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INTRODUCTION

Mr. Chairman, Members of the Committee - I appreciate very much the opportunity to present to you the work being done and planned by the National Aeronautics and Space Administration and the Atomic Energy Commission to provide nuclear energy systems for space applications. Attached is a very complete statement describing this work; I would like first to briefly summarize the highlights of this work and, in particular, to describe the accomplishments of the past year.

It is, as you know, generally agreed that nuclear propulsion will be required for propelling large and heavy spacecraft to the high velocities that are required to reach distant space objectives. In addition, it is generally agreed that nuclear reactors will be used to provide the source of electrical energy in high powered, long life space applications. Radioisotope energy sources, in which heat is generated from the radiation emitted by these isotopes has already been used in space; four satellites launched by the Department of Defense since June, 1961, have used electricity generated from the heat provided by radioisotopes. There is now a growing interest and a growing list of requirements for these radioisotope electric generating systems in NASA as well as in the DOD. Assuming a continuing, active, space exploration program, nuclear reactor systems will also eventually be needed to supply larger amounts of electrical power to the spacecraft than is possible with isotopes. Nuclear reactors will also provide the source of energy needed to propel heavy spacecraft, including manned spacecraft, to high velocities. It is, therefore, important to maintain a strong technology development program in this area to provide options in undertaking advanced missions and in

deciding how best to accomplish future missions.

The past year has seen continuing progress in these nuclear system developments.

The first reactor powered electric generating system - the 500 watt SNAP-10A system - was launched on April 3, 1965, by the U. S Air Force for the AEC and operated perfectly in space for 43 days. The sudden shutdown of the system in space, after 552 orbits, has been duplicated on the ground and can be explained as a sequential failure of electrical components in the spacecraft; the reactor electric power system appears to have operated well. In fact, a SNAP-10A system, exactly like the one that was flown has been operating on the ground in a vacuum tank for over a year continuously. It is planned to shut that system down in March after 10,000 hours of continuous operation so it can be disassembled and examined. These tests - on the ground and in space - have clearly proven that nuclear systems can be successfully developed in space environmental simulation facilities in a manner similar to that used in developing all other space systems; they have shown that the system can be safely transported, checked out prior to launch, and flown. Most important, the tests have shown that the ground and space operation of these nuclear systems is the same. No new, unexpected, basic phenomena arise in space use of nuclear reactors.

At higher power levels, an experimental version of the SNAP-8 reactor operated on the ground for a total of 8300 hours at or above SNAP-8 power levels. Fuel material cracking that was encountered during the test is being thoroughly evaluated and corrective action is being planned.

Components of the SNAP-8 turboalternator system to convert the heat of the reactor to 35 kilowatts and, eventually, as high as 50 kilowatts of electric energy have operated for hundreds and some for thousands of hours. The SNAP-8 power conversion system has been assembled and is now being prepared for extended tests. Funds are being requested by the AEC and NASA to continue the development of the reactor and the power conversion systems.

Significant advances have also been made in the use of radioisotopes for generation of electric power. Radioisotope systems are now under development by the AEC at NASA's request for application to the NIMBUS satellite and for powering experiments that will be placed on the moon in the Apollo Lunar Surface Experiment Package (ALSEP) by the early Apollo astronauts. In addition, technological development is under way to extend the capability of isotope systems from the tens of watts required for NIMBUS and Apollo to several hundred watts for possible application in DOD missions and on into the kilowatts of power that we believe will eventually be required in the space program for a wide variety of missions. Work on isotope fuel and thermoelectric conversion as well as some thermionic and dynamic conversion concepts is being carried out by the AEC. In addition, work on very efficient gas turbine systems to convert the heat given off by the isotope to electrical energy is being conducted by NASA. The combination of all this work should provide a capability to extend the use of isotopes to as high as 10 kilowatts of electrical power. Indeed, a most significant development in isotope power systems has been the general recognition that these systems will have important space mission

applications at power levels up to about 10 kilowatts if the technology of the isotope fuel and the conversion equipment can be suitably advanced.

The work during the past year on nuclear rocket propulsion continued the successful accumulation of experimental data that has proven the high performance capabilities of these systems. Specific impulse of over 750 seconds has been experimentally achieved; this compares to the 425 to 450 second specific impulse of hydrogen-oxygen chemical propulsion. A single reactor has operated at power for over 60 minutes with full power operation for over 16 minutes. Examination of reactor parts and promising laboratory results point toward still higher specific impulse and substantially longer operating times. Reactors have been started, stopped, and restarted without difficulty. The wide, stable operating range of these systems has been demonstrated.

The reactor testing during the past years, combined with development of non-nuclear components, such as turbopumps, nozzles, and controls has culminated in a series of tests that is now under way on a full "breadboard" engine system that combines all of the major components that will be needed in a flight engine, although they are not arranged in a flight arrangement. It has now been experimentally proven that such a self-contained engine will start on its own energy and will go stably to power operation without supplying external energy to the system. By opening the valve to the pressurized hydrogen supply and properly controlling the power of the reactor in a wide variety of possible control modes, the turbopump speed can be increased to pump hydrogen into the reactor producing engine thrust.

Our development approach, emphasizing component and subsystem development combined with thorough system analysis work has been verified by the success of our test operations.

We have proven nuclear rockets to be feasible; we have proven their high performance capabilities; we have established a technology that did not exist before; we have provided a technological understanding of these highly efficient propulsion systems so that we can confidently proceed with the development of a large NERVA (Nuclear Engine for Rocket Vehicle Application) engine having a thrust of 200,000 to 250,000 pounds that our mission analyses indicate could perform all of the future space missions for which nuclear rockets would offer significant performance advantages. Funds to initiate the development of such a large engine are included in both the NASA and the AEC Fiscal Year 1967 budget requests. In addition, the NASA budget request includes funding for design of test stands that will be required to develop this engine and any nuclear rocket stage or propulsion module into which this engine would eventually fit.

NUCLEAR ROCKETS

The nuclear rocket program is managed by the joint AEC-NASA Space Nuclear Propulsion Office. This Office was established by NASA and the AEC in August, 1960, to carry out both agencies' responsibilities for nuclear rocket propulsion development. The program is, therefore, planned and conducted as a single effort. The following discussion describes this total technical program; it does not attempt to differentiate between the NASA and AEC portions although the agreements between the agencies do define the responsibilities of each.

INTRODUCTION

The past year can be described as a year of transition in the nuclear rocket program, a year in which emphasis transferred from the establishment of the technology of graphite nuclear rocket reactors and demonstration of their high performance capability and operating reliability, to emphasis on engine system technology and engine operating and performance characteristics. The breadboard engine system tests now under way are indicative of this transition. Continued work is still required on the nuclear rocket portions of the system to achieve extremely long life and high temperature and high power capability. However, we are now in a new phase of the program in which we are developing as detailed and thorough an understanding of the operation of the entire engine system as we now have of the reactor.

Therefore, this is a good time to take stock of what has been produced in the nuclear rocket program to date before we go on to discuss the possible applications of nuclear rockets, the more specific accomplishments of the past year and the plans for the future.

We have operated reactors for significant periods of time at powers of over a thousand million watts (1000 megawatts) and at temperatures over 4000°F -- with white-hot temperature in the reactor and temperatures of 400° below zero only inches away. This accomplishment has required an understanding of graphite far beyond what had been generally available in that black art. Methods had to be developed to protect graphite from chemical corrosion and erosion by the hydrogen propellant. In the last three years we have progressed from a time when we could test graphite fuel elements in electrically heated furnaces with hydrogen flowing through them for only five minutes at exit gas temperatures of over 4000°F until today when we have had fuel elements run for over an hour and up to almost two hours at the same condition. The methods of designing nuclear rocket reactors have been defined; analytical methods have been developed to predict their operating characteristics under all conditions. In short, we have advanced a technical field from scratch to thorough understanding and brought almost all of the required basic reactor technology along in that time.

In addition, during this period we have established for the country a test site with substantial facilities in which nuclear rocket systems can be tested under required power conditions. Two reactor test facilities and one engine test stand are now available. Large radiation shielded facilities are available for remote assembly and disassembly operations. In this year's NASA budget submission, we are requesting additional funds for design of a facility consisting of two additional stands that would be used for engine and, eventually, stage testing of nuclear rocket systems. It is important in this regard to recognize the unique test capabilities that we have established at this Nuclear

Rocket Development Station located in Nevada. This nuclear rocket test installation is the only such capability in the United States and, as far as we know, anywhere in the world. Chemical rocket facilities are generally distributed throughout the country at all of the contractors' sites involved in that work. However, those facilities are adequate only for non-nuclear test work. They are used in our program for operations that do not involve the generation of nuclear power such as in component development and cold flow engine tests. But the country's capability for power testing of nuclear rocket systems is provided only at the Nevada Nuclear Rocket Development Station. Since the nuclear rocket program started, therefore, a significant facility capability has been established, and our current budget request provides for growth of the country's facilities in this area.

In addition, we have established a manpower capability - a resource of scientists, engineers, and technicians - well versed in the disciplines involved in nuclear rocketry. The experience of aerodynamicists, metallurgists, mechanical, civil, electrical, and chemical engineers has been broadened so that their scope and competence now includes nuclear physics, nuclear materials, radiation effects, and, generally, nuclear phenomena. They are all now deeply involved in the broader evaluation of their equipment in extreme environments, including nuclear radiation fields and hot and cold temperature. This resource of manpower is available in more than 37 government, industry, and

university organizations that are directly participating in the nuclear rocket program. In addition, there are many other engineers, scientists, technicians, and production people in the many vendor and lower tier subcontract levels involved in the program. The capability that has been established also includes the equipment and facilities at various contractor and government locations that provide for the country an ability to work in this area that was not previously available.

We have also, during this time, begun to define specific process and product improvements that were required by our program and that have imposed high demands on the ingenuity and initiative of industry. These improvements may also offer utility in other areas not directly associated with the nuclear rocket program or, for that matter, with either the space or atomic energy programs. These items vary from a portable instrument to indicate cracks in tubing of less than 1/8 inch diameter to a high-temperature liner in a smoking pipe.

We have indeed come a long way since 1955 to bring nuclear rockets from the idea stage to reality, from the paper promises of high specific impulse with reasonable weights to an experimental verification that now permits the already achieved performance to serve as a basis for future mission planning. But much still remains to be done to provide the systems that will eventually be needed in the space program.

The goal of the nuclear rocket program is to provide an advance in space propulsion performance for missions following Apollo. Since the exact course of the space program a decade or two from now cannot be

firmly specified, one of the objectives in our technology development programs must be versatility in mission application. An advanced propulsion system should be applicable to a wide spectrum of missions; a space propulsion stage should be useful in vehicles configured for a variety of missions. The nuclear rocket, used in an appropriate propulsion module, can offer such mission versatility. It is as a result of our application studies, which I will discuss first, that we have established the versatile mission applicability of nuclear rockets, and defined the nuclear rocket engine that will be needed for future space missions. The AEC and NASA budget requests that are now before the Congress contain an increment of funding to initiate development of that engine.

MISSION APPLICATIONS

Whatever route the space program follows beyond Apollo, there will be high-energy, high-payload missions. Nuclear rockets offer substantial advantages in all such missions, as has been described in previous years' testimony. We have, during this past year, made further studies of the nuclear rocket propulsion module which is shown in figure 1 (NPO 65-1933). It consists of a 200,000 to 250,000 pound thrust engine with necessary propellant tankage and stage subsystems. As I mentioned in the hearings conducted by this Committee last August on possible future space missions, this module may serve as both an orbital-assembly building block and as a Saturn V third stage.

Figure 2 (NPO 65-1874) illustrates the versatility of such a module. These various applications use the same basic propulsion module and would require development of only one basic set of subsystems: one engine

model, one set of stage systems, one basic tank configuration. Our studies indicate that even though we would use the same hardware for all of these various missions, significant performance advantages would be provided by nuclear rockets; the payload would be increased significantly for manned planetary landings or flybys, manned lunar missions, and unmanned deep-space probes. Thus, nuclear rockets can play an important role in a number of the alternate routes which the future space program may take.

Manned Planetary Missions

The manned Mars landing mission has received major emphasis in studying mission applications of nuclear rockets because of the high energy and payload requirements of that mission and its importance as a possible future space objective. Propulsion requirements for this mission are based on mission calculations such as illustrated in figure 3 (NPO 65-2197). Initial weight of the spacecraft for such a mission established in Earth orbit is plotted against launch year for two mission modes: (1) the straightforward, all-propulsive mode in which nuclear rocket propulsion is used for Earth-orbit departure, Mars-orbit establishment and Mars-orbit departure, and (2) the Mars aerocapture mode, in which atmospheric braking at Mars is used to decelerate the spacecraft into the Mars orbit. The latter is representative of mission modes which utilize special techniques or trajectories to reduce the energy requirements of the mission and, thereby, the total space vehicle weight. Another such mission mode is the Venus-swingby mode of Mars round-trips. The

figure shows that variations from one mode to another and over the full cycle of launch opportunities result in a range of initial space vehicle weights required in Earth orbit of 1 to 5 million pounds with nuclear rocket propulsion. Chemically propelled spacecraft would weigh two to four times as much, so millions of pounds of additional weight would have to be carried to Earth orbit if the less efficient space propulsion systems were used.

In addition to these gross mission calculations, detailed analysis has been conducted on the effect of nuclear rocket engine size or thrust on the spacecraft weights required in Earth orbit. Figures 4 and 5 (NPO 65-15885, Rev. 2/1/66, and 15886, Rev. 2/1/66) illustrate some of the results of this analysis for the manned Mars missions. Data are presented for 1978, the hardest year for accomplishment of the manned planetary mission, and for 1986, an easy year. These data were computed for the all-propulsive mode of mission accomplishment.

In figure 4, which is for the 1978 planetary opportunity, is shown the effect of engine thrust on the weight that would be required in Earth orbit to perform the mission and on the operating time of the nuclear engines that would propel the vehicle out of Earth orbit. It was assumed in these calculations that the propulsion out of Earth orbit would be provided by a cluster of propulsion modules. Therefore, data are presented for clusters of two, three, and four engines. It is assumed that single engines of the same size would be used in the second stage to enter the orbit at Mars and in the third stage to leave the Mars orbit. It can be seen

from this figure that if the thrust of the individual engine is too low, below approximately 150,000 pounds, the weight required in Earth orbit to perform the mission would rise rapidly. As the engine thrust increases, the weight required in Earth orbit is almost constant over a wide range of thrust. Therefore, in looking toward such a mission that is a long way off in the future and that involves many assumptions and uncertainties concerning the payload required, the number of men that will make up the crew, the radiation shielding required, etc., it is necessary to allow for a performance margin. This is done by working on engines having thrust levels significantly greater than the minimum thrust value. Further, only minor weight increases result from doing so.

The vertical band in figure 4 shows that an engine in the thrust range of 200,000 to 250,000 pounds, which is a good compromise value from many considerations, would adequately perform this mission. It is also important to note that as the power increases, for a fixed number of engines in a cluster, the operating time required for the engine decreases. Such a reduction in operating time on the engine may permit an increase in the specific impulse, which would further reduce the weight required in Earth orbit to perform the mission below the values shown here.

Figure 5 shows similar results for 1986. Here again, the important point is that at the higher power levels the weight required in Earth orbit to perform the mission is approximately constant so that the same engines as those indicated on the previous chart, shown again by the vertical band, could also perform the mission in this easy year.

It is, therefore, apparent that a single propulsion system could provide the thrust that would be needed to perform a manned Mars mission at all planetary opportunities - in the easy or hard years. Furthermore, with an engine thrust level of approximately 200,000 to 250,000 pounds, margin would be provided to compensate for and tolerate any uncertainties that might arise in the performance of the mission.

A stage module of about 200,000 to 250,000 pounds liquid hydrogen capacity, shown in figure 1, could serve as the space-vehicle building block. Uses of the module would range from a single-module, minimum-propellant stage for the Mars departure phase in a favorable year to a three or four-module cluster for Earth departure in an unfavorable year. For example, in 1986 the Mars-departure vehicle gross weight could be as little as 350,000 pounds. Although 200,000 to 250,000 pounds of thrust would be higher than the optimum value, only a small performance penalty would result. At the other extreme cited, when the Earth departure gross weight may be 5 million pounds, the compromise thrust level is high enough to keep the number of modules in the Earth-departure cluster down to a reasonable number (3 or 4).

In spite of the emphasis on Mars, the versatility of the proposed nuclear-rocket systems should be recognized. A vehicle configured, as shown in figure 6 (NPO 65-1875) to perform Mars landing missions in all or most launch opportunities would be adequate for Venus stopovers and, perhaps, manned missions to other destinations such as some of the asteroids. This mission flexibility would be particularly important

if interest in Mars should broaden into a general interest in manned solar system exploration.

Another manned planetary mission which may find a place in the future space program is a flyby of Mars or Venus. Flyby missions may precede manned landings on these planets. A single nuclear-rocket propulsion module, as illustrated in figure 7 (NPO 65-1876), could perform this mission with rendezvous in Earth orbit of one or two Saturn V payloads. The initial Earth orbital weight would be 400,000 to 600,000 pounds.

Saturn V Third-Stage Applications

As illustrated in figure 2, the same basic propulsion module (engine/stage combination) can serve as a third stage on Saturn V for direct flights to the moon or other solar system destinations. Potential gains in lunar missions, including manned direct-landing capability or a 65% increase in landed cargo per launch, have been described in the past. Another important point is that this third stage could be in many respects the same as the orbital-assembly module which would evolve for manned planetary missions. The tank sections and stage subsystems would be basically the same; the 200,000 to 250,000 pound thrust engine would be identical. Changes in insulation and some design features would be permitted by the less severe hydrogen storage requirements of the third stage Saturn V application.

The same third stage would be useful in heavy-payload or very-high-energy unmanned space missions, such as Mars or Venus orbiters, planetary probes, and close-in solar probes, as illustrated in figure 8 (RN 64-2076,

Rev. 8/18/65). In comparison to all-chemical Saturn V vehicles, payloads would be increased by 70-100 per cent by use of the nuclear third stage.

Thus, a nuclear third stage would extend the operational capability and useful life of the Saturn V for a large spectrum of unmanned solar system missions and the same nuclear propulsion module would give the country a capability for efficiently performing manned planetary missions.

PROGRAM DESCRIPTION AND OVERALL STATUS

The objective of the nuclear rocket technology program is to provide the country with the ability to satisfy these various mission requirements with a high specific impulse, reliable, multi-purpose nuclear propulsion system.

The introduction of a new propulsion system into space missions requires a solid foundation of technology and advanced development prior to the decision to use it in a vehicle or mission. The nuclear rocket engine and vehicle programs are being guided so that such decisions can be made with maximum confidence. To achieve this advance in propulsion, work is underway to establish the basic technology for such systems through the several elements of the nuclear rocket program, listed in figure 9 (NPO 65-1913).

Major emphasis has been and continues to be on the relatively near-at-hand graphite reactors and engines (KIWI-NERVA Graphite Reactor and Engine Technology) including longer term efforts (Phoebus) which will provide the basis for improving the performance of such systems beyond the near term goals. In addition, since nuclear rockets are a relatively new field of propulsion holding promise of long term usefulness, we have

been exploring other concepts (solid fuel element tungsten reactors and cavity reactors) which hold the theoretical promise of higher performance. In examining this spectrum of reactor possibilities it is important to keep in mind that the performance of graphite systems is well substantiated by experimental results, but the performance of advanced concepts such as cavity reactor systems is based largely on theory or assumptions with little or no experimental basis.

While the success of any nuclear rocket system depends heavily on nuclear reactor technology, advancement must be made in other areas also. The technologies of non-reactor engine components are covered in the activities of Item III listed on this figure.

The application studies, such as those discussed above, are used to guide the several elements of the technology program toward their most profitable goals. Based on these application studies, the thrust level of the nuclear rocket engine we will need to perform future missions has been determined to be 200,000 to 250,000 pounds, corresponding to about 4000 to 5000 megawatts of reactor thermal power. The graphite reactor and engine system technology, which is being carried out on 1100 megawatt systems, giving a thrust of about 55,000 pounds, has progressed to the point at which it is possible to proceed with initiation of development of this large (200,000 to 250,000 pound thrust) NERVA engine in FY 1967. This represents a logical technical progression from the technology development work that has been performed and the capability achieved in the program to date. The following discussion

describes the overall status of our technology work and how it contributes to the NERVA engine development.

Last year, when we reviewed the status of the nuclear rocket program, I described the successful reactor tests, listed in figure 10 (NPO 65-2079a), that we had conducted in 1964 and early in 1965. I was able to point to the successful operation of these three reactors (KIWI and NERVA NRX reactors) having a design power of about 1000 megawatts for a total of almost 15 minutes at high power and at temperatures equivalent to specific impulse of about 750 seconds. This successful reactor power operation continued during the past year with the testing of the NERVA NRX-A3 reactor and the Phoebus 1A reactor (also listed in figure 10).

The growth of operating time at about design power is shown in the next figure 11 (NPO 65-1927). You will recall that the first nuclear rocket reactor tests were run in 1959 at low power. The important feature of the data presented in this figure is the growth in full power testing since we resumed testing in 1964, after a 1-½ year suspension of power testing during which we conducted extensive design analysis and reactor component, subsystem, and full reactor system development work. The NRX-A3 and Phoebus 1A testing in 1965 increased our full power operating time by 27 minutes. These operating times do not represent an experimental limit of full power endurance for the reactors after tested, there is evidence that both were capable of longer operating times.

With reactor performance firmly established and demonstrated, we are able to devote increased attention and emphasis to the development of non-reactor components and subsystems and to their incorporation into

an experimental nuclear engine system. The engine system technology program is using the 1100 megawatt NERVA NRX reactor in 55,000 pound thrust experimental engine systems, to determine the allowable range of startup characteristics, to explore performance characteristics, engine operating limits and component interactions throughout the operating range, to evaluate various control concepts, and generally to develop design methods.

A significant step in this direction is the series of test operations on the NERVA breadboard engine systems (NRX/EST) shown in figure 12 (NPO 65-1915), which was started in December. The first power startups of this system on February 3 were a major milestone in advanced propulsion.

This test series is being carried out using a breadboard arrangement of a NERVA reactor, a NERVA turbopump and a jet nozzle containing a hot bleed port to provide hot gas drawn from the reactor exhaust to drive the turbine. For the first time we are accumulating data on the behavior of a complete system where fission energy is produced and the power to drive the turbine is provided by the system itself rather than from the test facility.

Beyond the NRX/EST tests, several tests that are listed in figure 13 (NPO 65-2079) are now planned. The NRX/EST test operations are enabling us to verify and improve our analytical predictions of nuclear engine behavior and are providing an improved basis for proceeding toward the XE engine, the ground test of an experimental nuclear engine system. The XE engine tests noted on the schedule chart are the final ground system tests in the 1,000 megawatt technology portion of our engine program, incorporating the features essential to the investigation of component interaction

and system operation in a test facility such as would be used in flight system developments.

Our technology development work on the behavior of these small size reactors and experimental engines provides directly applicable design and operating information for the higher power NERVA engine which will also be based on graphite reactors but of nominal 5000 megawatts power level. This technology is very similar to that of the small reactors and will be proven in the Phoebus reactor program. The development of hydrogen feed systems and nozzles adequate for ground testing of the higher power reactor (called Phoebus 2) is well underway based on our technology development work. These components will be used in the Phoebus 2 tests listed in figure 13.

As I pointed out earlier, we propose to initiate development of the nuclear engine of this 4000 to 5000 megawatt power which will have a thrust of 200,000 to 250,000 pounds in FY 1967. In addition, we will continue our studies on the fundamental aspects of the behavior of the materials and components to add to the catalog of data gathered in previous years which now serves us well in the design and development of the high powered nuclear engine. Design studies of engine test stands capable of testing this high powered engine under a simulated altitude environment are underway. These test stands will also be used for eventual development testing of the full propulsion module. Our vehicle technology work has emphasized propulsion module studies.

I will now discuss in more detail these elements of the nuclear rocket program to describe the specific accomplishments of this past

year, the work that is still required, our plans for the next year, and our longer range view of this nuclear rocket program effort. We will show in more detail how our technology work contributes to the NERVA engine development.

GRAPHITE REACTOR TECHNOLOGY

As indicated earlier, continued progress was made in 1965 in extending the demonstrated capability of the reactor and in improving our understanding of its behavior. The total operating time at or near design power was increased from about 14 minutes to more than 40 minutes in two reactor tests, the NRX-A3 and Phoebus 1A.

