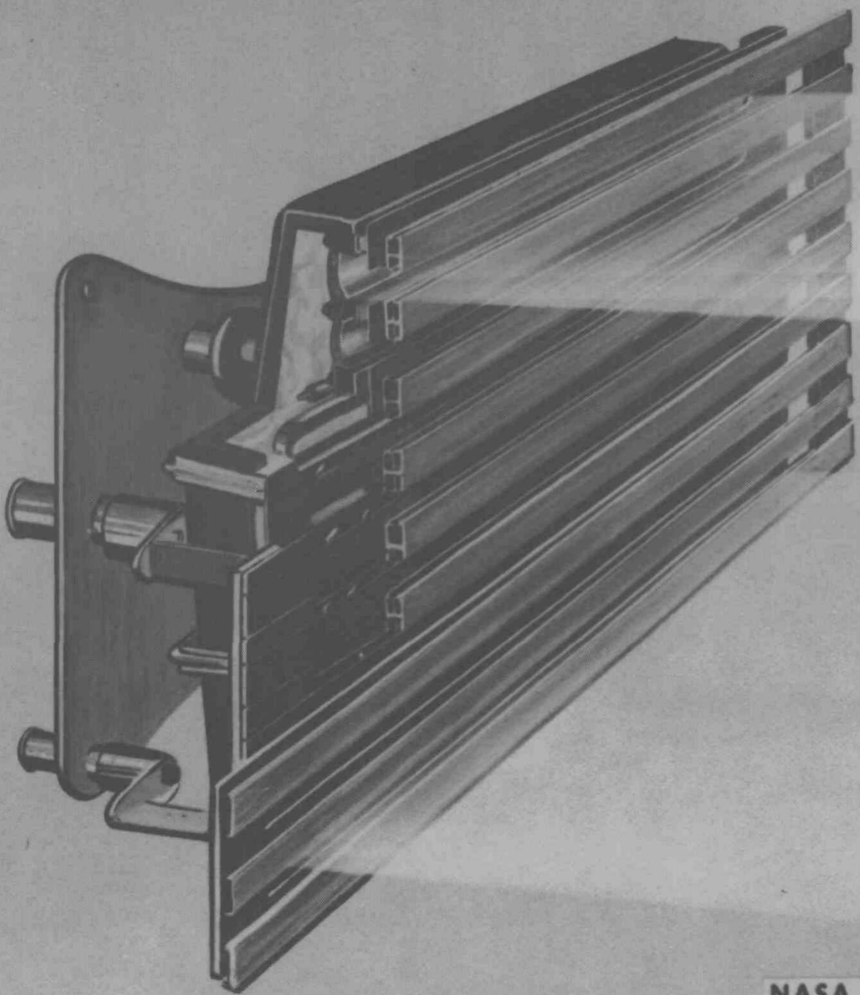
PLASMA JET
Isp=700-10,000 SECS.