NRX-A3 Test Series

The first of these tests, the NRX-A3, had the objectives of achieving long operating time, approximately 20 minutes, at design power in two cycles and performing a series of reduced power mapping and control experiments. Figure 14 (NPO 65-1961) shows the overall results of this testing.

During the first cycle of power operation the reactor was shut down after about three minutes at full power because of a spurious signal which indicated a turbine overspeed. The second run went smoothly, adding 13 minutes more of operation at design power for a total of 16-1/2 minutes at design power, the longest duration which has been achieved on a single reactor in the nuclear rocket program to the present time. The NRX-A3 reactor was operated through a series of operating paths and power holds

to determine its behavior as it approached the various design or operating constraints we have placed on the system. During these runs the reactor was operated in a variety of control modes including one in which the reactor was operated with the reactor control drums in a fixed position, using controlled variation of the hydrogen coolant flow to vary the reactor power. The reactor was also operated while alternately controlling temperature, power, or flow at a given value while varying the other reactor parameters. Throughout the 45 minutes of continuous operation required for these reduced power mapping and control tests, the reactor operated in a stable fashion adjusting rapidly to variations in the demand for power, temperature, or flow.

In this reactor test, as in all of our other reactor tests, the NRX-A3 propellant feed system, turbine drive system, and reactor power were independently controlled and not close-coupled as they would be in a nuclear engine where the effect of a change in reactor flow rate, for example, is felt in the pressure and temperature of gas available to drive the turbine.

Phoebus Reactors

This past year also marked the first reactor tests (Phoebus 1A) in the Phoebus advanced graphite reactor technology effort. The relationship between the Phoebus 1, Phoebus 2, and KIWI or NERVA reactors can be seen in figure 15 (NPO 66-367). The differences in design between the small size KIWI/NRX and Phoebus 1 reactors and the larger Phoebus 2 are all in the direction of performance improvements. The larger diameter

reactor core gives the designer a little more flexibility in achieving both improved performance and increased reliability.

You will note that the design objectives of the Phoebus 2 reactor are more than simply to scale up the KIWI/NRX reactors; they include higher exit gas temperatures (higher specific impulse) and greater power density (lower reactor and engine weight). These improvements translate directly into increased mission capability. The increase in temperature from 4100°R to 4800°R, for example, combined with some design changes corresponds to an increase of approximately 75 seconds of specific impulse. This specific impulse increase applied to a spacecraft leaving Earth for Mars would allow a reduction of about 375,000 pounds in the weight of the spacecraft below the weight required for the equivalent specific impulse of 760 seconds obtained from the KIWI/NRX reactors. This 75 second specific impulse increase, we believe, is well within the values that can be achieved in the Phoebus reactor development.

The three Phoebus 1 tests that are scheduled put us in a much better position to assure successful design of the Phoebus 2 reactors. The smaller size Phoebus 1 is an economical test device to verify design or process improvements which appear promising for incorporation into the Phoebus 2 reactors. As indicated in figure 15, fuel element modifications which promise much higher temperatures and longer operating durations are a primary test objective in the Phoebus 1 reactors. These modifications, if proven successful, can be used directly in the Phoebus 2 reactors. Higher local power density operation will also be tested in Phoebus 1

size reactors, and will give us an early experimental indication of what power density could be attained in Phoebus 2 reactors.

The Phoebus 1A reactor, tested last June, is shown in figure 16 (NPO 65-2143). It had the objective of testing several experimental reactor core design features. This reactor was able to complete only one of the three ten-minute runs at design power originally intended for it because a facility hydrogen tank ran dry near the end of the first run and the reactor overheated. A liquid level gauge indicated an ample supply of liquid hydrogen in the propellant tanks when, in fact, there was none. This erroneous liquid level indication has been determined to be the result of an irradiation effect on the gauge used to determine liquid level in the tank. This gauge has been replaced by one which has successfully passed a series of environmental tests, including radiation in excess of that which it will undergo in the test cell. We have, in addition, made a thorough review of present test practices and of our facilities. From this review a number of changes have been indicated and have been made both to the test facility and to the operating procedures to minimize the possibility of such an incident occurring again.

When the core overheated it suffered damage which obscured many of the effects of the ten-minute operation at power. We were able to make qualitative determinations of the value of several of the experimental design features, however. Operation during the ten-minute design power period was excellent, and reactor operating temperatures for the

ten-minute steady-state run were the highest yet achieved.

Test facility modifications are being made to allow testing of the higher power Phoebus 2 reactors. These modifications will be available in time for the next Phoebus 1 reactor test in Test Cell C this summer. These improvements include additional liquid hydrogen storage capacity (1,000,000 gallons) and an emergency pressurized liquid hydrogen storage dewar which can supply propellant in the event any mishap should occur to the turbopump feed system that is normally used. A photograph of Test Cell C showing the increased liquid hydrogen storage is shown in figure 17 (NPO 66-612).

The increased capability and operational flexibility of the Test Cell C will be fully utilized by consolidating all our future reactor test activities in that Test Cell. After tests of the NERVA reactor (NRX-A5) to be conducted next spring, we will close Test Cell A and conduct all of our reactor operations in Test Cell C. This will indeed complicate our scheduling; however, we believe that we will be able to cope with that problem, and the reduction in costs that would be achievable justifies the added complication of conducting operations in a single cell.

Reactor Fuel Element Development

Reactor performance is related in a major way, to the performance of the fuel elements within which nuclear fission energy is generated. The best measure of the marked progress which has been made in extending fuel element duration and simultaneously raising operating temperatures in the last few years is the increasingly ambitious goals we have

established in the reactor test series now underway. Because of the inevitable lag between laboratory accomplishments in development and the incorporation of that development into the design of a reactor, however, many of the reactor test goals have already been exceeded by laboratory results. The improved performance which has been achieved in the past few years may be seen in figure 18 (NPO 66-368), which relates reactor and laboratory test performance of fuel elements to mission and development requirements.

Successful sixty-minute test runs in our electrically heated, hydrogen corrosion test furnaces are now as common as ten-minute runs were only two to three years ago. Furthermore, the results of recent test runs in these furnaces indicate a potential for higher temperature operation than the 4800°R noted earlier. Our fuel element development people at Los Alamos, Westinghouse, and the Y-12 Plant of Oak Ridge deserve much credit for these accomplishments.

Future Reactor Tests

As shown in the schedule figure 13 (NPO 65-2079), the reactor test program in the coming twelve to fifteen months includes four more reactor tests, the Phoebus 1B and 1C by LASL and the NRX-A5 and A-6 by WANL. The NRX-A5 and A-6 objectives include the demonstration of increased operating duration and the evaluation of mechanical design improvements. The Phoebus 1B objective will be to demonstrate an average increase in power density of 40 per cent, but certain sections of the reactor core are designed so that they will be operating at thermal stresses comparable

to those expected in the larger, higher power Phoebus 2 reactors; this information should give us a better understanding of the design of the Phoebus 2 reactor to obtain its best performance and reliability.

Components for Higher Power Reactor Ground Tests

The step-up in power and temperature represented by the Phoebus 2 reactor designs requires that we develop turbopumps and nozzles to meet these advanced test conditions. The development of a feed system for ground testing the large Phoebus reactors has been underway for the past three years. Figure 19 (NPO 66-327) is a photo of this feed system, known as the NFS-3a. It is based on a modification of the turbopump system originally developed and used for the KIWI and NRX reactor tests at NRDS. In the NFS-3a two of these turbopump feed systems are operated in parallel to provide the higher flow rates required for the Phoebus 2 power level. In addition, the pumps are being developed to a higher pressure capability than was required in the KIWI and NRX tests. A single turbopump similar to this is installed at Test Cell C and using only one of the parallel pumps will be used for the Phoebus 1B test. This feed system has been successfully tested at up to 30,000 rpm, although we are at present having bearing problems at the higher speeds we will have to achieve.

Since our hearings last year, we have selected Aerojet-General Corporation through a competitive proposal evaluation to design, develop and fabricate a nozzle for the Phoebus 2 tests. The nozzle design chosen for Phoebus 2 reactor testing is similar in design approach to the U-tube

nozzle which has been successfully used for all of the NERVA NRX reactor tests. The Phoebus 2 nozzle, however, will be fabricated from Hastelloy-X instead of stainless steel to withstand the higher heat flux and temperatures of the Phoebus tests. The biggest problem in developing this nozzle is its large size. A comparison of the Phoebus 2 nozzle size with the nozzle used on the NRX-A3 reactor is shown in figure 20 (NPO 65-2107). The forgings for the nozzle pressure vessel, figure 21 (NPO 66-346), are the largest Hastelloy-X forgings ever made. The ones shown in the photo weigh over six tons each. The work we do on this nozzle will lead to a bleed port flight nozzle for higher power engines in the same way that the NRX-A nozzle led to the EST and XE nozzles. Here is one of many examples of the forward push of our program on this country's production process technology.

NERVA ENGINE TECHNOLOGY

During this past year we have increased our emphasis on the behavior of nuclear rocket engines systems. A number of related test events have demonstrated the nuclear rocket's ability to start smoothly, operate as commanded and perform stably over a wide operating range. These test events include the Engine System Test (NRX/EST) series, tests on cold-flow engines, and the NRX-A3 mapping experiments.

I would like to review quickly the essential features of the nuclear rocket engine system. Figure 22 (R-63-1294) is a schematic drawing of the nuclear rocket engine. After the propellant is pumped from the stage propellant tank through the nozzle wall and the reflector to cool those

components, it is turned around and flows through the hot fuel elements of the reactor core and out the jet nozzle. An important point to note is that a small amount of hot hydrogen is bled from the reactor exhaust through a hot bleed port in the nozzle wall and is mixed with cold hydrogen to a desired temperature. This hydrogen is then used to drive the turbine which drives the hydrogen feed pump. The turbine drive gas is expelled through the auxiliary nozzles shown. In such an engine system, a change in any of the controlling parameters may cause a corresponding change in another operating parameter. For example, a reduction in the flow rate will cause reactor power to drop because of the negative neutronic effect of the lower pressure or smaller amount of hydrogen in the reactor. This in turn causes a drop in temperature of the exit hydrogen gas so that the hydrogen to drive the turbine is lower in temperature.

Because there are many such complex interactions, the engine system work is of great importance in establishing nuclear rocket technology. The goal of this work is not only to assemble the necessary components and find a way to make the resulting engine operate to produce thrust. It is to thoroughly understand the way each component in the engine will operate under any given conditions, to have a clear outline of the limits under which engine operation is entirely satisfactory, and to know the margin which exists between normal and abnormal operation.

Although we have been working towards an understanding of engine behavior for some time, the Engine Systems Test (NRX/EST) series being carried out is the first operation of a powered engine assembly as a

self contained, self sustaining controlled system with no external energy assist. It uses the hot bleed hydrogen to drive its own turbopump which pumps hydrogen from a storage tank into the reactor. A photograph of the NRX/EST is shown in figure 12 (NPO 65-1915). A comparison of the NRX/EST configuration with earlier reactor test configurations is shown in figure 23 (NPO 65-2117a) and 24 (NPO 65-2117b). This breadboard engine is basically a modified NRX reactor test car having a NERVA turbopump and a NERVA jet nozzle containing a hot bleed port to provide gas to drive the turbine. The main differences between this system and that of the actual engine system are that the pump is not in its flight engine location (it is located in the closed compartment at the left end of the test car), the engine fires upward rather than downward, and the exhaust gases discharge into the atmosphere rather than into an altitude simulation (vacuum) duct. The engine operating information obtained during these tests is, however, indicative of and directly applicable to that of the actual engine system.

We have completed the first series of the NERVA Reactor Experiment/ Engine System Test (NRX/EST) power tests. The purpose of this test series was to demonstrate feasibility of engine system bootstrap start up, that is, start up and acceleration of the turbopump using as energy sources; reactor power, heat stored within the reactor, and the pressure of the stored liquid hydrogen. These start up tests were limited to approximately 1/3 full power. In addition to start up investigations, controls experiments were conducted at partial power to investigate dynamic response and alternate control systems.

The NRX/EST start up experiments to intermediate power were conducted on two separate days, February 3, 1966, which was the first time a nuclear rocket engine operated and eight days later on February 11, 1966. Two days of testing were needed because the liquid hydrogen storage capacity at the test cell was insufficient to conduct all the tests on one day.

On February 3, two start ups were conducted. The first start demonstrated bootstrap capability with normal initial conditions. In addition, the temperature control system was tested at partial power. The peak operating condition during this run was 440 megawatts at an exit gas temperature of 2550°R. The second run was conducted to demonstrate feasibility of starting the engine system after reactor components had been cooled with cold hydrogen. This test proved that the engine system could be started without using heat stored within the reactor; therefore, there is a wide range of initial temperature conditions (including those that might arise from space storage) under which satisfactory engine start up can be obtained.

Eight days later, after replenishing the liquid hydrogen supply, the NRX/EST was restarted three additional times. The first start demonstrated a bootstrap without moving the reactor control drums. This start showed a potential control simplification by using the engine pressure control system to control reactor power during the start up. The second start up was conducted with a lower liquid hydrogen supply pressure, more nearly approximating the pressure in a flight type tank. The start was terminated before steady state operation was reached because a test parameter limit was being approached in this breadboard system configuration. This type of start up

will be re-attempted. The third start up using nominal initial conditions was conducted to perform additional dynamic tests of the control system and to test an alternate reactor control system.

The NRX/EST operated at power range from 200 to 440 megawatts and at exit temperatures ranging from 2000°R to 2500°R during all of these intermediate power tests. The operating time at these power levels on February 3 was about 24 minutes and on February 11, 30 minutes for a total operating time of 54 minutes. During this operation, the engine was providing thrust at an equivalent space specific impulse of 520 to 590 seconds as compared to advanced chemical rocket engine specific impulse of 420 seconds. At full power and full temperature conditions which are planned for this breadboard nuclear engine and which have already been run in reactor tests, specific impulse values of over 750 seconds are achievable.

Figure 25 (NPO 64-669) shows the hydrogen feed system developed by Aerojet for the EST tests. This feed system uses a centrifugal pump designed to operate at 27,000 rpm, although the full power EST conditions require only 22,000 rpm. At 22,000 rpm the pump delivers 75 pounds per second of liquid hydrogen at over 900 pounds pressure.

The nozzle used on the EST engine is the basic Aerojet designed U-tube nozzle similar to the ones which have been used in the earlier NRX-A2 and A-3 reactor tests. This EST nozzle, however, is the

first to have a hot bleed port (figure 26, NPO 66-328) to allow withdrawal of hot gas from the nozzle chamber to drive the turbine.

The Engine System Test is the most dramatic and important of the steps taken to date in achieving a thorough understanding of engine operation. It was, however, preceded by mapping tests on all key components, by a great deal of analytical work, and by more than forty cold flow tests on cold flow engines at the Lewis Research Center and at Aerojet-General's plant in Sacramento. Cold flow engines are nuclear rocket engines which have no fissionable uranium in the reactor so that no power can be generated. The only energy available is, therefore, the heat picked up by the cold hydrogen as it flows through the ambient or atmospheric temperature materials of the engine. Tests using cold flow engines, however, can simulate the behavior of a real nuclear engine through the first several seconds of startup. This is a critical stage, when the possibility of hydrodynamic oscillations is greatest, and when the energy available in the engine to bootstrap (self start) the pump is at its lowest. Because cold flow engines are long lived and do not become radioactive, we are able to operate these tests fairly frequently and use the same basic equipment repeatedly.

More than 26 runs were made at the Lewis Plumbrook Facility in the test configuration shown in figure 27 (NPO 65-2128). More than 20 runs were made at Aerojet in the Cold Flow Development Test System (CFDTS) shown in figure 28 (NPO 65-1924). The work at the two facilities has been complementary with the Lewis program concentrating on engine

behavior using an axial flow pump, and Aerojet on engine behavior using the NERVA centrifugal pump.

The overall findings of the cold flow engine tests are that the nuclear engine is stable over wide operating limits during startup and can bootstrap (self start) under a wide range of conditions. They have provided important data on the behavior of the two systems using the different pumps which will aid in the eventual selection and design of a pump for the 200,000 to 250,000 pound thrust NERVA engine. Analytical models which describe the behavior of the engine with no power added have been developed. Methods of introducing liquid hydrogen to the pump have been developed which allow the engine piping to be chilled down to near the eventual operating temperature without causing oscillations.

Data from the Aerojet CFDTS were used directly to determine the useful range of test parameters for the EST test. An example of how these data were used is shown in figure 29 (NPO 65-2048) where the effect of tank pressure on the ability of the cold flow engine to bootstrap start is indicated. From data like these we were able to conclude that it was feasible to bootstrap the EST reactor against the atmospheric turbine backpressure which was present during the EST operations in our reactor Test Cell A. The EST cold flow tests have matched well with the results predicted using the CFDTS data and the EST power tests of February 3 indicated satisfactory bootstrap starts for these engines.

The series of mapping experiments carried out in NRX-A3 were described earlier in the Graphite Reactor Technology section. These

tests were important in that they treated the reactor as an engine component which might find itself subject to any of a variety of conditions; low flow and high power, high flow and low power, and many intermediate conditions. These data assured us that the tests planned for EST would not bring the reactor into an area which might cause it to malfunction in any way.

While the combination of analysis, cold flow engine, and EST engine system testing has provided a good understanding of the hot bleed nuclear rocket engine, the Ground Experimental Engine (the XE engine) which will be tested starting early in 1967 will provide further systems data and will evaluate the test facility technology as well as of component and system operation. Figure 30 (NPO 65-1926) is a drawing of the engine installed in our Engine Test Stand #1 (ETS-1) in which our first downfiring tests will be conducted.

The XE engine will use flight type components wherever the component characteristics would affect the system operation. Where they will not, such as in the pneumatic gas system of the engine, we will use facility type components. The flight type components which will be used in this engine include the nozzle, turbopump, and controls. We have a large backlog of component test data on these and are confident of their performance on the XE engine. In order to avoid having to radiation harden all engine components, an external shield will be added at the top of the XE engine to lower the radiation dose received to a level which can be tolerated. The XE engine will be tested in ETS-1, as shown in this

drawing. Cold flow testing of this XE engine is scheduled to begin late in 1966 and power testing early in calendar year 1967.

It has been our experience that the development and construction of facilities to test components is sometimes as difficult as the development of the component itself. This photograph (figure 31, NPO 65-1922) illustrates the size of the exhaust duct that is required for ETS-1 operation. The fabrication of this duct has turned out to be an extremely difficult technology item in itself. The high temperature hydrogen exhaust gases from the engine are directed away from the test stand by this duct so that these gases will not be a safety hazard. Pumping the duct down to below atmospheric pressure before the engine is started produces stable flow in the jet nozzle at an early stage in the start sequence.

Another area of concern in the development of the NERVA engine has been the need for remote assembly and disassembly. We have concluded that a modular approach which would allow us to remotely connect and disconnect major subassemblies is more practical than trying to develop a capability for remote reassembly of each component in the system. We continue to consider remote operations in our component and assembly designs.

Such remote assembly and disassembly operations will take place in the E-MAD (Engine Maintenance, Assembly and Disassembly Building) as will other assembly, disassembly, and post-mortem activities. Construction of the E-MAD facility has been completed for several months, and its activation is now in progress. The large disassembly area is shown in

figure 32 (NPO 65-1930). The two major remote handling systems in the facility are the wall-mounted handling system and the overhead positioning system shown here in the disassembly bay. The wall-mounted handling system is used to do the major tasks of disassembly remotely so that components which are radioactive can be examined. The overhead positioning system is used to place the various engine subsystems and components in position to be operated on by the handling system. The E-MAD facility is scheduled to receive the first reactor for disassembly early in 1967.

Component Development

Other engine components which have received attention (besides the reactor, feed system, and nozzle), include control systems and instrumentation. The objective of our control systems work is primarily to provide systems that are simple and that will be reliable in the environments in which they must perform.

The work we have carried out over the past few years has resulted in the establishment of the technology of pneumatic actuators for engine and reactor control. This type of actuator appears more reliable in the radiation and thermal environment of the engine than hydraulic actuators now in hand. The photograph in figure 33 (NPO 65-1914) shows two pneumatic actuators under development for the NERVA engine technology part of our program. The first actuator powers the turbine power control valve and uses a pneumatic gear motor drive. The second actuator, which rotates the reactor control drums, uses a piston driving a rack and pinion assembly to provide rotary motion. These actuators have undergone

radiation testing either as a complete assembly or as critical components and have been tested over a wide range of expected operating conditions. The turbine power control valve actuator is being used during the EST test series. The pneumatic reactor control drum actuators will be used during the ground experimental (XE) engine testing.

We have also been active in applying the principles of a new field to the problems of nuclear rockets. Fluid interaction devices, similar in principle to electrical and electronic devices can be combined to perform the functions of computation and for motor drive for which electrical and electronic devices are now generally used. While the use of fluid interaction devices to replace electronic parts is expanding rapidly in every industrial usage, these devices are particularly valuable to meet nuclear rocket requirements since they are relatively insensitive to extremes of temperature, and to radiation. We have developed fluid interaction devices to use with the actuators discussed above, to replace the few electromechanical components of the pneumatic actuator selected for use in the NERVA engine. In addition, a completely pneumatic control actuator using GH_2 working fluid which appears to meet all our requirements for use as a reactor control drum actuator, or an engine turbine power control valve actuator has been designed and fabricated. This actuator combines the control logic elements with the actuator elements in a small package, eliminating transmission lines and increasing reliability. It is now undergoing breadboard tests at the Lewis Research Center.

The problems of instrumentation in the NERVA technology program are

not much different than the normally difficult problem of measuring temperatures from -423°F to 4000°F, except that the intense radiation field is an added environmental burden which must be considered. For example, many of the instruments used to make high temperature measurements need to be well insulated electrically. The intense level of gamma radiation, however, generates very high temperatures in the internal parts of the instrument which would cause it to melt unless good paths are provided to conduct the heat away. The requirements are basically in conflict; good electrical insulators are generally good at preventing heat from being transferred out as well. Our approach has been to work with the instrument manufacturers, testing their instruments for our requirements and modifying them to meet our needs. A sampling of the instruments which have been screened for just a few measurements is shown in figures 34 through 36 (NPO 66-345, 347, 348).

Radiation Effects on Materials

The programs which have been carried out over the past few years to determine the properties of engineering materials which are subject simultaneously to both cryogenic temperatures and high radiation doses have provided a catalog of useful information which is now available for the designers use. Generally, the combined effect of both radiation and cryogenic temperature has not been much different than the effect of cryogenic temperature alone for metals which will not be used in the highest radiation fields of the nuclear engine. The threshold for many of these metals to begin showing effects, however, appears to be between the low and high dose levels found at various locations of the nuclear

engine. We are now engaged in extending the range of radiation doses for which data are available to the highest doses expected to be reached in the 5000 megawatt NERVA engine.

Applicability of 1000 MW NERVA Technology to 5000 MW NERVA Engine Development

It is important to summarize briefly the direct applicability of all of the work being performed in developing the technology of nuclear rocket engines in the 1000 megawatt, 55,000 pound thrust engine size to the large, 5000 megawatt, 200,000 to 250,000 pound thrust NERVA engine development, particularly since our 1967 budget request provides funds for initiating development of such an engine.

The KIWI and NERVA NRX reactor tests have proven the ability of nuclear rocket reactors to achieve the high performance that was predicted for them. The materials, fuel element configurations, and general design features and design methods developed in this part of the nuclear rocket program are those that are being directly used, almost identically, in the design of the large NERVA engine. Advances in reactor technology that will be required are being evaluated first in the Phoebus 1 reactor tests before proving them conclusively in the Phoebus 2 reactor tests. In addition, laboratory testing is continuing to provide the methods for achieving the highest possible fuel element life and temperature.

The engine system technology work is providing analytical methods for predicting nuclear rocket engine performance and operating characteristics under all design and off-design conditions, including both steady state and transient operation. These analytical methods are being

evaluated in the cold flow test systems and in the breadboard Engine System Test (EST) and will be further evaluated in the Ground Experimental Engine (XE). Though, as indicated in figure 37 (NPO 65-2010), the 200,000 to 250,000 pound thrust NERVA engine is much larger than the Ground Experimental Engine, introducing primarily fabrication technology items that are not fully proven, the engine system design and analysis methods that are now being evaluated in the smaller size systems will be used directly in the larger system design and development. In addition, the component design methods that have been established are also directly applicable to the large engine components.

Most important, the development approaches that will be needed for a flight engine development are being developed as part of our engine technology program. The experience that is being and will be obtained with the engine test facilities is providing a firm basis for the construction of the test stands that will be needed to develop the large NERVA engine and the propulsion modules or vehicle stages that will use that engine. The required foundation of technology for the development of the large NERVA engine is being firmly built by the smaller hardware of the 1000 megawatt systems which are less expensive than the large systems will be, but the technology of which is nevertheless, completely applicable to the large system.

ADVANCED RESEARCH AND TECHNOLOGY

In addition to the work underway to establish the graphite reactor and NERVA engine technology, the advanced research and technology portion of the nuclear rocket program conducts research and development on

tungsten reactors, analytical and experimental work to develop analytical models for operation of nuclear rocket systems, studies of the effect of radiation on the properties of materials and the behavior of components, the development of advanced, radiation resistant control components and instrumentation and basic studies to extend our fundamental knowledge of such diverse phenomena as heat transfer, fluid flow stability, and optimal control of systems behavior through the application of the mathematics of non-linear systems. Research work on the very advanced cavity reactor nuclear propulsion concepts such as dust bed, liquid, and gaseous fuel reactors is also carried out in this part of the program. This work emphasizes the fundamental problems involved in a variety of concepts so as to be broadly applicable to whichever concepts appear promising. Finally, we have been active in work on radioisotope propulsion in which the isotopes are used to heat hydrogen which produces thrust.

Tungsten Reactors

Because of the importance of nuclear rockets in space exploration, we have conducted a relatively small effort on the technology of reactors using tungsten-uranium dioxide fuel elements which offer promise for extremely long operating time. The high melting points of both materials, the good structural properties of tungsten at high temperature, and the freedom of this material from corrosion by hydrogen indicated the possibility that this material system might provide extremely long operating duration at high temperature. The major problems anticipated and investigated in this effort on tungsten based nuclear reactors were the

fabricability of suitable tungsten-uranium-dioxide fuel elements and the compatibility of tungsten-uranium-dioxide fuel material in a hydrogen environment when subjected to various steady state temperatures and cyclic temperature variations. In addition, there were the usual problems of analyzing the design, neutronics, and control characteristics of a reactor based on materials with which there had been little previous experience.

The first thermal cycling test, carried out in 1963, resulted in a rapid disintegration of the fuel materials after only a few temperature cycles. Figure 38 (NPO 65-2011) indicates the effect of the thermal cycle on the structure of the tungsten-UO_2 matrix early in our investigation. Uranium has been released from the UO_2 and has penetrated the grain boundaries. Further reaction of the UO_2 uranium in the grain boundaries has caused loss of all structural integrity of the sample. One of the major thrusts of the research effort on tungsten-based reactors since that time has been understanding and developing solutions to this problem. By 1964 we were able to extend the useful cyclic operation by a factor of 10, and in 1965 increased understanding of the phenomena has resulted in further extension of the thermal cycling ability of this fuel so that there appears to be little problem in meeting any cyclic capability desired for a mission use or for development at temperatures equivalent to specific impulses in the range of 750 to 800 seconds. The 1965 specimen shown in figure 39 (NPO 65-1999) has undergone more than 100 temperature cycles of the same kind that caused breakup of the 1963 specimen in figure 38 (NPO 65-2011). The new specimen does not appear

to have reached its limit of operation.

Research and development on fabrication methods carried out in the past three years have developed several methods of fabricating structurally and metallurgically acceptable fuel elements. The extent of our ability to fabricate tungsten in 1963 is shown in figure 40 (NPO 65-1990). This simple shape had few of the characteristics required for successful operation as a reactor fuel element. Our evaluation and development effort on tungsten fabrication methods carried out in 1964 and 1965 considered every conceivable method of fabrication. Some of the fabrication techniques and fuel element geometries considered during 1964 and 1965 are shown in figure 41 (NPO 65-2000). As a result of this broad survey, it was possible early this year to define satisfactory fabrication methods for producing satisfactory fuel element subsections. Sound fuel specimens are now being supplied for simulated environmental tests to complete the final step in our tungsten reactor evaluation, the determination of the performance capabilities of reactors based on this fuel form.

While our mission studies have revealed some interesting benefits from the use of low thrust, light weight, long duration nuclear rockets, both in manned and unmanned applications, such missions are not well defined at this time. As a result of the uncertainty of its uses and the need to restrict our budget, our tungsten work will be phased out in fiscal year 1966. The work which has been performed, however, will have provided a sound basis for evaluating an operational system based

on these materials should a mission need arise. In addition, it will have provided valuable technology for the advanced space power systems which will be based on the use of refractory metals such as tungsten.

Advanced Concepts

In the last year's discussion of work on very advanced cavity reactor concepts such as dust bed, liquid core, and gaseous core reactors, I mentioned that the very high performance potential of these advanced propulsion concepts is balanced by the immensely difficult technological problems which must be overcome before their performance potential can be realized. Our work on advanced concepts includes work on concepts with various orders of increased performance potential, and closely related increasing development difficulty. Figure 42 (NPO 65-1996) lists three of these advanced concepts: the dust bed in which the fuel is in the form of fine dust particles containing a mixture of one of the carbides of uranium and other metals, and the liquid core reactor in which fuel is allowed to become molten, and the gaseous core in which the fuel is in the form of gaseous uranium atoms. Figures 43 through 45 (NPO 65-2081, 65-1991, 65-2092) are artist sketches illustrating the essential features of such concepts.

These advanced concepts have several characteristics. Because the fuel form is operating at temperatures beyond the maximum operating temperatures of the pressure vessel container, the container walls must be cooled. In order to obtain the maximum performance from the system, heat transfer to the propellant gas must be maximized, while the proportion

of energy reaching the walls is reduced. Reasonable thrust to weight performance requires fairly high flow rates of propellant through or around the fuel. Fuel economy and other reasons, however, dictate that the fraction of fuel entrained or carried off with the propellant be kept to a minimum.

One can readily see why, as the performance potential of these concepts increases, so does the development difficulty. In the dust bed fuel concept, materials behavior and heat transfer regimes which must be studied are limited to something below about 6700°F since this is the highest melting point of any solid material known. While such studies are difficult, they are comparatively limited extensions of our work on solid core graphite reactors. The liquid nuclear fuel introduces a host of new and difficult problems. Simply devising an experimental apparatus to study the behavior of material in the molten state up to 10,000°F is a difficult scientific and engineering achievement. Precise measurements of the vapor pressure, stoichiometric ratio, and other thermodynamic property data, are tasks that in other ages would have been a life's work, and probably unsuccessful, for a dedicated scientist but can, at least, be considered now. The gaseous reactor concept which has the highest performance potential of all envisages fuel in the plasma state. Studies of this concept indicate that it might be necessary to obtain temperatures as high as 140,000°F in the center of the gas core in order to achieve the high specific impulse potential (2500 seconds) desired. As the temperature goes up, the pressure needed to keep the uranium fuel density within the

limits of criticality also goes up. At 140,000°F the system pressure required would be about 15,000 psi. At these conditions atoms lose many of their electrons and have properties which cannot be accurately predicted. Before we can design and develop this kind of reactor, we will have to find ways of attaining these temperatures under the controlled conditions of a laboratory where measurements can be made of the properties of mixtures of hydrogen and uranium as they will be in a gaseous core reactor.

In spite of these difficulties, the performance potential of such concepts is so great that a reasonably-sized research effort in their direction is justified. Progress for a long time, however, will be measured in greater understanding of problems rather than solutions to them. Working in such very advanced areas, it is of paramount importance that the investigators be chosen for their demonstrated outstanding competence. In this regard, I believe we have an excellent mixture of scientists and engineers from the Nation's best research laboratories and universities hard at work on these difficult problems. A partial list of those engaged in this work is shown in figure 46 (NPO 65-1993 and 65-2001).

Radioisotope Propulsion

Recent mission studies have indicated a number of potential uses for light weight, very low thrust systems with reasonably high specific impulse such as might be achieved by the use of radioisotope propulsion systems. The radioisotope heat source is encapsulated in a refractory metal as

shown in figure 47 (NPO 66-607). When no propellant is flowing, enough heat energy is transferred away from the capsule by radiation to maintain the capsule at a reasonable temperature so that it does not melt. When in operation, a valve is opened to allow hydrogen flow to pass from the propellant tank into the fine passages around the capsule where it is heated to a fairly high temperature and exhausted out the nozzle. Such systems could be useful for attitude control and station keeping for satellites, and for propelling deep space probes.

The work to date has been largely limited to studies of the problems of providing high temperature isotope fuel forms and capsules and studies of heat transfer, supported by the AEC. Should the usefulness of these devices appear to warrant further development, a system development effort would be initiated.

TECHNOLOGY UTILIZATION

It has been possible in the past year to increase our emphasis upon identifying and reporting inventions, innovations, processes, etc., which have evolved from the nuclear rocket effort, but which also may have some potential application in the Nation's commercial markets. This search and documentation program functions under policies and procedures that have been established by NASA in the frequently enunciated belief that the civilian economy should reap maximum benefit from our space efforts.

The results of this utilization effort have been successful in at least two respects. First, we have created formal new technology reporting organizations in important segments of our contractors -- Aerojet

General and Westinghouse. These organizations have come to recognize that patentability is no longer the guiding criterion by which ideas should be judged for their possible interest to the Government. This realization, coupled with their top level management enthusiasm for our objectives, has led to a second result -- namely, a marked increase in their reporting activities as indicated in figure 48 (NPO 65-2188). The quantity of Reportable Items received from each company during the past year has exceeded the total of submissions for the four previous years.

Coupled with the quantity improvement is a noticeable increase in quality. In figure 49 (NPO 65-2083) are shown three typical items to demonstrate this fact, as well as to indicate the variety of subject matter. The portable Eddy Current probe can detect virtually invisible cracks in extremely small tubing. Its adaptation to the inspection of heat exchangers, air conditioning and refrigeration equipment requires, only, logical extensions of the basic design. The High Temperature Thermocouple may be of significant value to the steel industry. The smoking pipe is already being marketed on the West Coast. It features the use of a pyrolytic graphite liner -- the technology of which being a direct offshoot of development work in the nuclear rocket KIWI reactor.

We are pleased with the progress attained so far in this important effort. Such progress has been realized through the creativity and inventiveness which our contractors have brought to bear in the solution of difficult problems within the program. Many of these solutions may impact, either directly or indirectly, upon technological requirements of the non-aerospace community. Our purpose is to share this knowledge with

the widest possible spectrum of users, in the anticipation that these solutions will eventually bear fruit in new products and processes of benefit to all.

NUCLEAR ROCKET SUMMARY

It is a pleasure this year to be able to report continued progress in our reactor activities, and to outline for you the steps we are taking towards a thorough understanding of the systems behavior of nuclear rocket engines. The wide stable operating range that has been demonstrated in reactor tests and being demonstrated in the first engine systems test early this year is a major step in providing an assured technological base for the high powered engines which will one day take men to Mars.

Each reactor test has been successful in substantially extending the proven performance domain in time or temperature. Our component test results on fuel elements which have not yet reached reactor test indicate good prospects for further improvements. The breadboard engine system tests (EST), in addition to making a major contribution to systems understanding, is a test bed for a number of components whose performance is vital to the success of the nuclear rocket. Underlying these successful reactor and EST test operations in Nevada, is a carefully built up structure of understanding, beginning with analysis of component behavior and extending through environmental tests such as the cold flow engine tests which are almost as complex as the tests of the nuclear engine itself. I would like to make it very clear that it is this thorough, careful structure of

understanding which is the technological basis for the next step forward in space propulsion systems; the individual success of tests of reactors and engine systems are gratifying in that they verify that this structure is sound. It is as a result of this sound technological base that we are confident of our ability to proceed into the development of the large NERVA engine that will be needed for future space missions.

Our tungsten reactor program has determined the performance potential and development difficulties of tungsten based reactors for space applications and has provided an excellent technology base should a mission need for such systems develop. Even as we prove the ability of many of our components, more advanced versions appear. For example, the field of fluid interaction devices promises to allow the designer freedom from harmful effects of temperature and radiation. Our research progress on cavity reactor concepts has continued.

Another important year lies ahead -- final preparations for the first XE Ground Experimental Engine test, the transition of our work in NERVA technology to components for the high power engine, preparations for the first 5000 megawatt Phoebus reactor power test, and the conduct of the first Phoebus 2 cold flow test. All of this work is planned to assure that this country has the ability to exercise mission options that will keep it pre-eminent in space exploration for the indefinite future.

ELECTRIC POWER IN SPACE

INTRODUCTION

Electric power is essential in all space vehicles. Because there is no one power system that can meet all of the current or anticipated mission requirements, we are developing or improving the technology of a variety of solar, chemical, and nuclear power systems, i.e., solar cells, solar collector systems, batteries, fuel cells and radio-isotope and nuclear reactor systems. Future missions will require substantially improved solar and chemical system performance and the successful development of practical nuclear systems. The power levels required will range from watts for small unmanned space science vehicles to megawatts for large manned interplanetary spacecraft utilizing electric propulsion.

In discussing our work on power generating systems for space applications, we have generally grouped the various system concepts in accordance with the source of energy that was used in the power system. However, the work that we are describing is advanced technological development work aimed at providing mission planners and developers with the information and hardware experience that is required to permit them to choose the power system that will best fit their mission requirements and provide them with confidence that the system they select will operate reliably under all required conditions.

As is indicated in Figure 50 (RN64-350 Rev.) each of the power sources that are available tend to fall into certain regions of power and life applicability. In this figure, we have presented the region of power and operating duration in which each energy source appears to provide low weight systems. These are important system variables in making a selection of a power system for a particular mission application. Although the boundaries between the systems cannot be accurately defined and we are working to extend the boundaries of each energy source, the data indicate that the chemical battery systems that have been used in every space mission are short duration systems. The solar cell systems are long duration energy sources suitable for those missions that are in sunlight for a significant part of their mission trajectory. The combination of solar cells and chemical batteries has provided power for all of our earth orbital unmanned missions. In these applications, the batteries provide the power when the satellite is in the dark or night part of its flight and the solar cells provide power during the day or sunlit parts of the flight including the power needed to recharge the chemical batteries after their power is depleted by dark time operation. Figure 50 (RN64-350 Rev.) indicates that if sufficient sunlight is not available for the space mission, or if other mission or system considerations make solar systems unsuitable, then radioisotope systems can provide the source of electrical energy up to perhaps as high as 10 electrical kilowatts and nuclear

reactors can provide the source of energy for higher powers.

Our advanced technology development work covers all of these various sources of energy for electric power generation. We are trying to increase the life of the chemical batteries including the fuel cells and we are trying to provide more power per pound of weight for these systems. In the solar cell and solar collector systems, we are trying to reduce the weight of the large solar panels so as to increase the power level capability of solar energy devices. In addition, we are trying to find ways of extending the use of solar energy to further distances from the sun than now appear efficient and also to distances closer to the sun than our current, relatively low temperature solar cells will permit.

In the nuclear area, NASA and the AEC are working closely together to assure that all of the required technology is available to permit radioisotope and nuclear reactor energy sources to be used in our space missions.

In connection with the nuclear development activities, it is important to point out that close,effective and consistent collaboration exists between NASA and the AEC. In addition to my duties as Director of Nuclear Systems and Space Power in NASA, where I am responsible for NASA's technology development work on electric systems, I am also Director of Space Nuclear Systems in the AEC and have responsibility for the AEC's development work on nuclear electric power systems. Since the AEC program also supports the DOD nuclear power requirements, there

is a close relationship among the nuclear plans and programs of the three agencies. In addition, the normal coordination arrangements, such as the Interagency Group on Power and the AACB, further help to assure coordination of DOD and NASA programs.

Up to this point, I have summarized the energy sources that are available to generate electrical power in space. However, with each energy source, there are several different means for converting the source energy (for example, the heat generated by a nuclear reactor) to electrical energy. Figure 51 (RN65-1942) shows some of the various energy conversion systems that are being investigated as part of the NASA advanced research and technology program. Operational systems that we are trying to improve are listed with an asterisk. The remaining systems listed are advanced concepts that are under investigation and development. It should be pointed out that these are not the only conversion systems that are possible nor are they the only ones that are being investigated by the various agencies of government. For example, in the AEC, we are investigating a mercury Rankine system that may be used with isotope power sources and we are also initiating some exploratory work on an organic Rankine system for isotope sources. In addition, we are investigating thermoelectric devices for conversion of reactor heat to electricity. In fact, the SNAP-10A which was flown by the AEC in cooperation with the Air Force last year, was a nuclear reactor-thermoelectric power supply.

It is important also to emphasize that most of our work in this area is not done on full power systems. Rather, work is done on the components of the energy sources and of the power conversion systems until such a time that the combination of these components into energy source subsystems or into power conversion subsystems is required to provide understanding of and experience with the operation of these separate subsystems. With new types of system concepts for which the available experience is limited or non-existent or for systems that are to be used in planned space missions, we would combine the energy source and the power conversion subsystems into a full system so that its performance could be fully evaluated, understood, and operational experience provided. This is essentially our plan on the SNAP-8 system in which the AEC is now developing the reactor heat source and NASA is developing the mercury Rankine power conversion system. Because these subsystems have never been investigated in a full, combined system and because there are technical questions that remain unanswered about such full system operation, we would expect to put these subsystems together when they have each reached a point that they are understood, well developed, and can operate reliably. We are not yet at that point; this will become clearer later in this discussion. Therefore, although we have a tendency to describe our work in terms of the various systems to which our work is applicable, it should be understood that we are conducting a technology program on the various components and

subsystems of the various types of electric power systems that can be used in space.

Although solar and chemical systems will continue to play an important role in space for the indefinite future, and we are actively trying to extend their operating regimes, I will restrict the following discussion to work on electric systems using nuclear energy sources, the area in which both NASA and the AEC are participating.

The work underway in the AEC and in NASA on nuclear electric power system technology is aimed at providing a broad range of nuclear electric power systems from watts to megawatts for currently planned and advanced mission use. It is important to re-emphasize here the cooperation and collaboration, which I mentioned earlier, between NASA and the AEC.

Figure 52 indicates the various kinds of nuclear heat sources that are now under investigation by the AEC. These are the small and large (or low and high powered) isotope heat sources, the SNAP zirconium-hydride reactors, and advanced reactor concepts aimed at providing hundreds of kilowatts of electrical power up into the thousands of kilowatts of electrical power. As I indicated earlier and as is shown in the figure, there are many different types of systems for converting the heat developed in these nuclear heat sources to electrical energy. Some of them, such as the thermoelectric and the thermionic devices, convert the heat energy directly to electrical energy without requiring

moving parts in the system. Others, such as the mercury and potassium turbine-alternator systems and the Brayton gas turbine system, are called dynamic systems because they require moving or rotating parts. It is shown in this figure that some of these conversion systems can apply to several different heat sources. Each of them has advantages in certain areas that require that we give them a fair technical evaluation in order to provide enough information to permit informed selections to be made of those systems that will finally be developed for space flight mission use.

RADIOISOTOPE ELECTRIC POWER SYSTEMS

The AEC develops all thermoelectric, radioisotope electric generators for NASA use. The AEC also provides all of the DOD needs for space radioisotope generators. There is no funding in the NASA budget for the advanced development of the low power radioisotope-thermoelectric systems although NASA is evaluating conversion systems that will be applicable to high power radioisotope systems and funds are provided in the NASA request for such work.

The widespread and growing NASA interest in radioisotope applications is indicated in Figure 53 (RN65-2055) by the many Centers that have been testing AEC-developed radioisotope power generators. In addition, some of the NASA Centers, particularly Ames and Langley, assist the AEC safety programs by conducting analytical and experimental investigations in areas such as re-entry burnup and trajectory analysis where NASA has special competence. This interest and activity by NASA Centers has led to two missions that are firmly committed to using radioisotope power. The first, NIMBUS B, will utilize two 30-watt SNAP-19 generators, mounted as shown in Figure 54 (RN65-2192), to provide supplementary power in an experimental application of isotope power. NIMBUS B is presently scheduled for a late 1967 flight. Since this is the first NASA spacecraft which will have a nuclear generator aboard, NASA and the AEC are preparing an interagency agreement which will give the NASA NIMBUS contractors the necessary insurance

protection against nuclear hazards afforded by the Price-Anderson Act.

A major new program initiated by the AEC at NASA's request during 1965 is the development of the SNAP-27 thermoelectric generator for the Apollo Lunar Surface Experiment Package (ALSEP) which will be placed on the moon by the Apollo astronauts, Figure 55 (RN65-1987). The SNAP-27 system is being developed by the AEC for the NASA Manned Spacecraft Center. It will provide 50 watts to power experiments left on the moon for at least a year and will weigh about 40 pounds. The current design will utilize a single plutonium fuel capsule which will be inserted in the generator on the lunar surface by the Apollo astronauts.

The above two systems are representative of a family of low power thermoelectric devices which have been developed over a period of years by the AEC. Four such isotope power systems have already been used in space. One of these units launched in 1961 is still operating after 4 1/2 years in space. All of these units were fueled with Plutonium-238 and operated satisfactorily in Navy navigational satellites. Some performance decrease was encountered during the operating period of these systems; however, the performance decrease is understood and corrections have been made in follow-on designs that should eliminate the possibility of such decrease. The electric power achievable in these radioisotope-thermoelectric devices is now limited by radioisotope availability and cost considerations to values of about a kilowatt. For

radioisotope systems developing powers higher than about a kilowatt, there is a need for better power conversion efficiency than can be obtained from thermoelectric power conversion. Several dynamic conversion systems are, therefore, being investigated for the higher power isotope units.

The mercury working fluid turboalternator system that has been under investigation by the AEC for several years has been operating for significant periods of time. This is a difficult development requiring extreme attention to temperature gradients, thermal distortion, bearing design and clearance, avoidance of corrosion, etc. Efficiencies of 7 or 8 percent have been achieved compared to the 5 percent that may be possible with thermoelectric elements. The efficiency of this equipment could be increased if the maximum operating temperature could be increased and some efficiency gain could also be achieved if the temperature in the radiator were decreased. An efficiency of about 10 percent appears to be as much as could be reasonably expected for this equipment. This would permit delivering twice as much electric power with a given isotope loading as is possible with thermoelectrics.

In our efforts to achieve still higher efficiency, we are now initiating, under AEC contract, preliminary investigations to determine the feasibility of using organic fluids, which are essentially oils, in low temperature, turboalternator systems. Such systems may

operate with efficiencies up to 15 percent even though they operate at maximum temperatures of only 600-700°F. These low temperatures should ease the problems associated with development of the isotope power systems and may permit increased reliability. No commitments are being made to carry these organic conversion systems further into hardware evaluation until the operation of the fluids at operating conditions is evaluated and appears satisfactory.

Beyond these two dynamic systems, the Brayton gas turbine type of system offers the possibility of efficiencies of 20-25 percent---4 to 5 times as high as could be achieved with thermoelectrics--if high component efficiencies and low losses can be achieved. It appears on the basis of test work done by NASA contractors and by the Lewis Research Center, that such component performance can indeed be achieved.

The Brayton gas turbine cycle is schematically illustrated in Figure 56 (RN65-2170). With this gas turbine power conversion system, it may be possible to obtain as much as 10 kilowatts of radioisotope electric power, which is probably an upper limit, considering radioisotope cost and availability. The radioisotope Brayton system is, therefore, of particular interest in future manned missions such as orbital laboratories in which these higher powers are likely to be needed. Such a radioisotope-Brayton cycle power system installation in a representative orbital laboratory concept is shown in Figure 57 (RN65-1950). It should be noted that the Brayton cycle is also of

interest in solar power systems where its high efficiency will reduce the size of the collector needed.

The AEC is conducting research and development on heat sources having the capability of operating at the higher temperatures and higher powers that will be required and the NASA Lewis Research Center is studying both axial and radial flow Brayton cycle power conversion turbomachinery such as shown in Figure 58 (RN66-285). Excellent test results and efficiencies were obtained from cold flow tests of the radial flow turbine and compressor under investigation at Lewis. The development and experimental hot gas testing of a gas bearing supported, radial flow, turbocompressor and gas-to-gas recuperator or heat exchanger is continuing as part of a broad technology program on Brayton cycle component development, with particular emphasis on high efficiency and reliability. This work which is conducted on the critical problem areas, such as the high temperature gas bearings, component efficiencies at low Reynolds numbers, recuperator effectiveness and flow distribution, and component off-design performance, is providing an excellent foundation for future systems development at any required level of power. The program will continue in FY 1967 with the objective of obtaining performance characteristics of a breadboard system using the radial and axial flow turbomachinery equipment.