GENERAL UNDERSTANDING

NASA R63-730

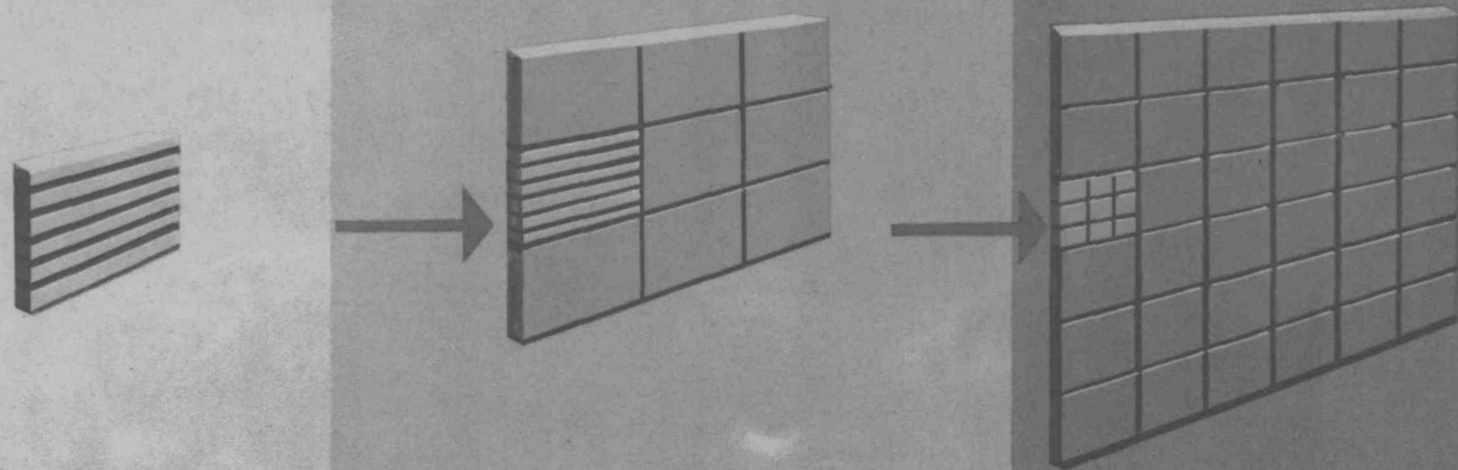
3 KW ION ENGINE MODULE



NASA R63-322

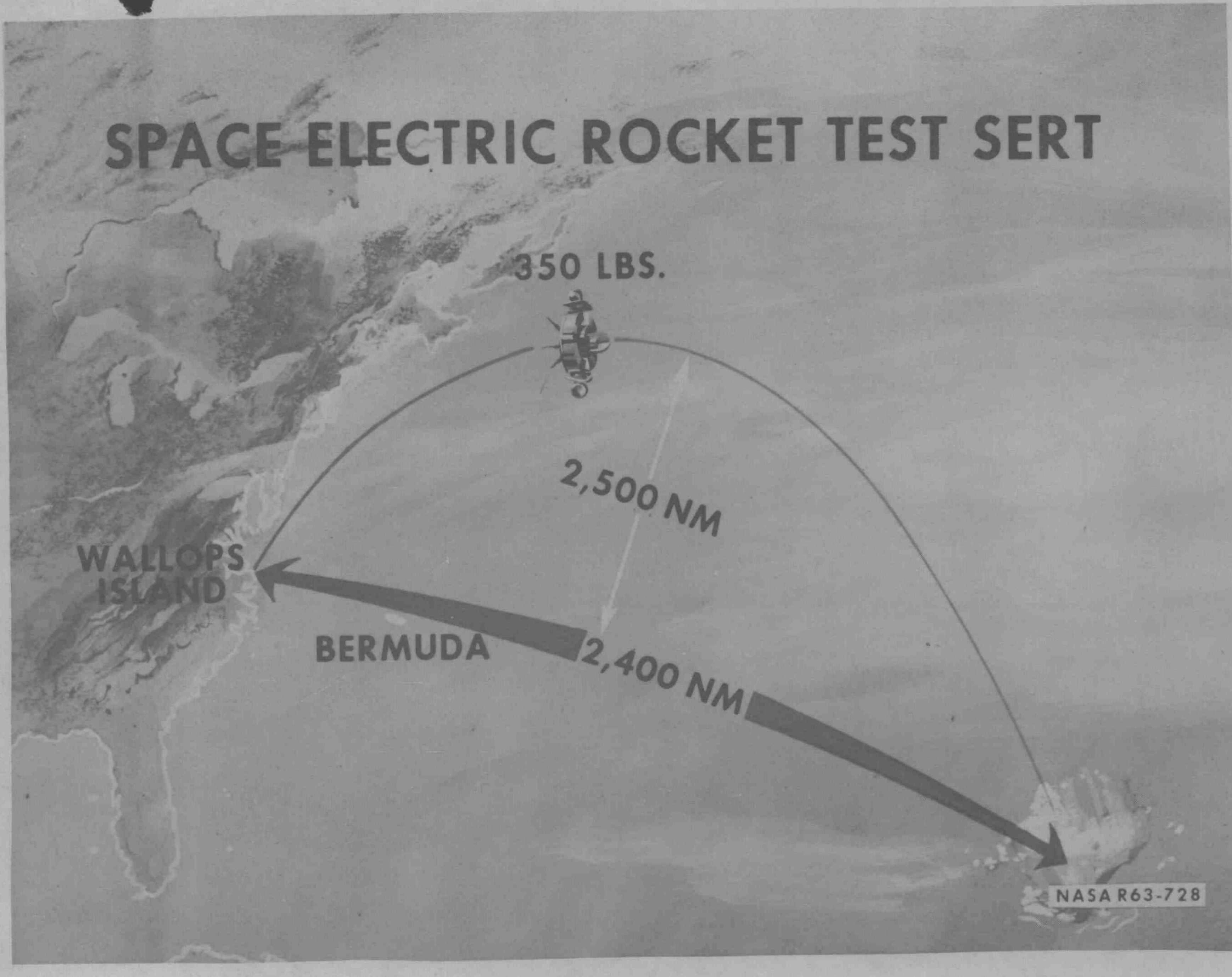
ELECTRIC ENGINE DEVELOPMENT

3 KW MODULE	30 KW MODULE	MEGAWATT CLUSTER



•BASIC DEVELOPMENT •SOLAR POWERED PROBE	•PROPULSION SYSTEM UTILIZING SNAP-8 ELECTRIC GENERATING SYSTEM	•LARGE VEHICLE PROPULSION

NASA R63-320


SPACE ELECTRIC ROCKET TEST SERT
350 LBS.
2,500 NM
WALLOPS ISLAND
BERMUDA
2,400 NM
NASA R63-728

Nuclear Rocket Program ART

PRINCIPAL WORK AREAS

- REACTORS
- NOZZLES
- CONTROLS AND INSTRUMENTATION
- TURBOPUMPS AND FLOW SYSTEMS
- SYSTEM STUDIES AND MISSION ANALYSIS
- ADVANCED CONCEPTS

R63-811