NUCLEAR REACTOR ELECTRIC POWER SYSTEMS

SNAP-10A

An important demonstration of the ability of nuclear reactor electric power supplies to operate in space in a manner similar to operation in ground test facilities was accomplished during the past year. The 500-watt SNAP-10A system (Shown in Figure 59) made up of a SNAP zirconium-uranium-hydride fuel reactor and thermoelectric conversion elements was launched on April 3, 1965. It was started up automatically on command from the ground. Its operation for 43 days duplicated almost exactly the operating characteristics that had been measured in ground test facilities. Although both the space and ground test operations indicated some minor deviations from the design values, the system operated in a fully satisfactory manner and gave important information that will help in future designs.

On the 43rd day after the unit had made 552 orbits of the earth, the system stopped operating. It was apparent that the cessation of operation was abrupt since no indication of impending failure had been indicated in data that were telemetered to the ground in the 552nd or earlier orbits. Based on the telemetered data made before shutdown, observations made immediately after the shutdown, and data that were transmitted by the spacecraft later, several failure mode explanations were formulated. Each of these was experimentally evaluated by simulated testing of the components and subsystems on the ground. Although no absolutely certain explanation can be made

by such simulation, the ground test data strongly support the conclusion that the shut-down was the result of a sequential failure of electrical components in the spacecraft resulting from a failure of a voltage regulator. All of the operating characteristics encountered in space can be duplicated on the ground through this piece-part failure mode analysis.

It should be emphasized that the SNAP-10A nuclear reactor power system itself operated well. In fact, a duplicate of the system that was flown has been operating continuously in a ground test facility for over a year. On February 16th, we increased the operating temperature on that system and it has continued to operate well since that time. It is planned to continue the operation of that system through a total of 10,000 hours which will be reached in March; at that time we will shut the system down to disassemble and examine.

Perhaps the most important results achieved in this flight test program of SNAP-10A were associated with proving that reactor power systems can be developed, transported, installed, checked out, launched, and operated in space in a safe and predictable manner. The data obtained during the tests clearly indicate that reactor systems can be developed in ground facilities that simulate the space environment in a manner very similar to the development techniques used for all other space systems. The operation in space can be simulated on the ground and no unexpected space phenomena arise to affect the operation of

reactors. The next three figures (Figures 60, 61, 62) are intended to indicate how reactor systems can be shipped through cities, how they can be checked out in advance of launch by personnel having direct contact with the reactor system, and how little additional instrumentation is required in the launch control room during launch and space operation of the system. This SNAP-10A flight should serve to dispel any concern that may exist among those mission planners who are unfamiliar with nuclear systems about the problems that might be introduced by using such systems in space. No unusual problems were encountered.

SNAP-8

The SNAP-8 ground development project is aimed at developing a 35 to 50 kilowatt power system using a mercury Rankine power conversion subsystem being developed under NASA contract and a nuclear reactor that is being developed under an AEC contract as the heat source. A schematic diagram of the SNAP-8 system is shown in Figure 63 (RN65-561). It is designed to be suitable for a wide variety of potential mission applications such as a lunar base power plant, direct broadcast TV satellite, large orbital laboratories, and manned planetary missions. To provide mission flexibility and because we wish to make as much use of state-of-the-art technology as possible, the components are separated wherever possible and a low temperature lubricant/coolant is provided. Aerojet-General is the NASA contractor for the power conversion system, working under the direction of the Lewis Research Center, and Atomics International is the AEC contractor for the reactor.

The AEC has completed its test on the SNAP-8 experimental reactor (S8ER) shown in Figure 64 (RN66-290). The reactor, which is less than two feet in diameter, was started up in May 1963, and was shutdown in April 1965, after completing a year's operation under SNAP-8 power conditions. Since the shutdown, detailed examination of the fuel rods has shown that a majority of them have cracks in the metal cladding. The cause of the cracks and their significance have not yet been fully determined. It appears that the cracks resulted

from irradiation embrittlement of the metal cladding alloy combined with fuel swelling; detailed examination of the fuel rods will be completed in the next few months. Some corrective action is already being taken, but fabrication of the development reactor fuel is awaiting complete evaluation of the data obtained from examination of the experimental reactor.

Since January, Aerojet has completed performance testing of the major prototype power conversion components and has initiated component endurance testing. Figure 65 (R66-344) summarizes the maximum single unit operating time obtained for the components listed as of the end of last year. A single mercury pump, Figure 66 (RN65-1946) has run for 750 hours and appears in good shape. A NaK pump, Figure 67 (RN66-286) has just satisfactorily completed a planned 3000-hour endurance test. A lube/coolant pump, Figure 68 (RN65-1944) has been operated for over 3500 hours without any indications of difficulty. Similarly, the condenser, Figure 69 (RN65-1945) has operated well during its 1400 hours of testing. Finally, the alternator, Figure 70 (RN65-1947) which is coupled to and driven by the turbine has demonstrated acceptable electrical performance in a 830 hour test. In all, we have achieved a total of about 13,000 component test hours during 1965. The above-mentioned components are satisfactory for continued development and will be used in power conversion system tests. However, the last two components listed in Figure 65 (RN65-2153), the turbine and the boiler

cannot yet be considered as fully satisfactory, although they can be used in the ground test program.

Endurance testing of the turbine as a part of the complete mercury test loop terminated at 830 hours due to mechanical interference of an internal retaining ring with the first stage turbine wheel as indicated in Figure 71 (RN65-2068). One of the retaining rings is shown mounted on the third state diaphragm. Correction of this design fault and several other potential failure modes found during the post-test inspection involved straightforward mechanical modifications which have been completed. Tests of the redesigned turbine in a turboalternator package have been started.

The boiler, Figure 72 (RN65-1939) has also been redesigned. As noted on Figure 65 (RN65-2153) the first design ran for 1400 hours; however, it did not give satisfactory startup performance. The second generation design has now been tested for over 450 hours as indicated by the dashed line in Figure 65. The above tests have shown significant improvement over the first design, but further methods of improvement are being investigated. The problem is one of obtaining satisfactory heat transfer to the mercury immediately upon startup in a controlled and reproducible manner and is apparently greatly affected by the cleanliness of the system, the boiler tube surface condition, and the materials used in the boiler tubes. This problem, in varying degrees of severity, has been a long standing one in all boiling mercury systems. Currently the Lewis Research Center is conducting a joint

investigation with the AEC to seek a complete and practical solution.

During FY 1967, we plan to continue with power conversion system development leading to the eventual development of a 10,000-hour endurance capability. Our program plan calls for 30,000 hours of power conversion development testing, supported by work on heat transfer, materials, and other technical areas. It is planned to assemble the development reactor and install it in the Ground Prototype Test Facility, shown in the Figure 73, that has been built by the AEC. The reactor will be tested in a performance checkout test of up to 2500-hours duration. A second phase of the program is then planned after specific technical restraints or goals have been achieved in the power conversion system development phase. This second phase will consist eventually of a test of the combined SNAP-8 reactor and power conversion system. At least 1000 hours of component and power conversion system endurance will be required before we will begin fabrication of combined system test support equipment and about 2500 hours of endurance will be required before delivery and installation work of the power conversion system are initiated.

It should also be pointed out that the reactor being developed for the SNAP-8 Mercury Rankine System could also be used to provide the source of heat for a thermoelectric conversion system. Concepts are now under study as part of the AEC program to evaluate the capabilities and development problems associated with providing thermoelectric elements that could operate at the 1300°F output temperature

of the SNAP-8 reactor. Such a combined SNAP-8 reactor--thermoelectric power system could give up to about 20 kilowatts of electrical power with an overall efficiency of up to about 5%. In effect, such a concept would be an extrapolation of the system experience obtained in SNAP-10A. It also indicates the versatile applicability of much of the technology being developed in our electric power program. Various kinds of power conversion equipment can be used with the various heat sources under investigation. This work should, therefore, put us in a better position to select the best possible power source for any particular family of applications.

Advanced Reactor Electric Power Systems

SNAP-8 is an early turbogenerator system that could be available for use by the middle 70's. A comprehensive technology program aimed at providing the information required in the selection and design of higher powered systems that may be needed in the future for both auxiliary power and electric propulsion applications is also being conducted. The goals of the advanced nuclear electric power technology program are light weight, especially for electric propulsion, and long life--over a year. Such lightweight, high power systems cannot be built with information available today.

In meeting these goals of high power (hundreds to thousands of kilowatts) and lightweight (10 to 30 pounds per electrical kilowatt), and long life (years), we are inevitably forced toward higher and higher temperature. High temperature is not generally compatible with

extremely long life; however, the importance of going to high temperature in order to achieve the extremely low weights that are required to make deep space, high payload electric propulsion advantageous causes us to aim at such an objective. From our analysis, it appears that the lowest weight, high powered systems could be achieved with either liquid-metal-cooled-reactors with turbine-alternators driven by vaporized metals, or with liquid-metal-cooled-thermionic-reactors in which the nuclear fuel element is the hot side of a thermionic diode that converts nuclear heat directly to electricity.

However, because high temperature liquid metal systems are beyond our current technological capability, we are also pursuing work on a gas cooled reactor that could provide high temperature gas to a Brayton gas turbine power conversion cycle similar in concept to the gas turbine cycle being investigated for the isotope and solar collector heat sources. Such a gas system will probably not be as low in weight as either of the liquid metal systems; however, should those systems encounter major difficulties because of their high temperature fuel element and liquid metal environment, the gas system could serve as an appropriate alternate to provide large amounts of on-board electric power. It could probably not, however, satisfy the requirements of large electrically-propelled spacecraft, because it would not be low

enough in weight. In addition, such a gas system may have other advantages including the avoidance of zero-gravity condensing and boiling effects and elimination of the need to provide heat during long term storage in space to keep the metal working fluids in the molten state as would be required of liquid metal systems.

The work being conducted by NASA and the AEC in this advanced power area is all aimed at establishment of the technologies involved. None of it is as yet associated with putting major subsystems together or with developing full system hardware. This technology development work is, however, being done with an understanding of system operating problems and performance requirements developed over the years through studies conducted by many industrial and government groups throughout the country.

In the reactor area, work is being initiated at the AEC's Lawrence Radiation Laboratory, to investigate the technology that would permit building a liquid metal cooled reactor operating at the highest possible temperature. This is a broadly based technology development area that aims at the best possible performance by starting with a fundamental investigation of containment materials, nuclear fuel forms, and working fluids. It starts with the technology that was provided in the SNAP-50 reactor power system program and aims at improving on that technology.

Although, as the following discussion will indicate, very encouraging progress and accomplishments have been made in the thermionic conversion of heat directly to electrical energy, studies of thermionic reactor concepts are still required to define system operating characteristics and problems. Such studies will be undertaken and should help to serve as a basis for eventual reactor development.

The high temperature gas cooled reactor (710 reactor) work is being continued under AEC contract and is now directly oriented toward the space power systems applications. Work on fuel element materials and on the flow of inert gases through sample fuel elements is now underway as is evaluation of the radiation behavior of these materials. Such work is required before commitments are made to development of a fast reactor for this application.

It is important to point out that all of these reactor types are being investigated in a phased technical program approach. A decision to build a reactor of any of these types will have to wait for the establishment of the fuel materials, physics, flow system, etc. technology which will provide a basis for evaluating the feasibility and performance capabilities of these concepts before decisions are made to embark on full reactor experiments. The AEC program provides for continuing work in all of these areas.

In the NASA program, the technology of the advanced power conversion systems listed in Figure 74 (RN65-1948) is under investigation. The major portion of the NASA effort is on the liquid metal Rankine turbogenerator power conversion system and the thermionic direct conversion system. A small continuing effort is underway on the magnetohydrodynamic converter concept and the Brayton gas turbine work being carried out for isotope and solar collector applications will provide applicable technology for high power, but not in extremely lightweight systems. Generally our approach in this advanced power system area is to obtain basic design and component information, test breadboard systems, and to ultimately demonstrate full system performance as required. The critical problems of turbogenerators and thermionic converters as well as those common to both are shown in Figure 75 (RN65-2181). Indicated under the Rankine cycle are problem areas typical of those that are involved in trying to extend the operating limits of long-lived turbomachinery to higher temperatures than they have ever been operated at before. We will continue to work on these problems in FY 1967.

The lightweight Rankine cycle system program discussed in prior years is continuing. As you will recall, the achievement of lightweight Rankine systems is dependent upon achieving high system temperatures, Figure 76 (RN65-2171). We have been obtaining the basic high temperature information, such as heat transfer, materials

strength and corrosion properties, etc., that is required for the design of components. Typical of this information was the data needed for the design of high temperature ($\sim$2000°F) boiler and high temperature ($\sim$1500°F) condensers. In order to obtain these data, it was first necessary to design and construct facilities of a type never before attempted. These facilities were placed in operation during FY 1963 and in the ensuing period, over 6000 hours of useful testing have been obtained. A major phase of the boiler-condenser program--the accumulation of single tube boiling-condensing heat transfer data--will be completed by the end of FY 1966. The heat transfer pressure drop data have indicated that from a heat-transfer standpoint, once-through lightweight boilers and lightweight condensers are feasible. The test facilities are now being modified for the next step, obtaining multitube boiler-condenser test data. This testing will begin during FY 1967.

With regard to our high temperature turbine program, we have satisfactorily completed 2000 hours of testing on a two stage potassium turbine assembly at 1600°F, Figure 77 (RN66-605). The excellent condition of this turbine after the test is shown on Figure 78 (RN66-604). It is planned to continue this program into FY 1967 towards an endurance goal of 5000 hours. In addition, a three stage turbine assembly will be built and tested in order to obtain a more realistic simulation of the turbine blade erosion conditions

that may occur in a full scale five stage potassium turbine. It is important to recognize that this test unit is essentially an experimental unit, mounted on oil bearings and not suitable for use in an actual power conversion system. However, the important turbine characteristics, such as blade height, blade tip speed, aero-dynamic design and working fluid are accurately represented.

A continuing effort is planned on radiators. Programs on micrometeorite penetration mechanism and protective devices (bumpers) as well as investigations of newer concepts, such as segmented radiators utilizing vapor chamber or heat pipe devices, are underway. Preliminary estimates of radiators designed to utilize the heat pipe or vapor chamber concept indicate that weight reductions of 40% at the desired high reliability and confidence factors are possible. Important information has been obtained from the Pegasus satellites as well as from high velocity impact damage experiments. The Lewis Research Center has recently completed an investigation of a condensing radiator operating between 1400°F and 1600°F and has correlated the results with predicted performance. Finally, significant progress is being made on the development of high emissivity coatings for radiators. Such coatings are needed to promote high rates of heat radiation from the radiator surfaces in order to minimize the size of the radiator. One material, iron titanate, gave exceptionally good results at temperatures near 1700°F when operated for a year under simulated space conditions.

The major problems associated with thermionic converters concern the very high temperatures that are required to obtain lightweight systems. This is illustrated on Figure 79 (RN65-1937). The AEC and NASA are conducting and supporting coordinated nuclear fuel research programs aimed at investigating two broad classes of materials: the uranium oxides and the uranium carbides. We have been concentrating upon the fabrication and materials problems associated with operating these devices in an intense radiation environment at fuel temperatures exceeding 3000°F, Figure 80 (RN66-606). During FY 1967, fuels will be irradiated to determine the suitability of the fuel under conditions expected to be encountered at high power densities. Fission product management and fuel evaporation and condensation will also be studied. The results have continued to be encouraging. Diode operating life in electrically-heated non-nuclear tests has increased from a few hundred hours in 1961 to nearly 10,000 hours, as shown in Figure 81 (RN65-1934). Single converter tests of diodes in test reactors have also shown good progress. However, reproducibility from cell to cell is not yet satisfactory and additional test data and development are needed.

One of the problems peculiar to nuclear fueled diodes is that fuel materials and fission products can diffuse through the fuel element cladding, as indicated in Figure 82 (RN65-2152), into the diode and collect on the anode. Because the presence of such impurities in the diode might affect the performance of the diode, it was considered to be

important to measure the rate of this transport of the fuel and fission products through the clad. This was done during the past year and the rate determined to be quite low.

During the past year, a high capacity electromagnetic pump was operated at 2000°F for several thousands of hours, Figure 83 (RN65-2127). This achievement has encouraged us to design a lightweight version which will not be any heavier than the usual mechanical pump and will offer the potential reliability inherent in a component which has no moving parts. Also, during FY 1966, considerable progress was made in determining the suitability for high temperature operation of various electrical insulators, magnetic materials, electrical conductors and bore seal materials. During FY 1967, tests of promising materials will be extended to long times and higher temperatures. This is of particular importance since considerable amounts of heat, perhaps 150KW, will have to be rejected from a typical one megawatt alternator. As is well known, the rejection of heat to space occurs most efficiently at high temperatures and it is, therefore, important to try to determine the highest temperatures at which promising new electrical materials and components can operate.

The liquid metal MHD conversion system may be likened to a no-moving part turbo-alternator for possible use with Brayton or Rankine cycle power conversion systems. Because it has no moving parts, the MHD system has potential reliability advantages. However, there are

several basic problems such as liquid metal separation and high losses that require solution and are under study as part of an in-house program. Gaseous MHD systems are also under study in an in-house program as very high temperature devices which, in theory, could be very lightweight systems. In these systems the efficient production of high strength, magnetic fields is a prerequisite to obtaining high efficiency systems. Consequently, we are conducting an in-house evaluation of super conductive magnet materials.

NUCLEAR ELECTRIC POWER SUMMARY

In summary, we are finding growing interest in and application of the radioisotope systems for the generation of power in space. The NASA Centers are becoming increasingly familiar with these power supplies and are considering these systems for many missions that are being studied. In addition, isotope systems are being investigated for possible Department of Defense missions. A major development during the past year has been the recognition of the potential applicability of these isotope systems up to power levels as high as 10 electrical kilowatts.

The space flight experience with the SNAP-10A system has proven that nuclear reactor operation in space can be simulated in ground test facilities; no new phenomena in space were encountered during the SNAP-10A flight.

Test experience has continued to accumulate on the components of the SNAP-8 reactor-mercury Rankine electric power system. Problems that have been encountered during this component test phase are being investigated

to develop fully satisfactory solutions. Further endurance testing will be conducted on the reactor and the power conversion subsystems before they are put together in a full system test.

Work on the technology of still higher power systems is under investigation. This work should provide a basis for a factual assessment of the feasibility of developing the systems that are potentially able to provide high powers in light packages; this technology will also provide a basis for evaluating the real performance that can be expected from the various candidate systems. Such information will provide a sound basis for eventual development of high power (hundreds to thousands of kilowatts) systems.

The overall program on nuclear electric power technology is providing the information that will permit building power supplies of any required power level and that will permit selection of the best possible system for a particular family of applications. The growing need for power in space exploration missions requires the flexibility provided by such a broad technological development approach.

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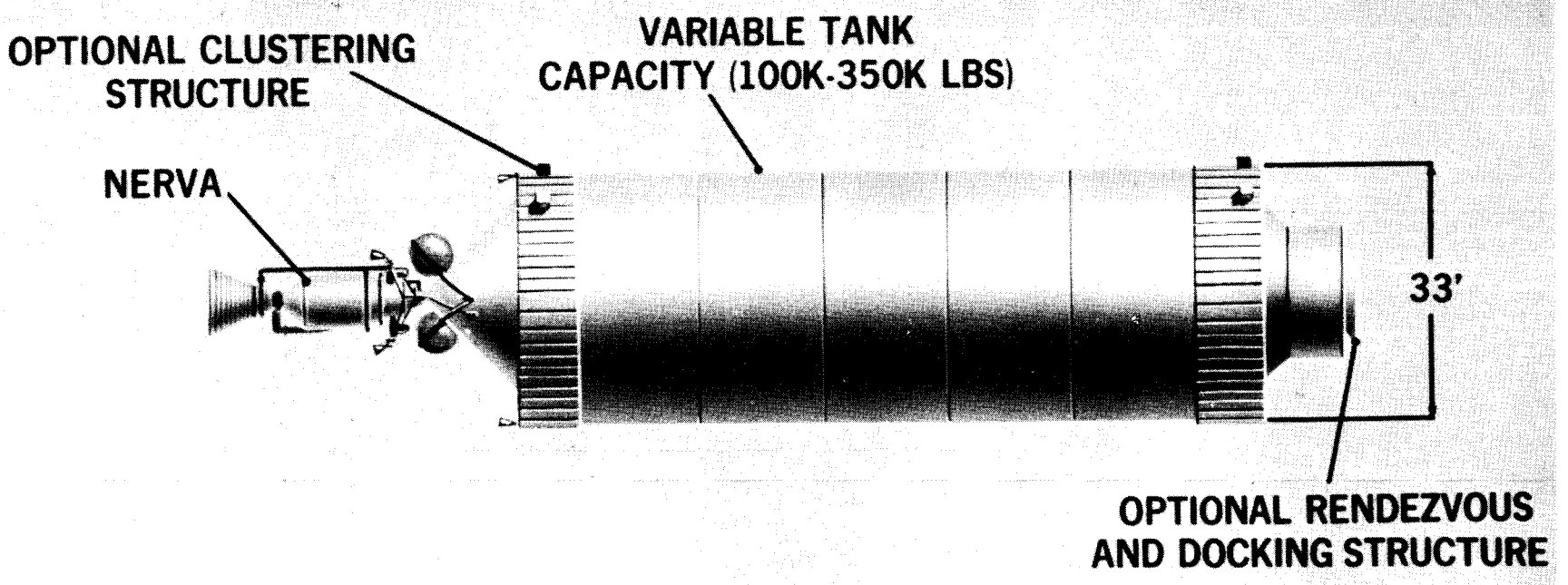
GPO 900-660

PROPULSION MODULE CONCEPT



NASA NPO 65-1933
12-14-65

Fig 1

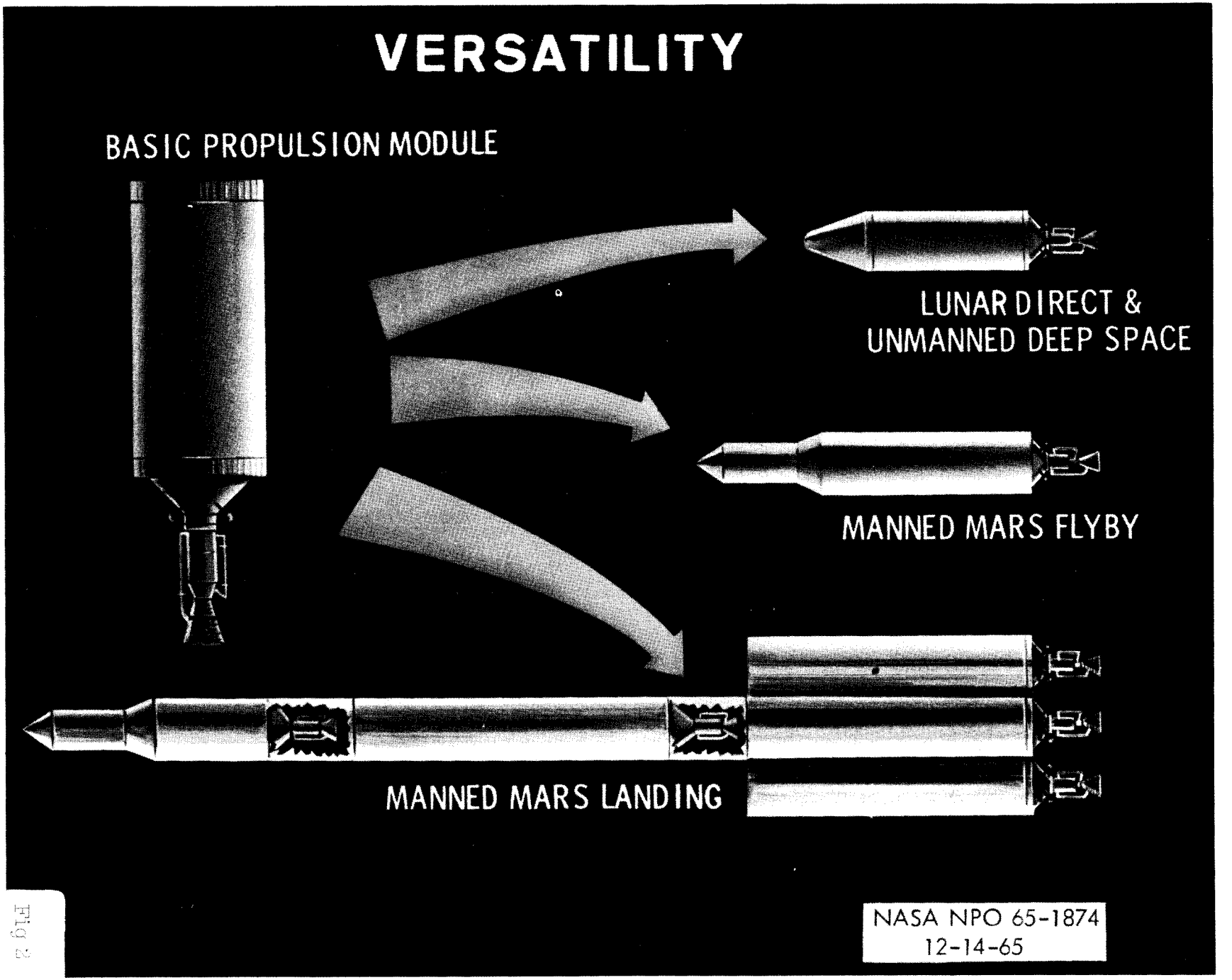
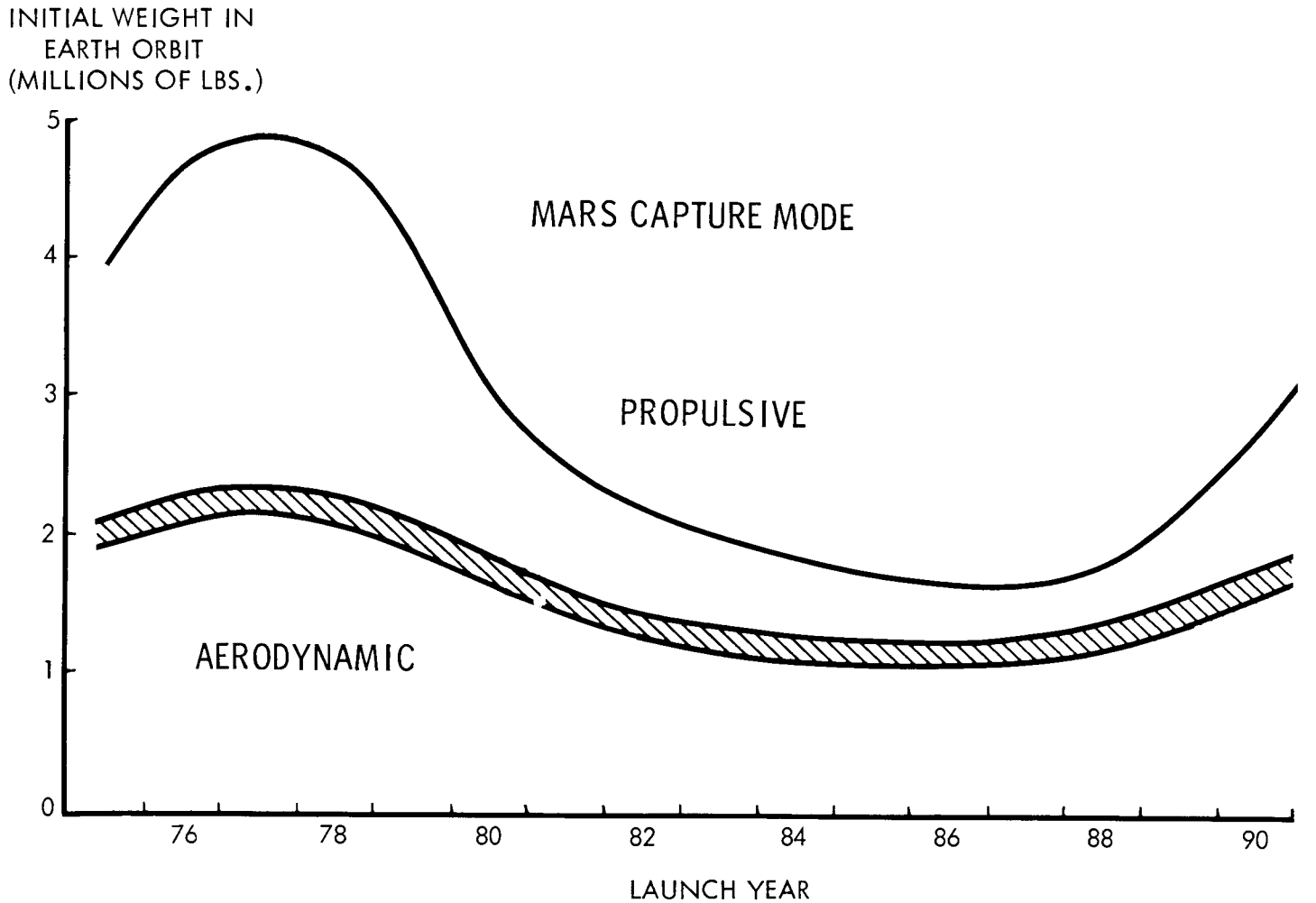

VERSATILITY
BASIC PROPULSION MODULE
LUNAR DIRECT &
UNMANNED DEEP SPACE
MANNED MARS FLYBY
MANNED MARS LANDING
NASA NPO 65-1874
12-14-65

Fig 2

EARTH-ORBIT WEIGHTS FOR MANNED MARS MISSIONS

NUCLEAR-ROCKET PROPULSION AT EARTH DEPARTURE AND AT MARS
CHEMICAL RETRO TO 50,000 FT/SEC AT EARTH RETURN

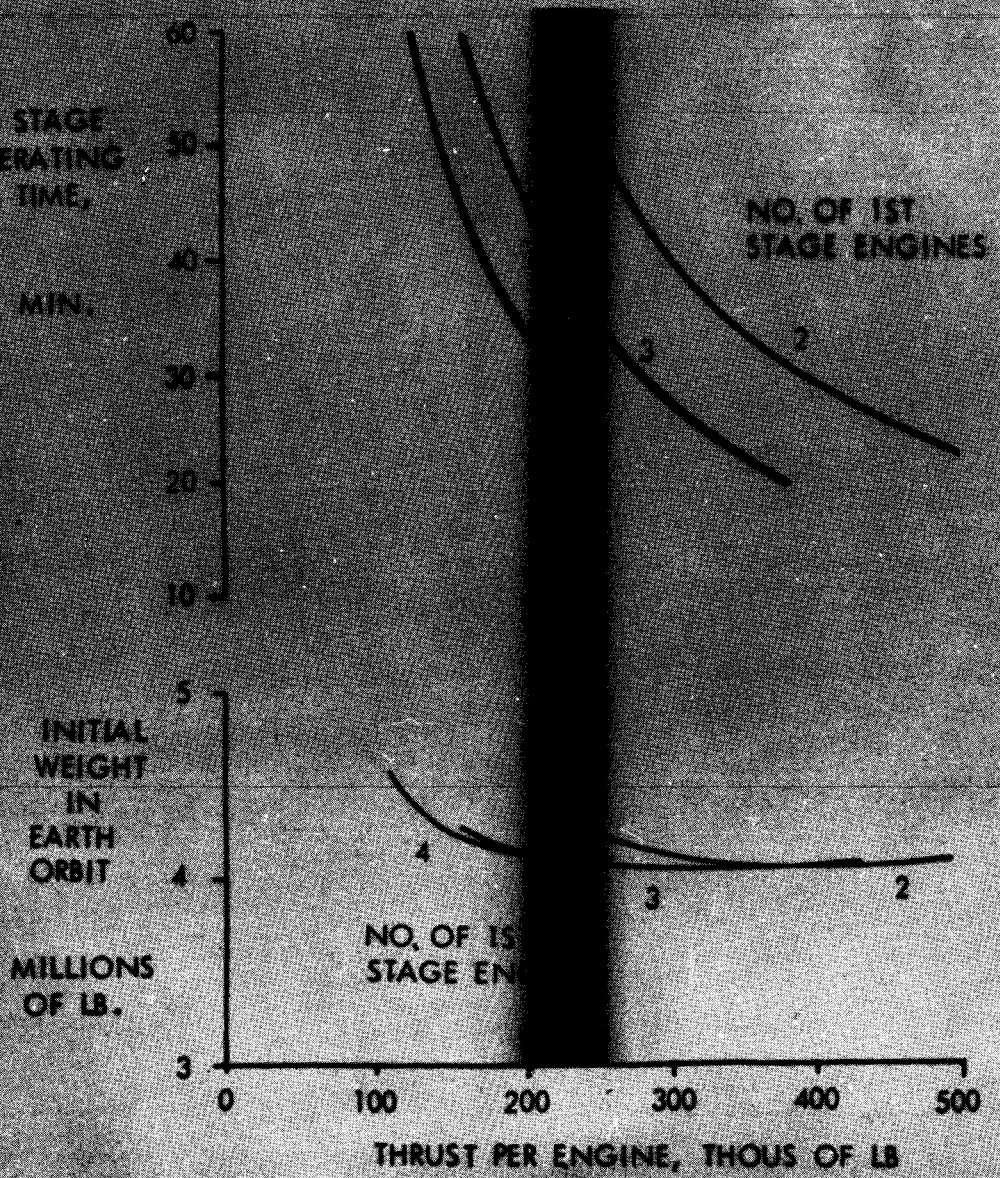


NASA NPO 65-2197
12-14-65

Fig 3

MANNED MARS LANDING MISSION, 1978

EFFECT OF ENGINE THRUST ON INITIAL WEIGHT AND OPERATING TIME

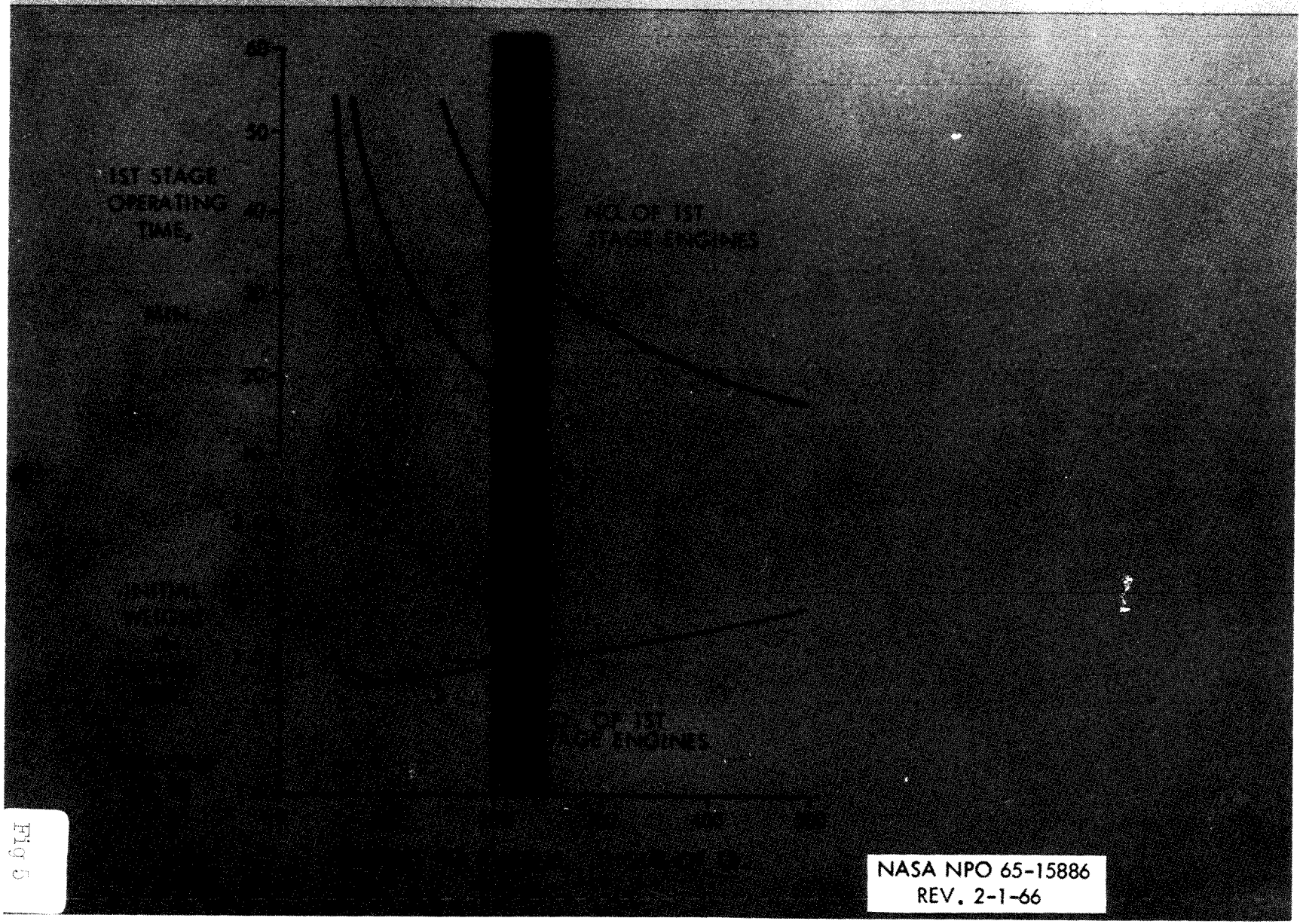


NASA NPO 65-15885
REV. 2-1-66

Fig 4

MANNED MARS LANDING MISSION, 1986

EFFECT OF ENGINE THRUST ON INITIAL WEIGHT AND OPERATING TIME



NASA NPO 65-15886
REV. 2-1-66

Fig 5

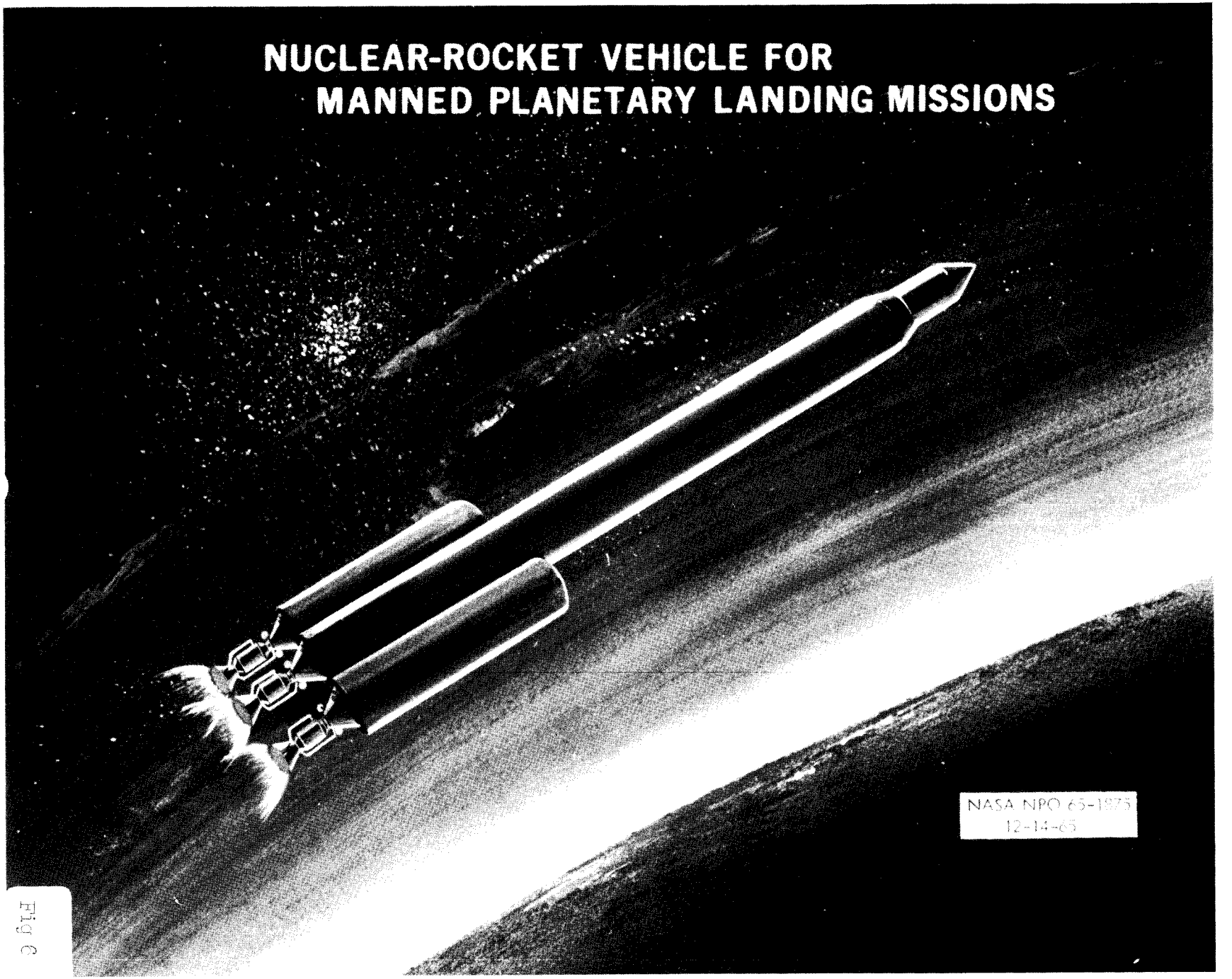

NUCLEAR-ROCKET VEHICLE FOR
MANNED PLANETARY LANDING MISSIONS
NASA NPO 65-1875
12-14-65

Fig 6

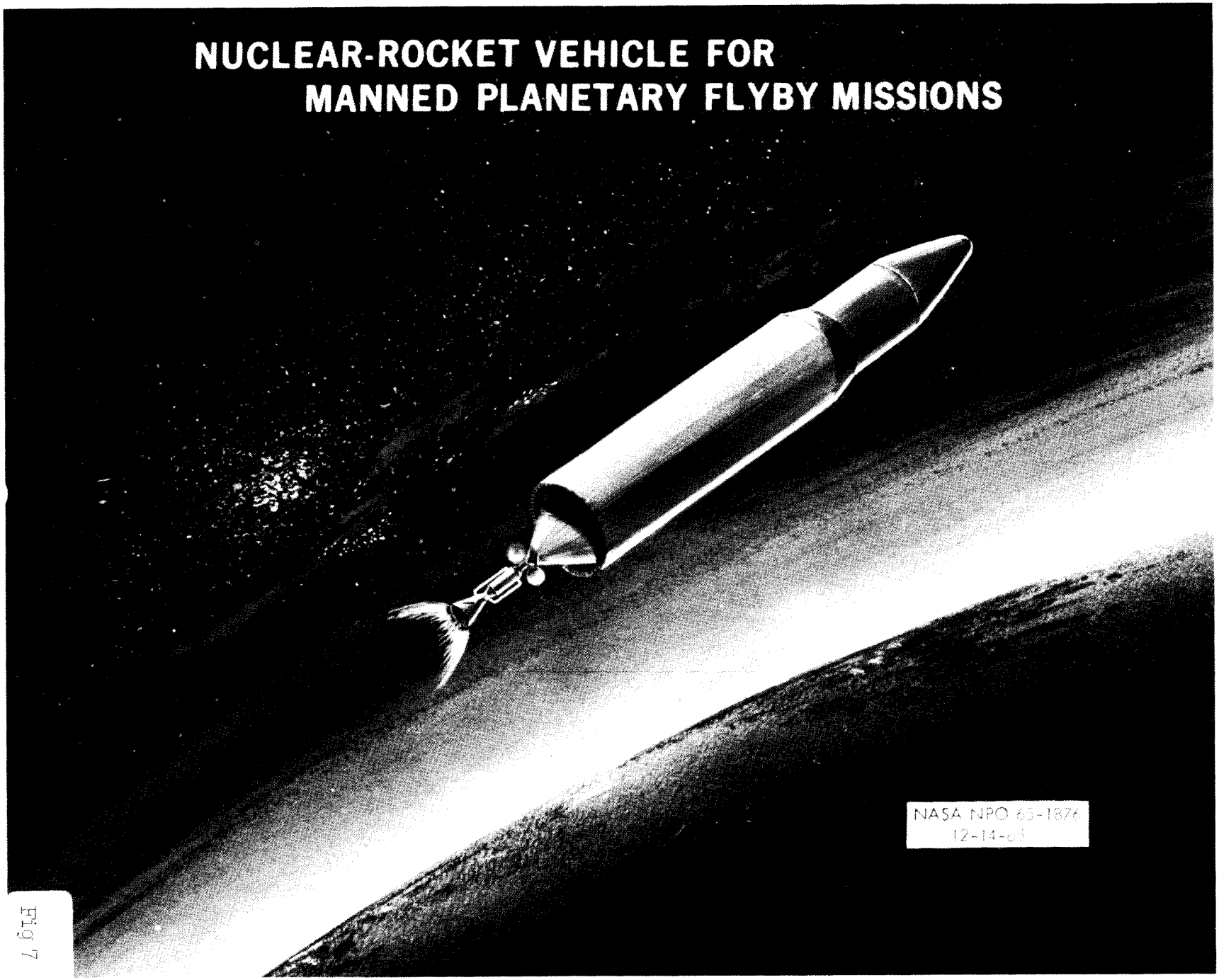
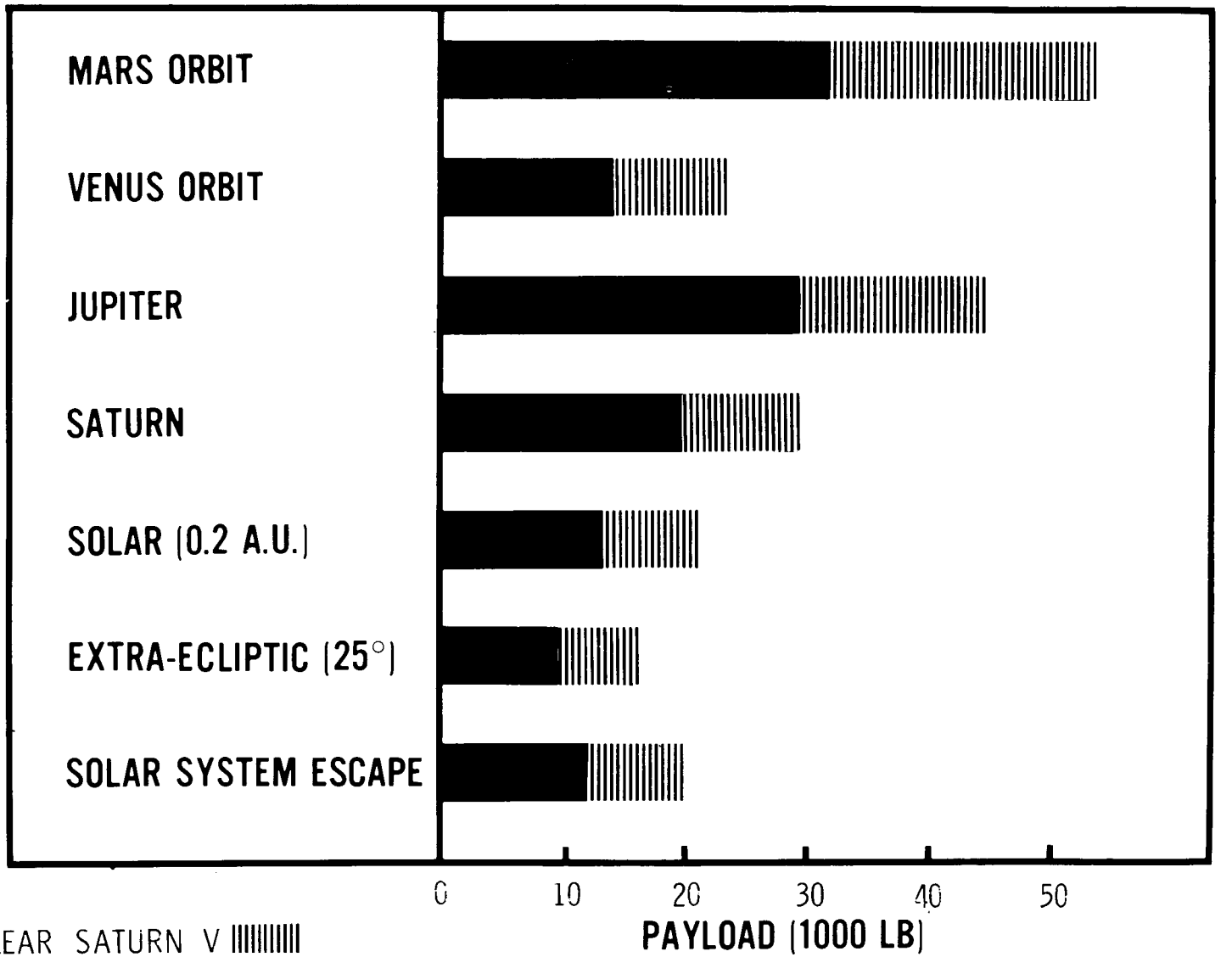

NUCLEAR-ROCKET VEHICLE FOR
MANNED PLANETARY FLYBY MISSIONS
NASA NPO 65-1876
12-14-65

Fig 7

INTERPLANETARY MISSION SUMMARY



NUCLEAR SATURN V
SATURN V

NASA RN 64-2076
REV. 8-18-65

Fig 8

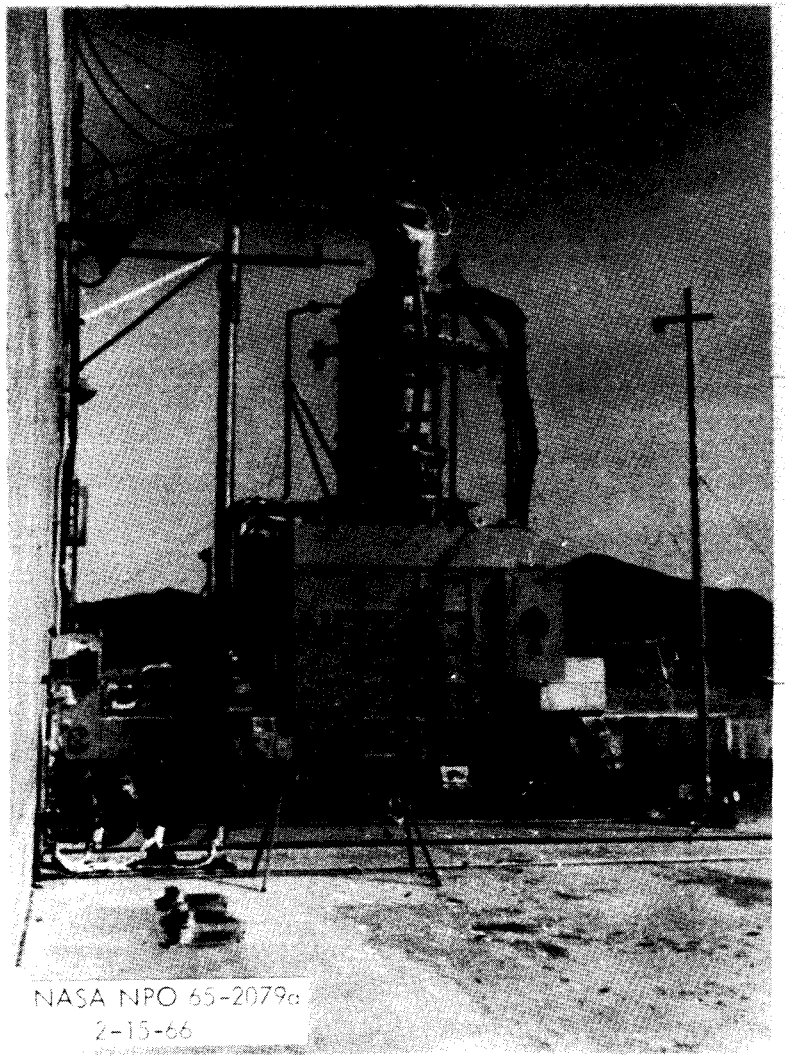
NUCLEAR ROCKET PROGRAM PARTS

- GRAPHITE SOLID-CORE REACTORS AND ENGINES
  - KIWI/NERVA REACTORS - LOS ALAMOS, AEROJET AND WESTINGHOUSE
  - NERVA ENGINE TECHNOLOGY—AEROJET AND WESTINGHOUSE
  - PHOEBUS REACTORS—LOS ALAMOS
  - PROPOSED NERVA ENGINE DEVELOPMENT—AEROJET AND WESTINGHOUSE
  - STAGE TECHNOLOGY
- OTHER CONCEPTS
  - TUNGSTEN SOLID-CORE REACTORS—ARGONNE AND LEWIS
  - CAVITY REACTOR CONCEPTS
- NON-REACTOR COMPONENT AND ENGINE SYSTEMS TECHNOLOGY—LEWIS
- APPLICATION STUDIES

NASA NPO 65-1913
12-14-65

Fig 9

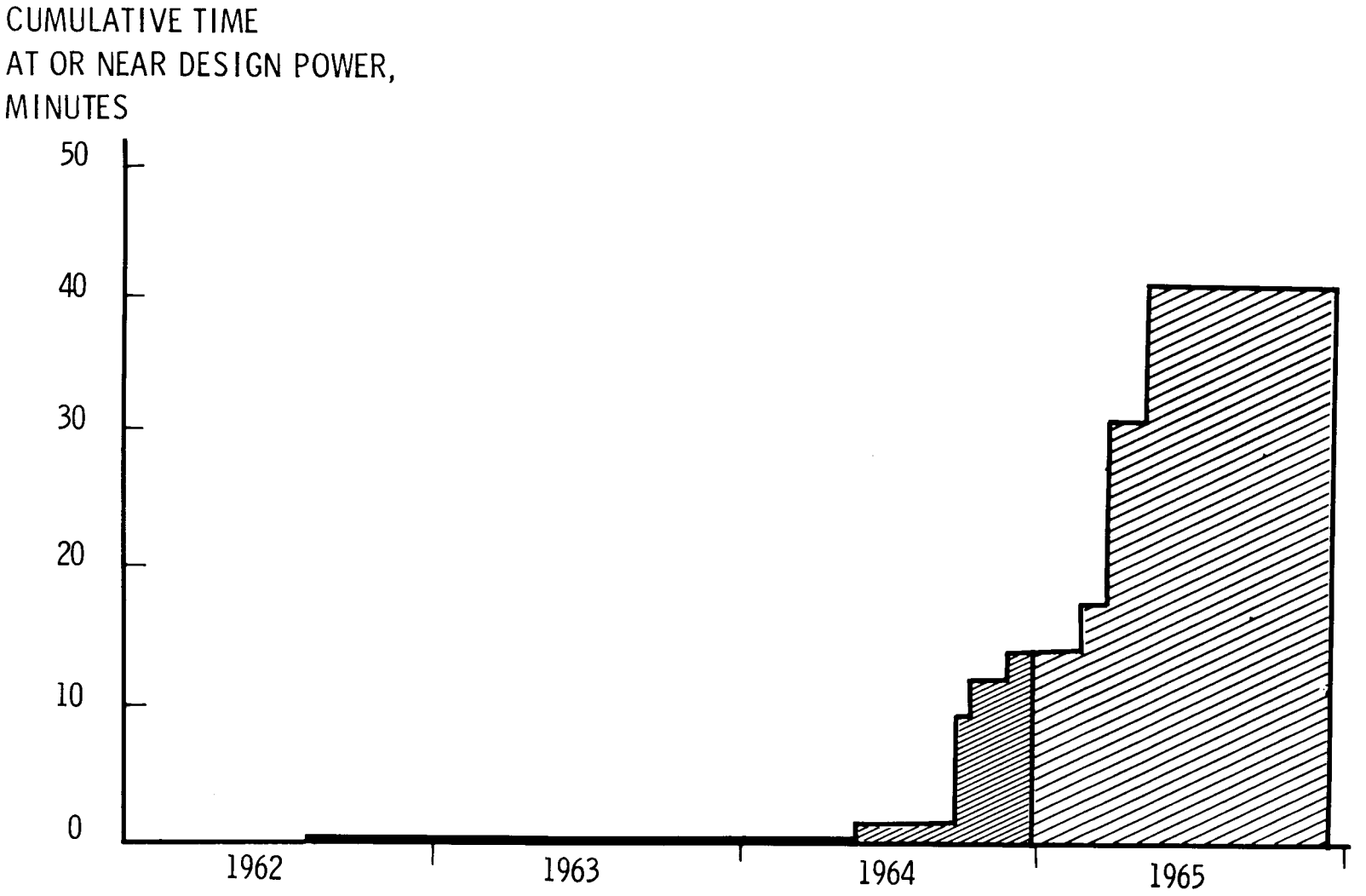
GRAPHITE REACTOR AND ENGINE SYSTEM
TEST ACTIVITIES



KIWI-B4D POWER	MAY 13, 1964
KIWI-B4E POWER	AUGUST 28, 1964
KIWI-B4E RESTART	SEPTEMBER 10, 1964
NRX-A2 POWER	SEPTEMBER 24, 1964
NRX-A2 RESTART	OCTOBER 15, 1964
KIWI TNT	JANUARY 12, 1965
NRX-A3 POWER	APRIL 23, 1965
NRX-A3 RESTART(1ST)	MAY 20, 1965
NRX-A3 RESTART(2ND)	MAY 28,1965
PHOEBUS-1A POWER	JUNE 25, 1965
NRX/EST	DEC. 1965-EARLY 1966

Fig 10

REACTOR TEST LOG



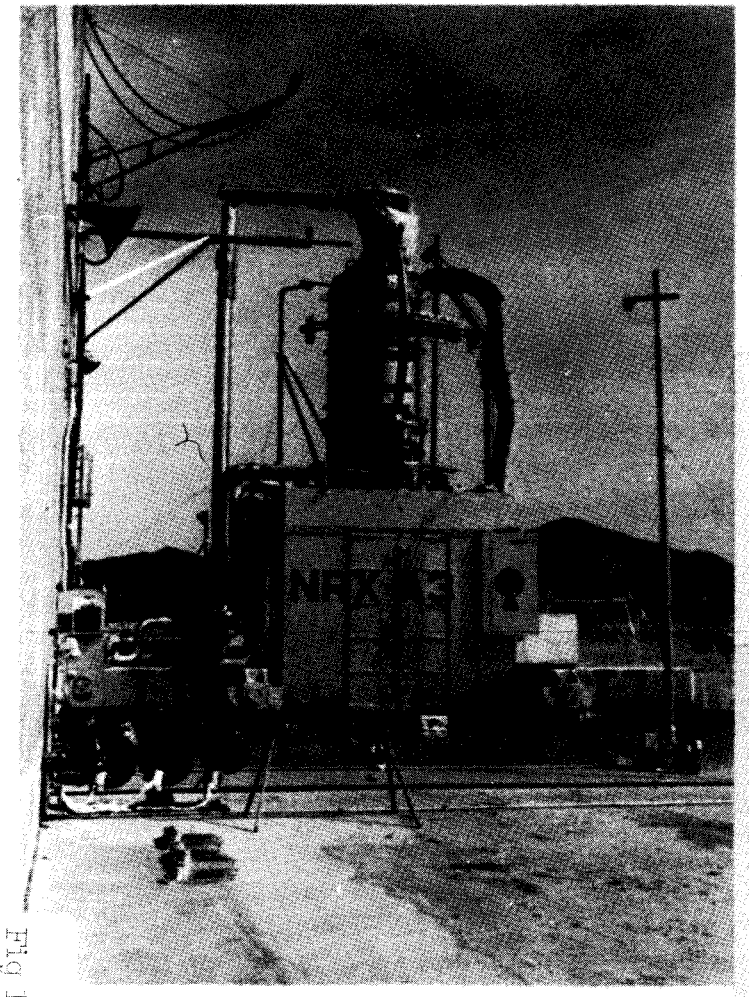
NASA NPO 65-1927
REV. 2-15-66

Fig 11

ENGINE SYSTEM TEST (EST)

Fig 12

GRAPHITE REACTOR AND ENGINE SYSTEM
TEST ACTIVITIES



KIWI-B4D POWER	MAY 13, 1964
KIWI-B4E POWER	AUGUST 28, 1964
KIWI-B4E RESTART	SEPTEMBER 10, 1964
NRX-A2 POWER	SEPTEMBER 24, 1964
NRX-A2 RESTART	OCTOBER 15, 1964
KIWI TNT	JANUARY 12, 1965
NRX-A3 POWER	APRIL 23, 1965
NRX-A3 RESTART(1ST)	MAY 20, 1965
NRX-A3 RESTART(2ND)	MAY 28,1965
PHOEBUS-1A POWER	JUNE 25, 1965
NRX/EST	DEC. 1965-EARLY 1966
NRX-A5 POWER	SUMMER 1966
PHOEBUS-1B POWER	SUMMER 1966
NRX-A6 POWER	WINTER 1966 -67
PHOEBUS-2CF	SPRING 1967
PHOEBUS-1C POWER	SUMMER 1967
XE-1 POWER	SPRING 1967

NASA NPO65-2079
Rev. 2-21-66

Fig 13

NRX–A3 TEST RESULTS

	STEADY STATE DESIGN CONDITIONS	1st FULL POWER TEST	2nd FULL POWER TEST	PARTIAL POWER MAPPING TEST
DURATION AT POWER, MINUTES	-	8	18	45
DURATION AT FULL-POWER HOLD, MINUTES	-	3 1/2	13	-
POWER, AT FULL-POWER HOLD, MW	1120	1120	1090	420 MAX.
CHAMBER TEMPERATURE, °R	4090	3970	4010	2500 MAX.
PROPELLANT FLOW RATE, LB/SEC	71.3	73.5	71.0	54 MAX.
CHAMBER PRESSURE, PSIA	569	567	560	292 MAX.

NASA NPO 65-1961
12-14-65

Fig 14

KIWI/PHOEBUS-1/PHOEBUS-2 COMPARISON

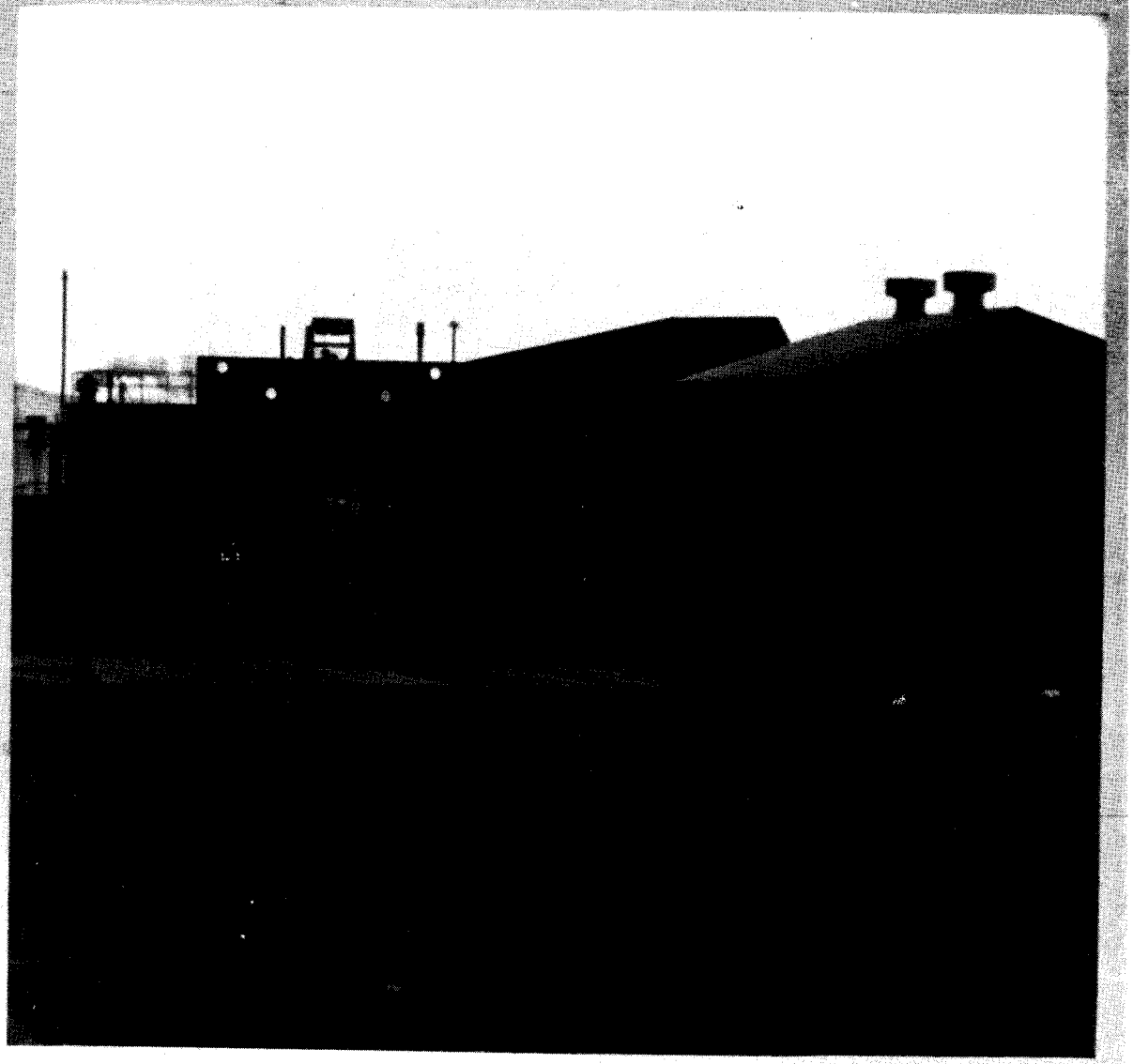
NOMINAL DESIGN VALUES

	KIWI	PHOEBUS-1	PHOEBUS-2
DIAMETER	35"	35"	55"
DESIGN POWER	1120	1100-1500	5000
REACTOR FLOW RATE	70 LB/SEC	70-94 LB/SEC	285 LB/SEC
EXIT GAS TEMPERATURE	4100°R	4100-4500°R	4500-5000°R

NASA NPO 66-367
2-1-66

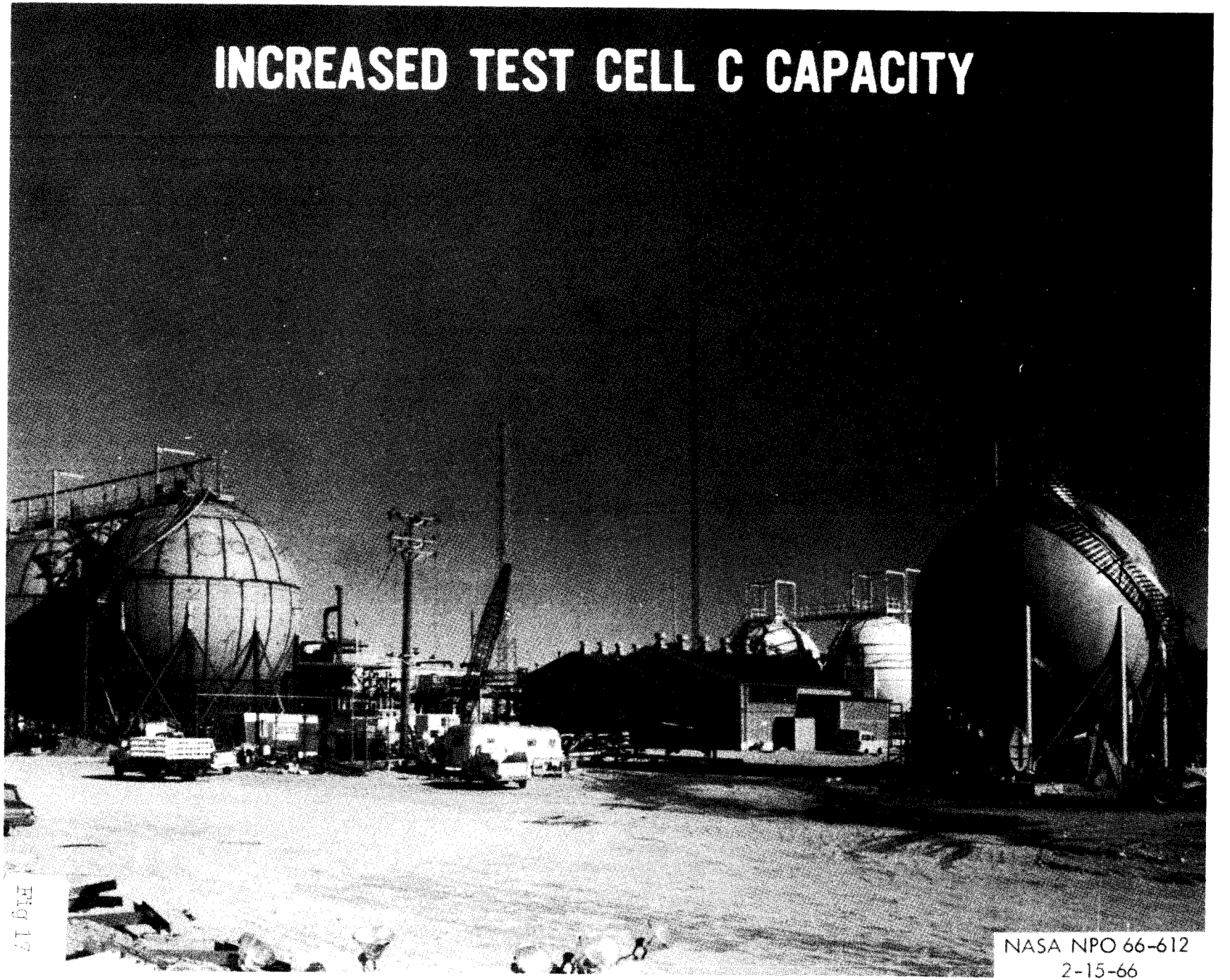
Fig 13

PHOEBUS-1A REACTOR AT TEST CELL



NASA NPO -2143
12-14-65

Fig 16



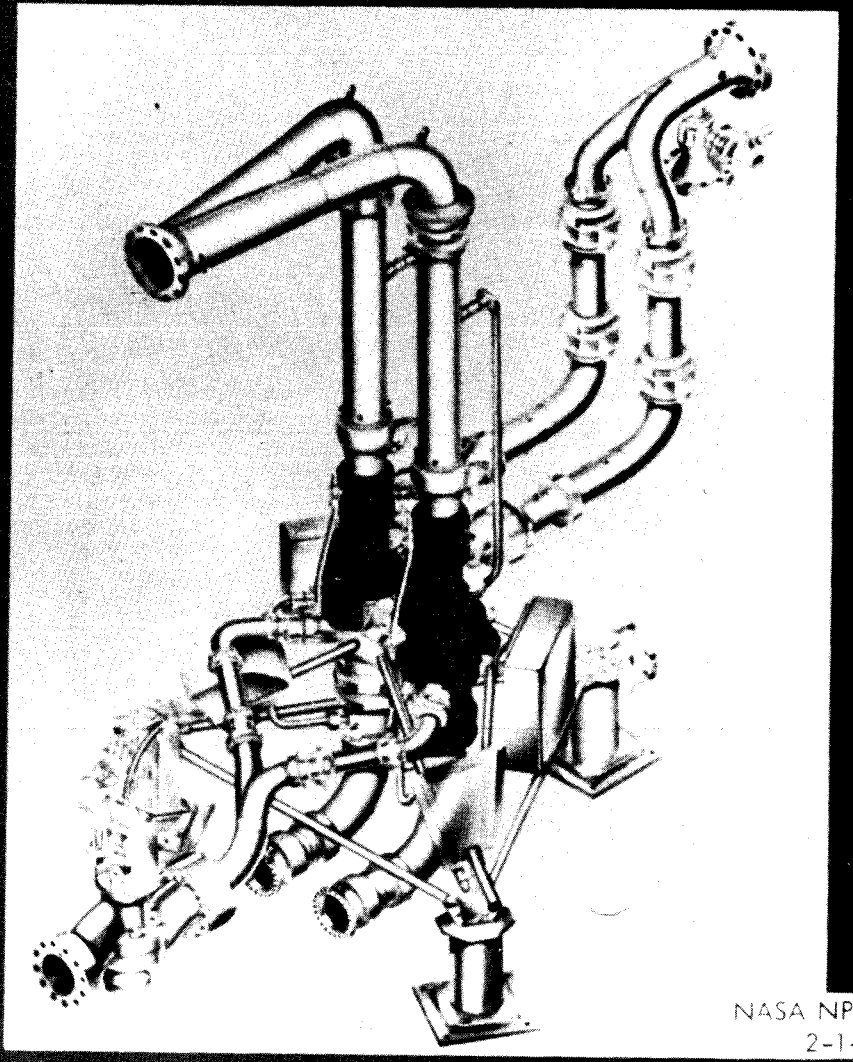
NASA NPO 66-612
2-15-66

Fig 17

NASA NPO 66-368
REV. 2-15-66

Fig 18

FACILITY FEED SYSTEM FOR PHOEBUS REACTOR



NASA NPO 66-327
2-1-66

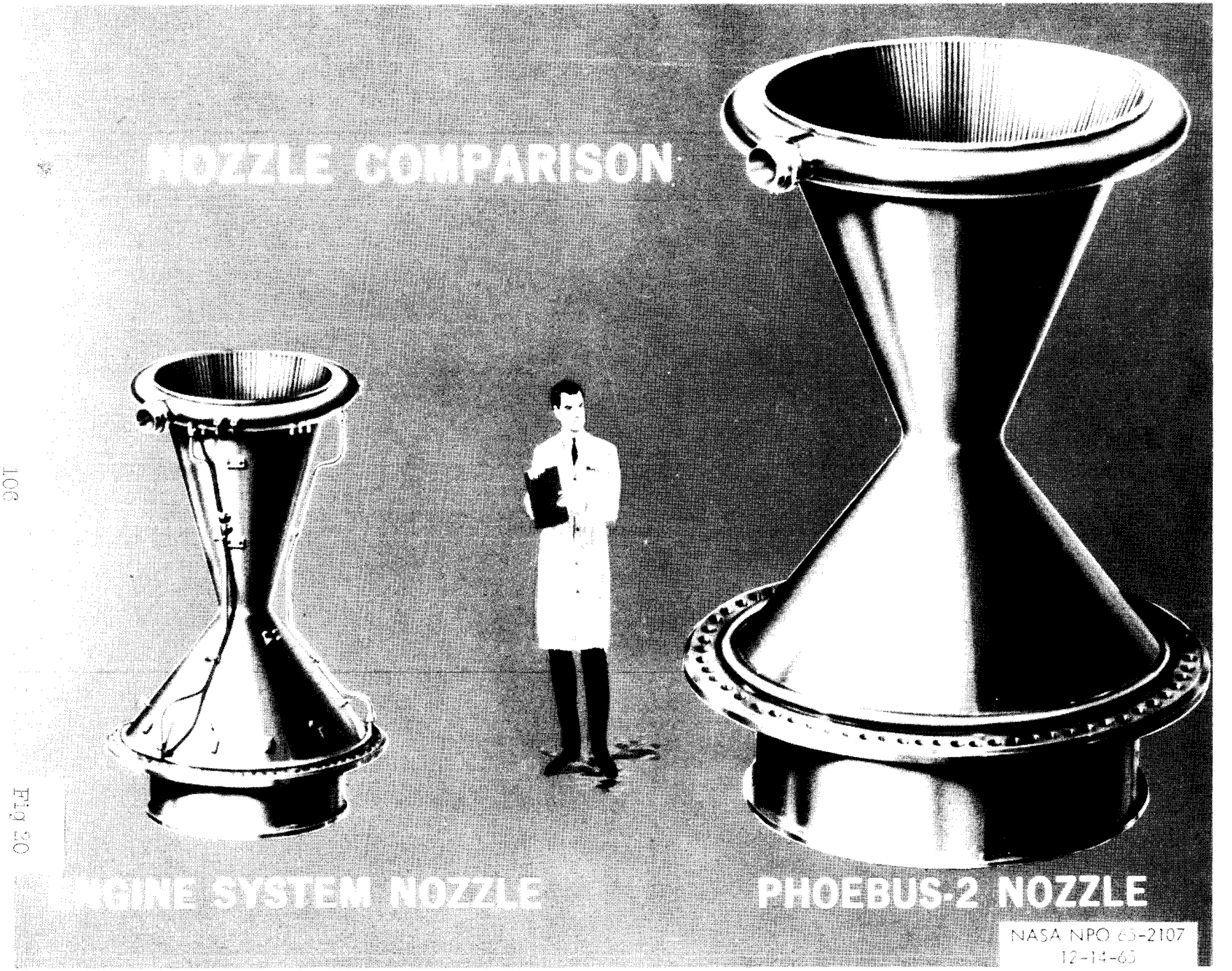
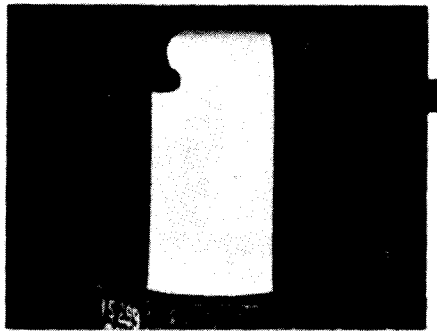

NOZZLE COMPARISON
ENGINE SYSTEM NOZZLE
PHOEBUS-2 NOZZLE
NASA NPO 65-2107
12-14-65

Fig 20

PHOEBUS-2 NOZZLE DEVELOPMENT
PRESSURE VESSEL FABRICATION



INGOT READY FOR BARREL FORGING STEP

BARREL FORGING

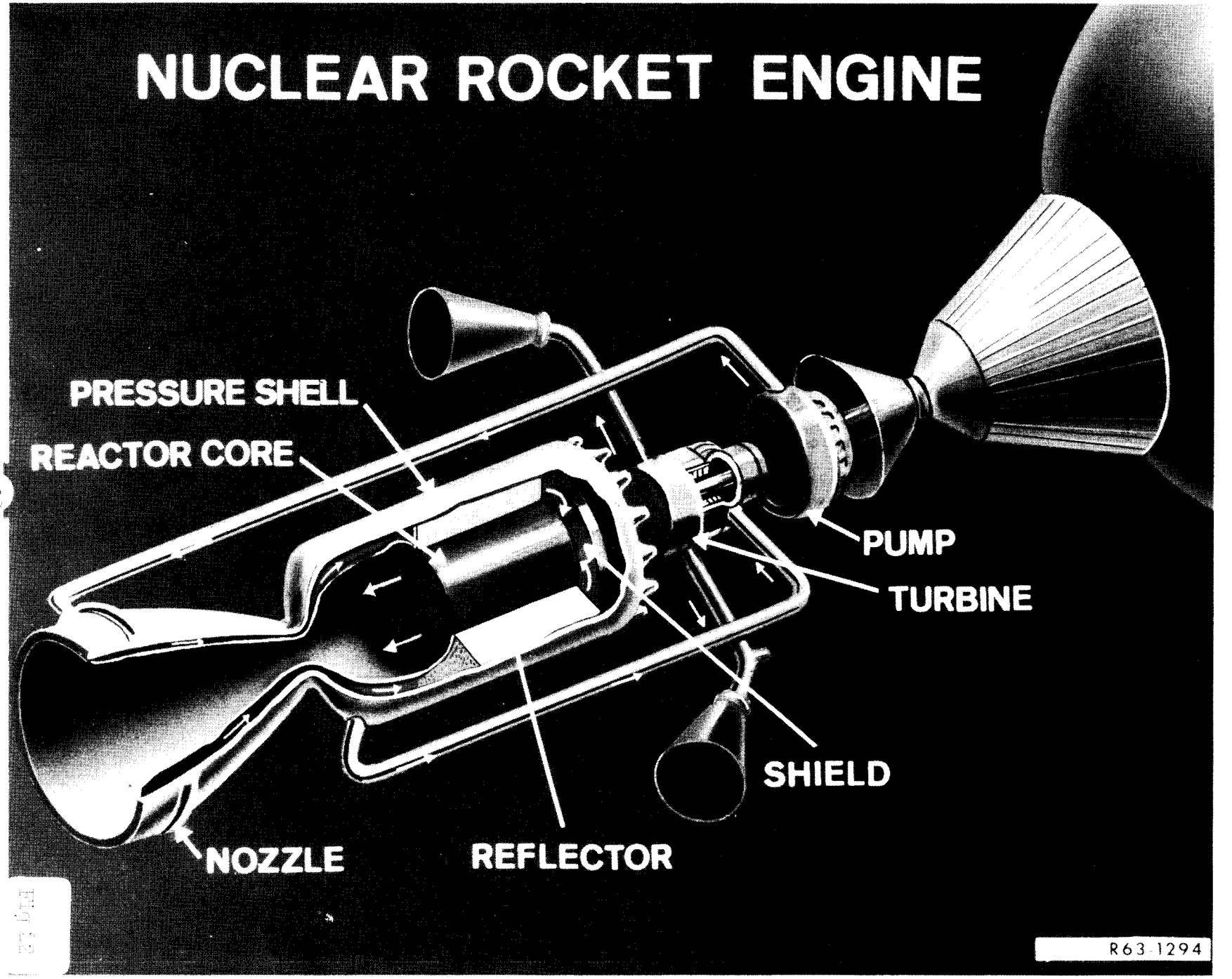
DIE FORGED

PANCAKED FORGING

ROUGH MACHINED

NASA NPO 66-346
2-1-66

Fig 21


NUCLEAR ROCKET ENGINE
PRESSURE SHELL
REACTOR CORE
PUMP
TURBINE
SHIELD
NOZZLE
REFLECTOR
R63-1294

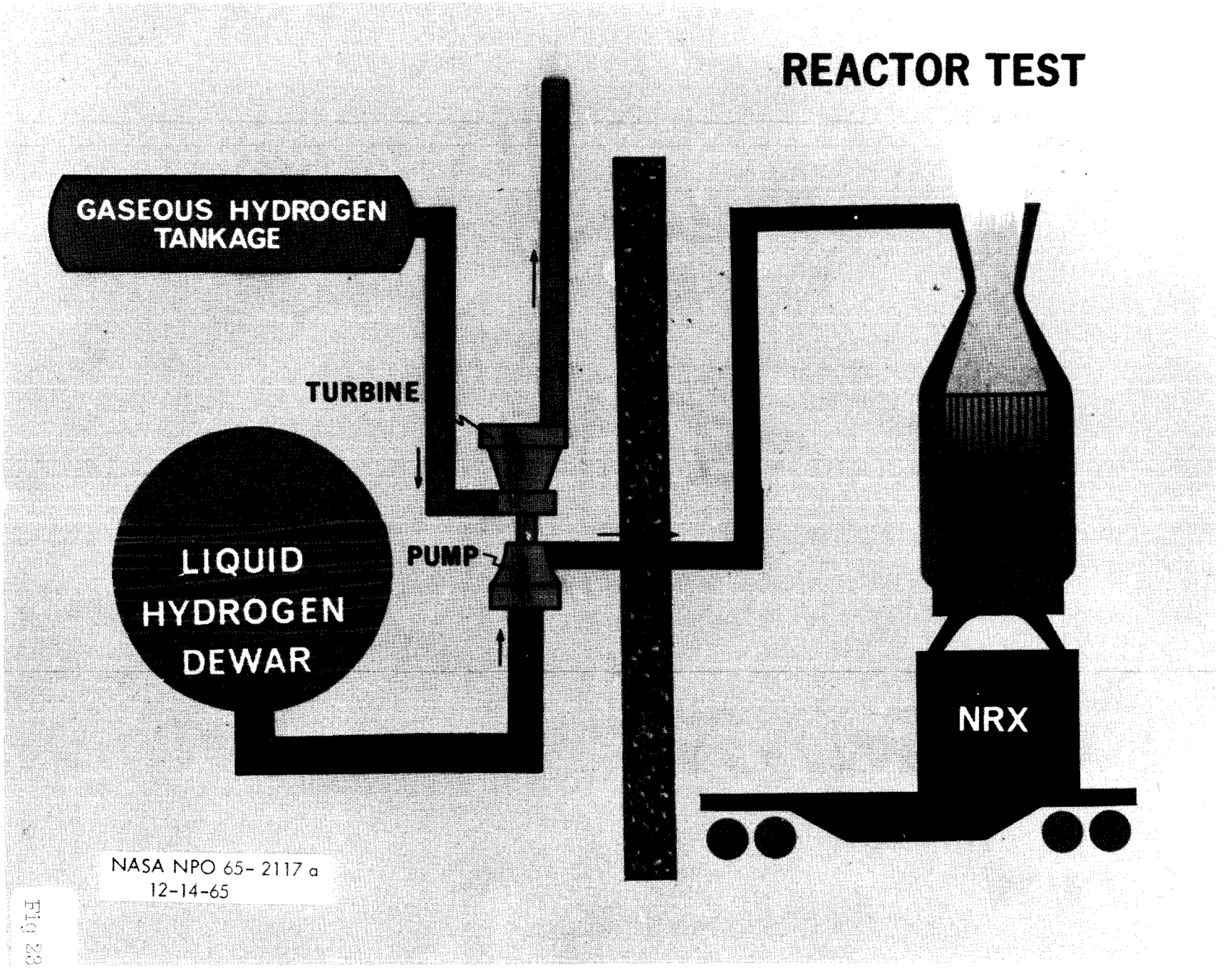
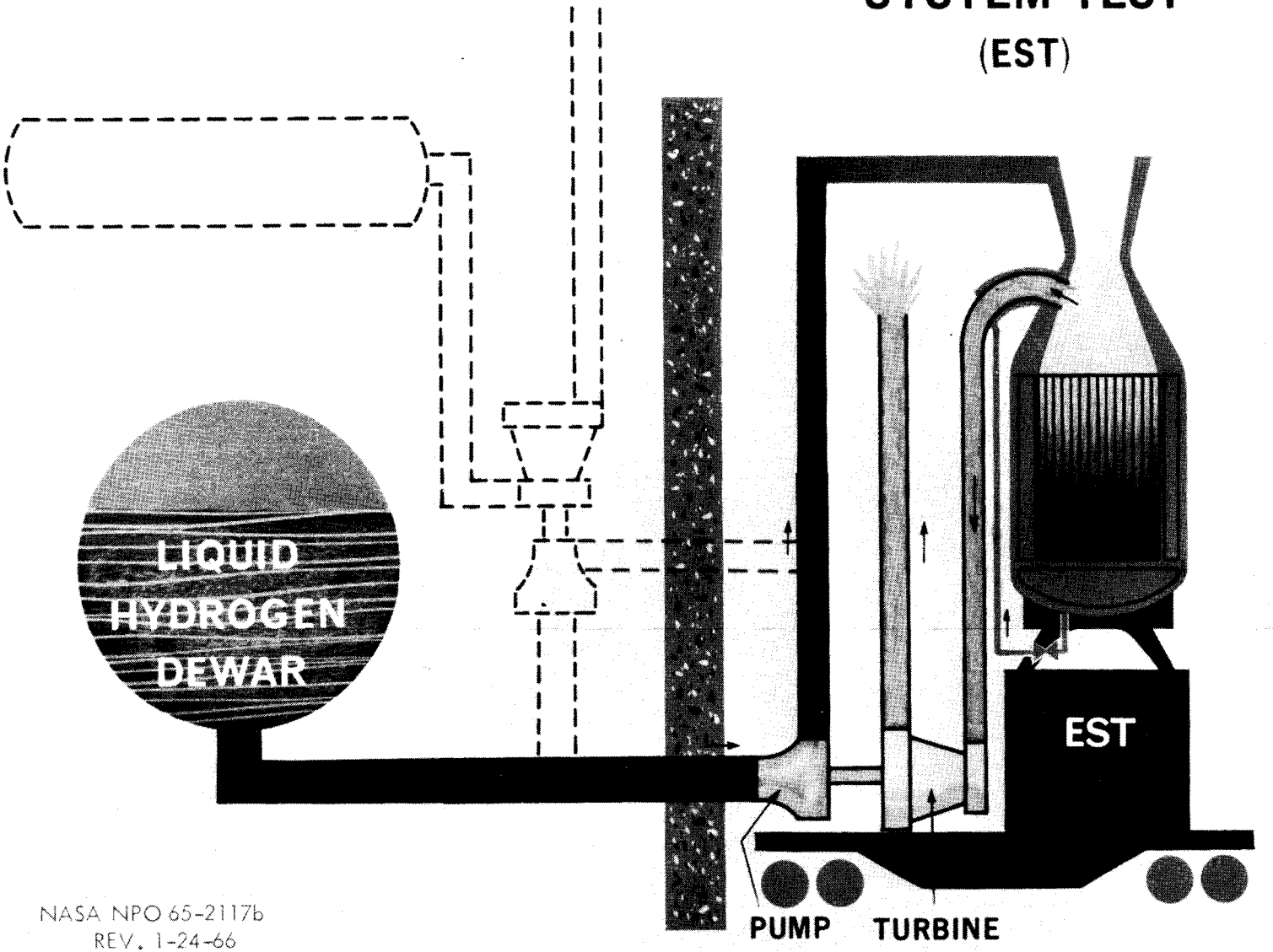

REACTOR TEST
GASEOUS HYDROGEN TANKAGE
TURBINE
PUMP
LIQUID HYDROGEN DEWAR
NRX
NASA NPO 65- 2117 a
12-14-65

FIG 28

BREADBOARD ENGINE SYSTEM TEST

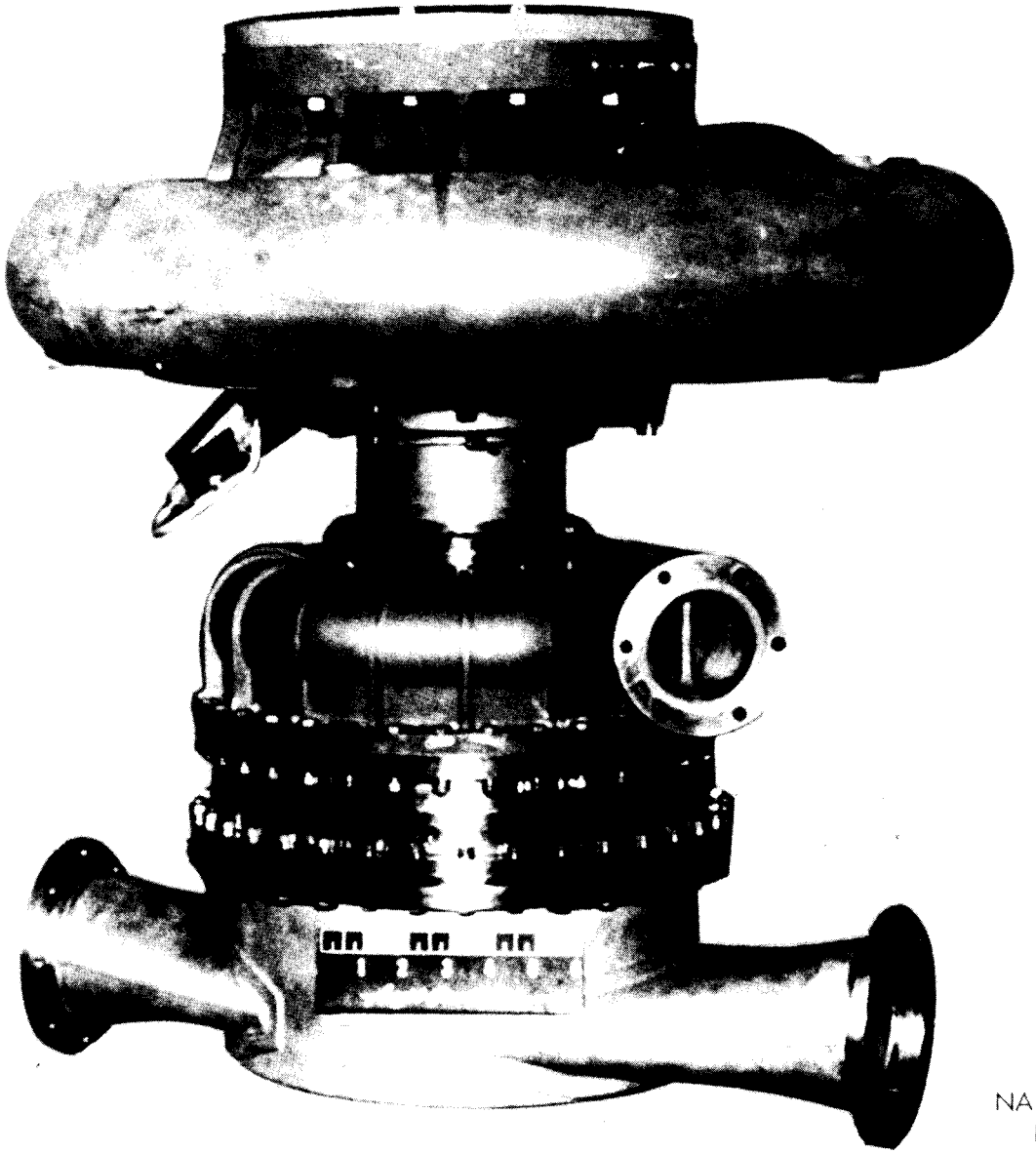
(EST)



NASA NPO 65-2117b
REV. 1-24-66

Fig 24

NERVA/EST TURBOPUMP



NASA NPO 64-669
REV. 1-24-66

Fig 25

HOT BLEED PORT NOZZLE - ENGINE SYSTEM TESTS

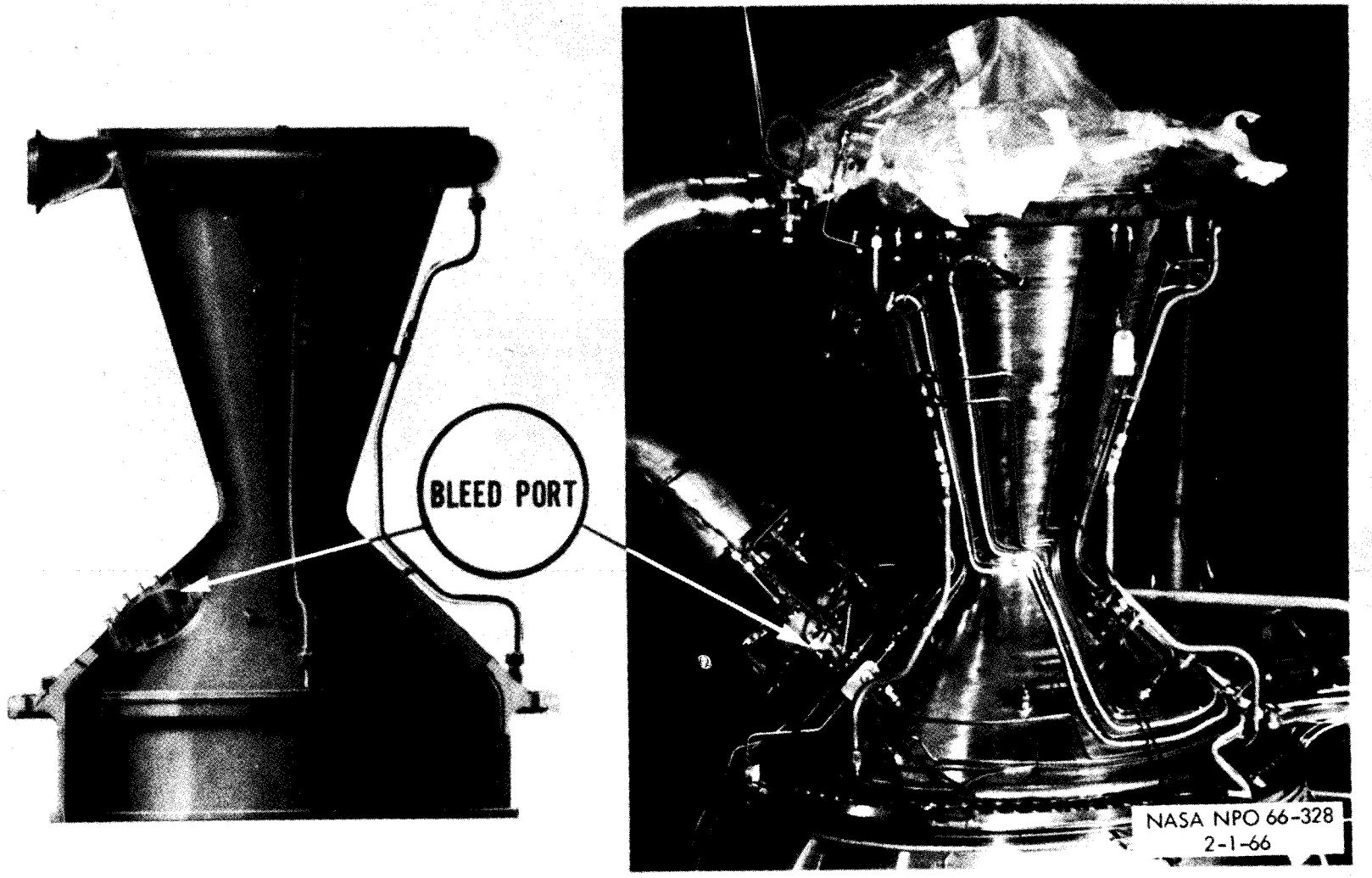


Fig 26

NUCLEAR ROCKET SYSTEMS EXPERIMENT

LEWIS RESEARCH CENTER

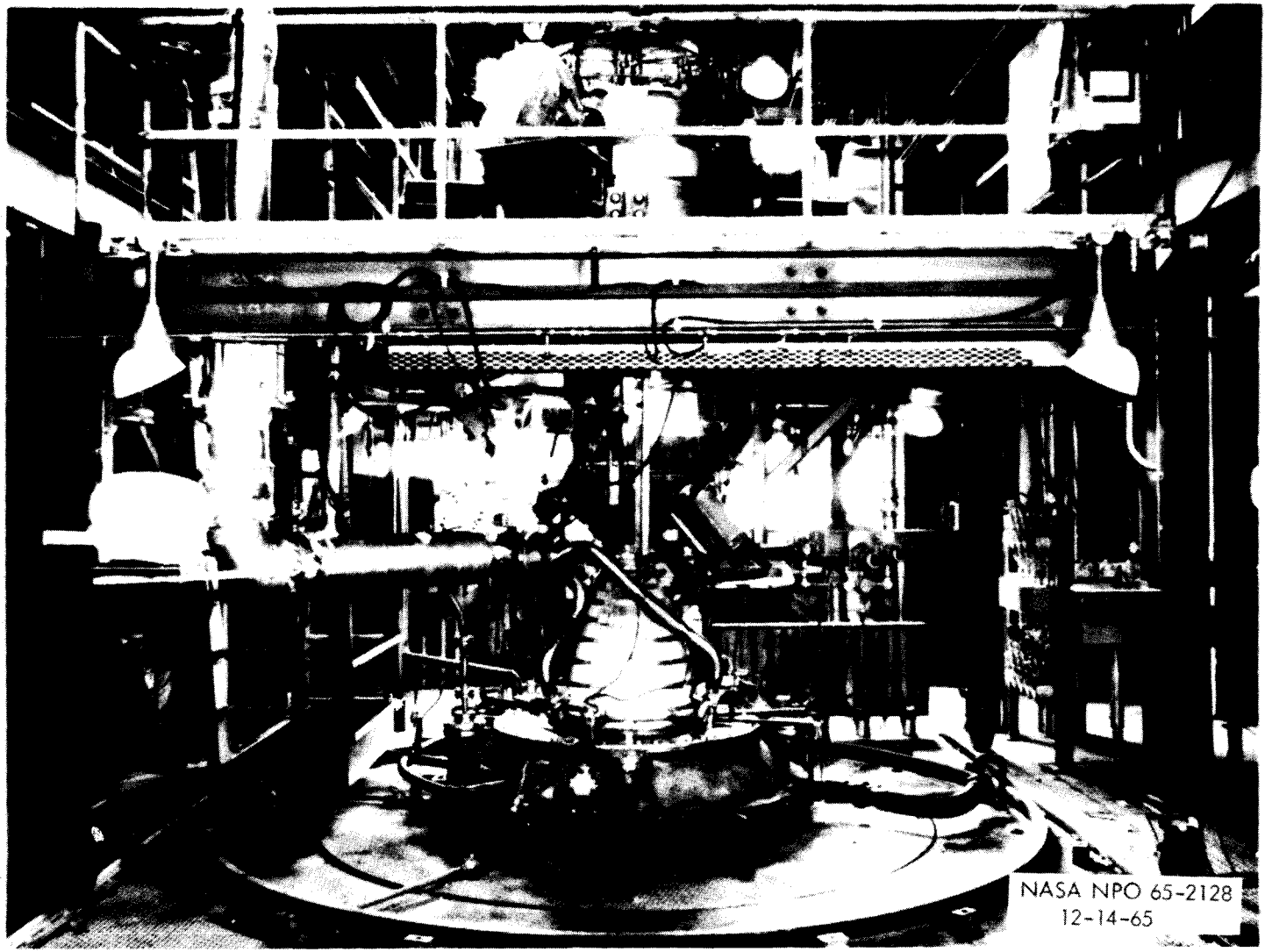
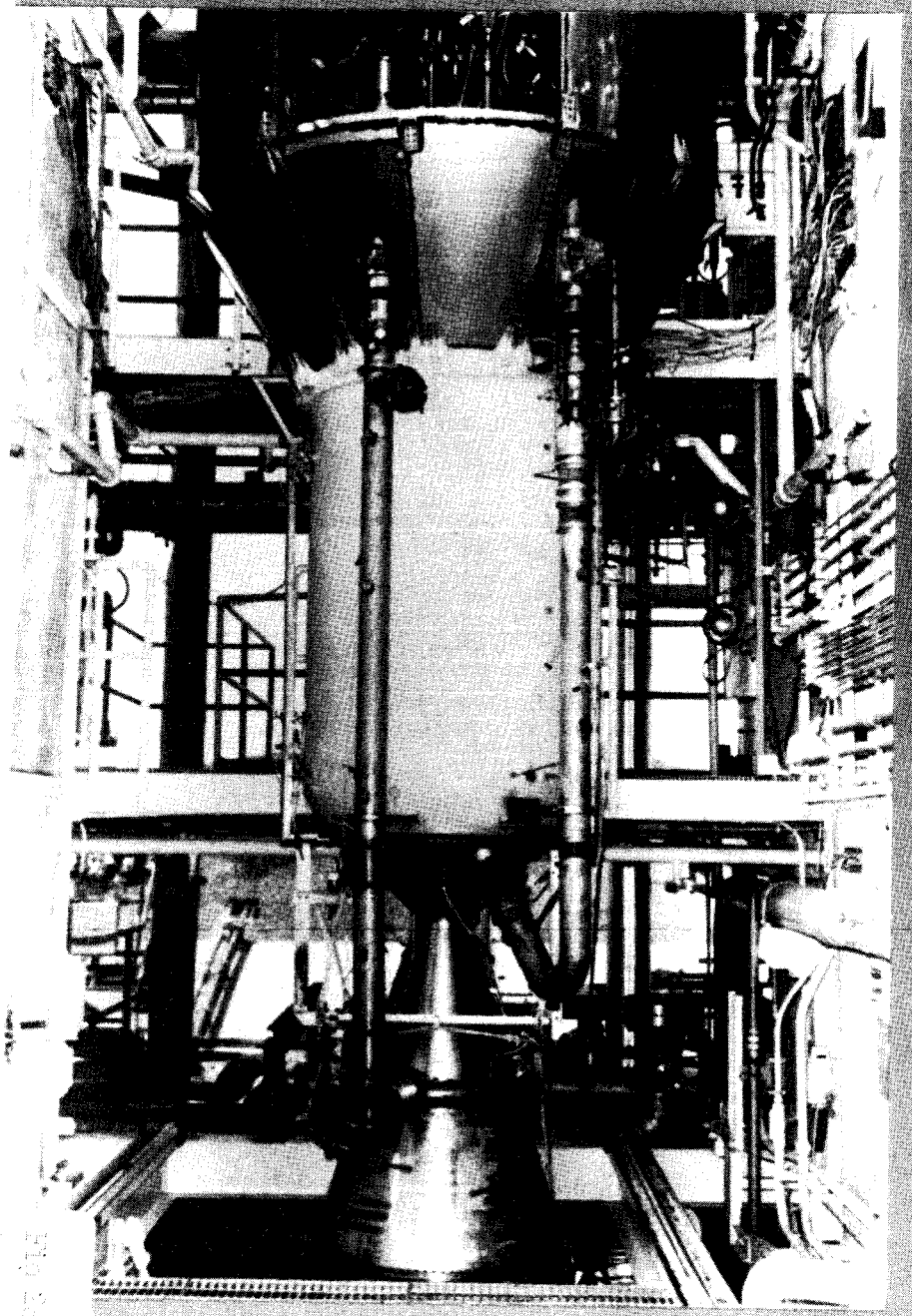


Fig 27



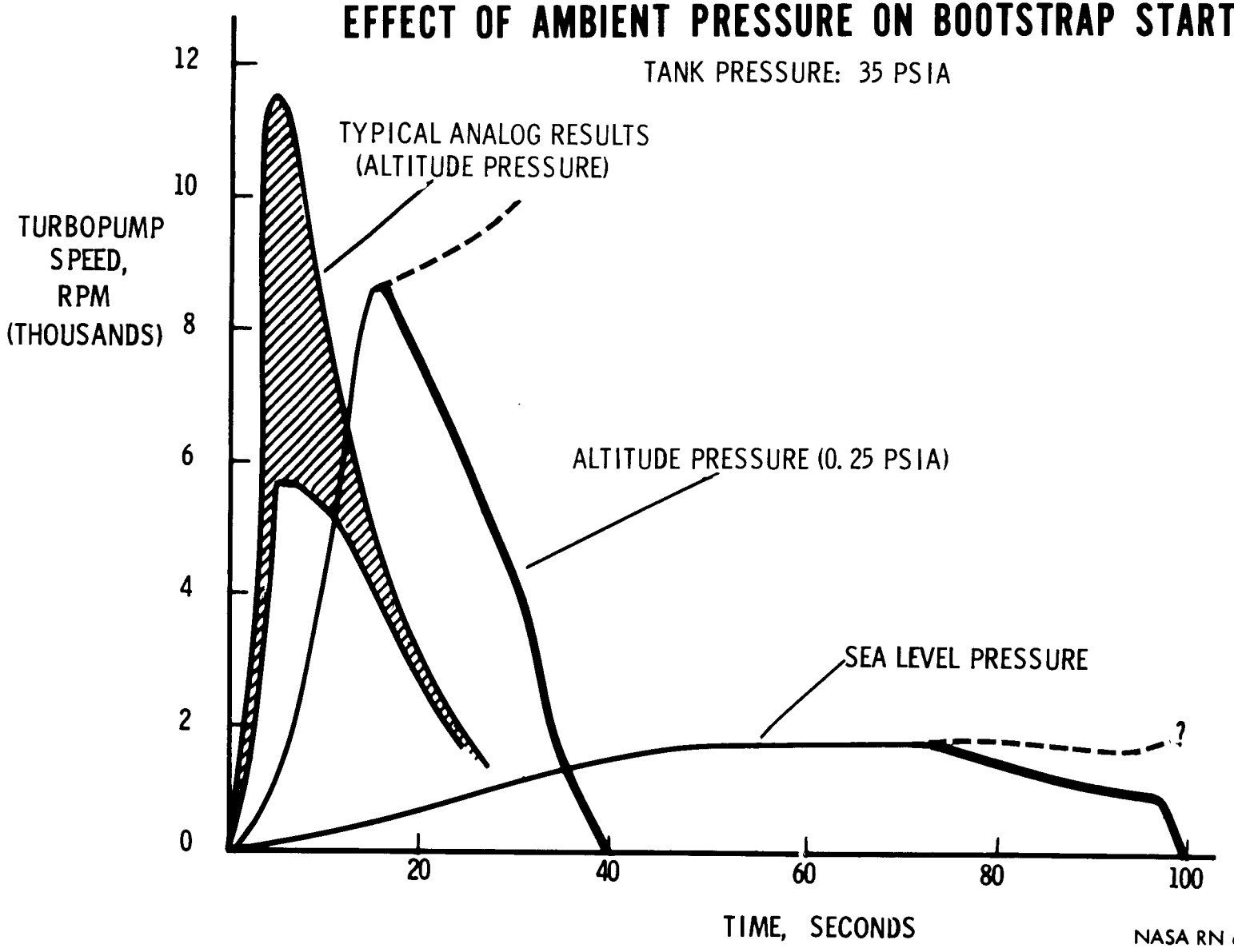
COLD-FLOW ENGINE SYSTEM

(INSTALLED AT SACRAMEN

NASA NPO 65-15,24
12-13-65

COLD–FLOW ENGINE TESTS
EFFECT OF AMBIENT PRESSURE ON BOOTSTRAP STARTUP

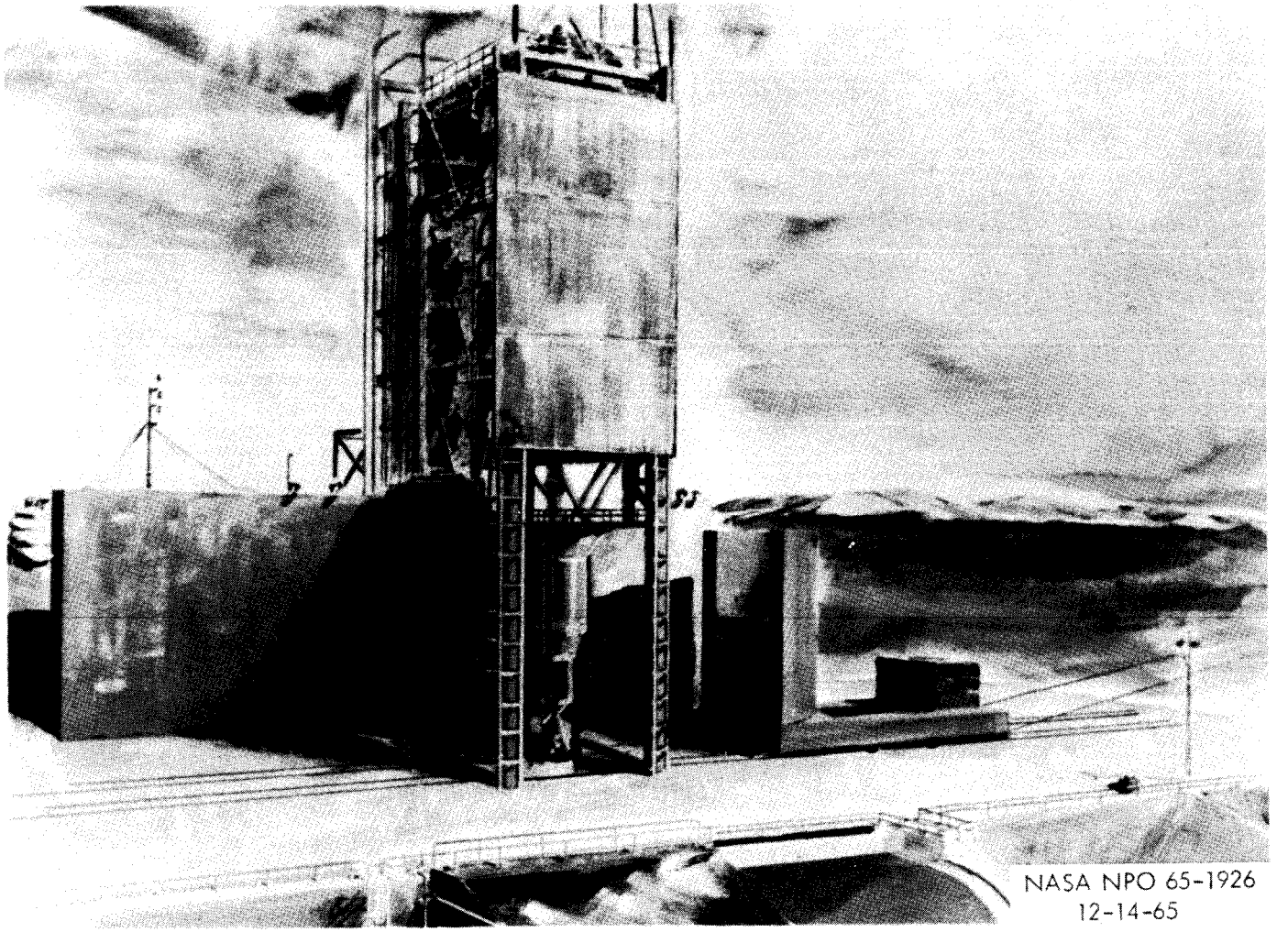
TANK PRESSURE: 35 PSIA



NASA RN 65-2048
12-14-65

Fig 29

GROUND EXPERIMENTAL ENGINE IN TEST STAND



NASA NPO 65-1926
12-14-65

Fig 30

EXHAUST-DUCT ELBOW FABRICATION
(ETS-1)

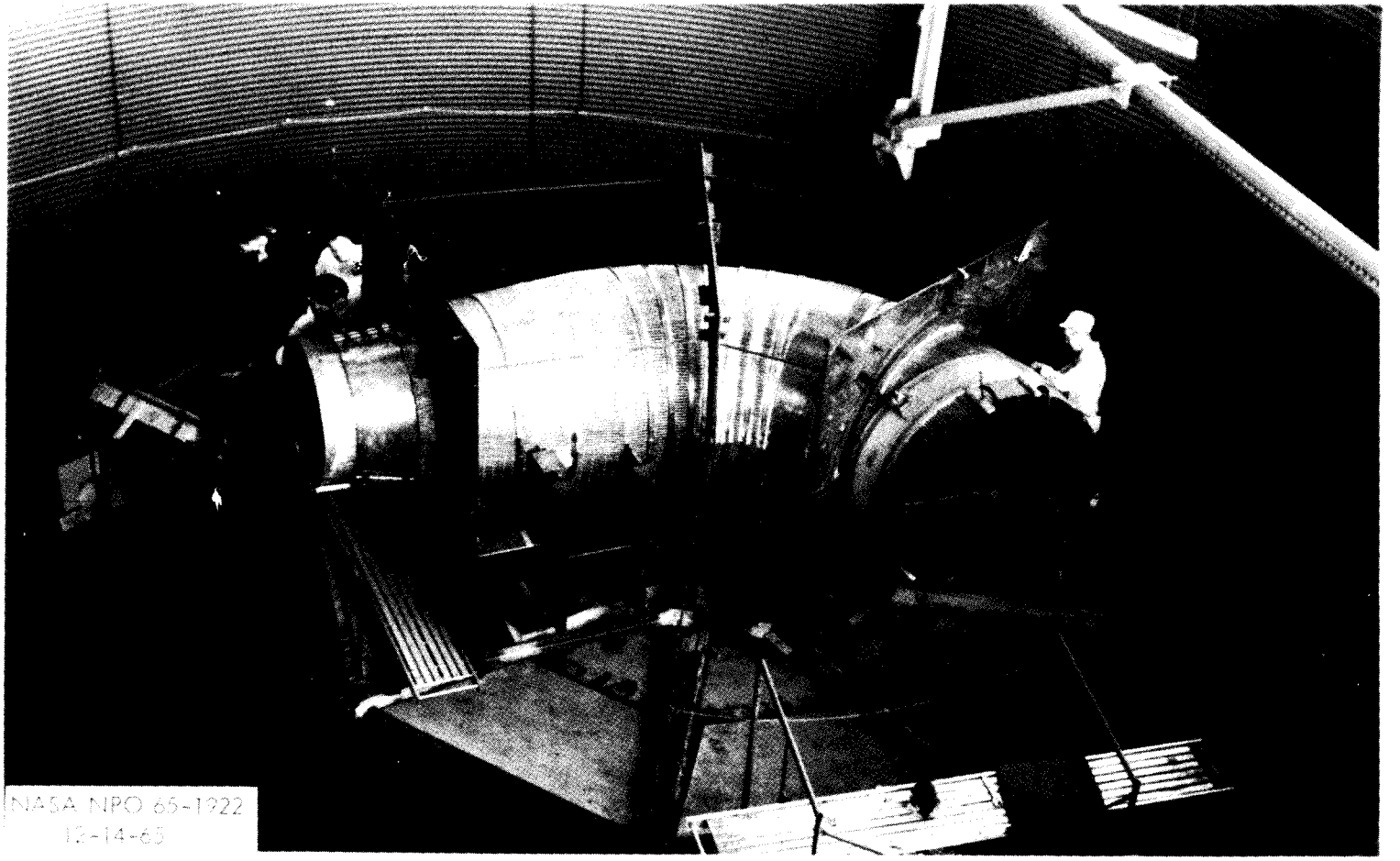
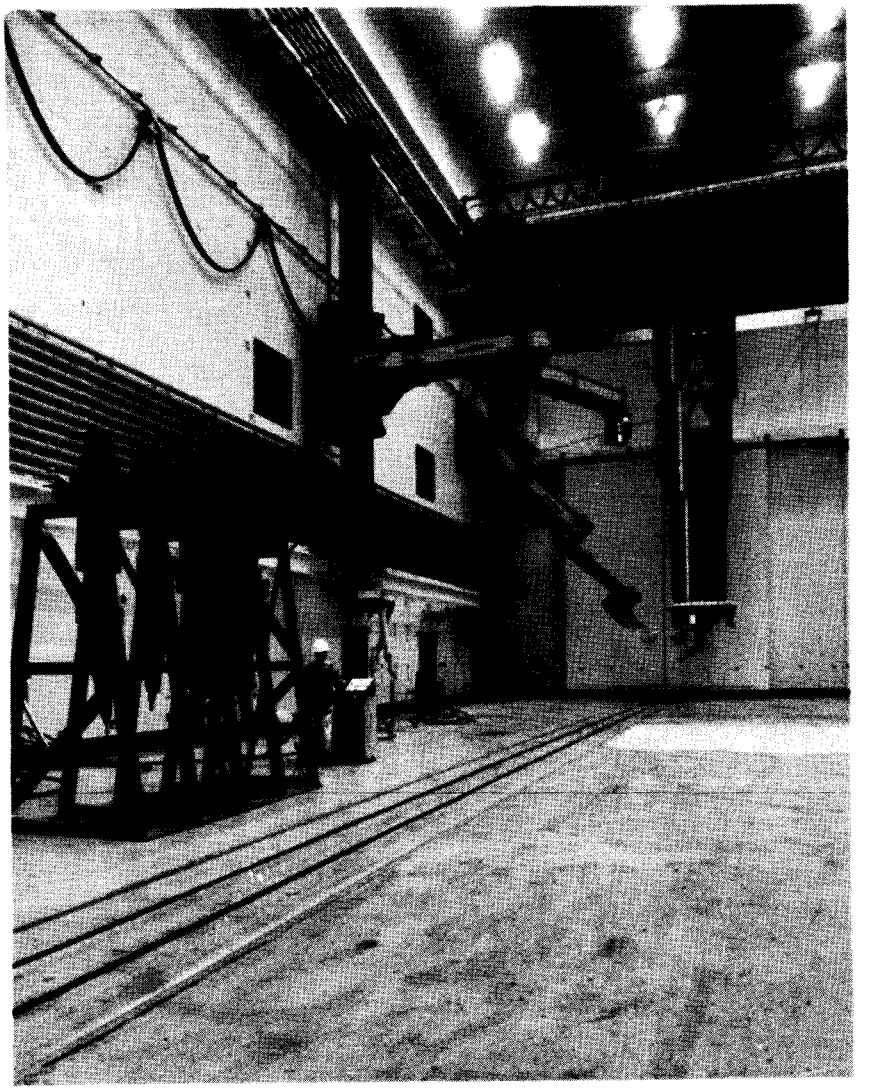


Fig 31

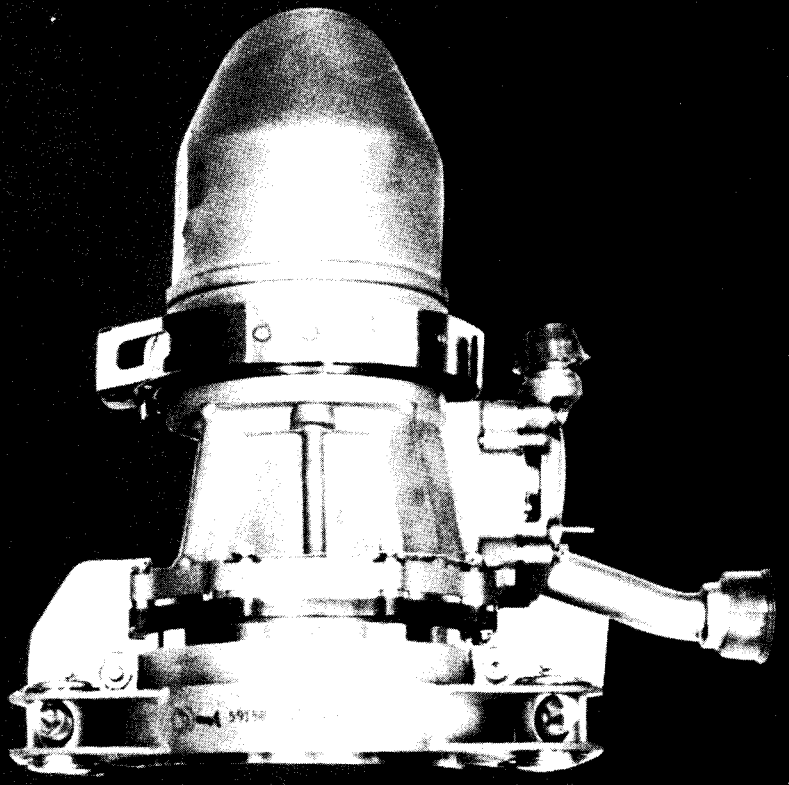
E-MAD HANDLING EQUIPMENT



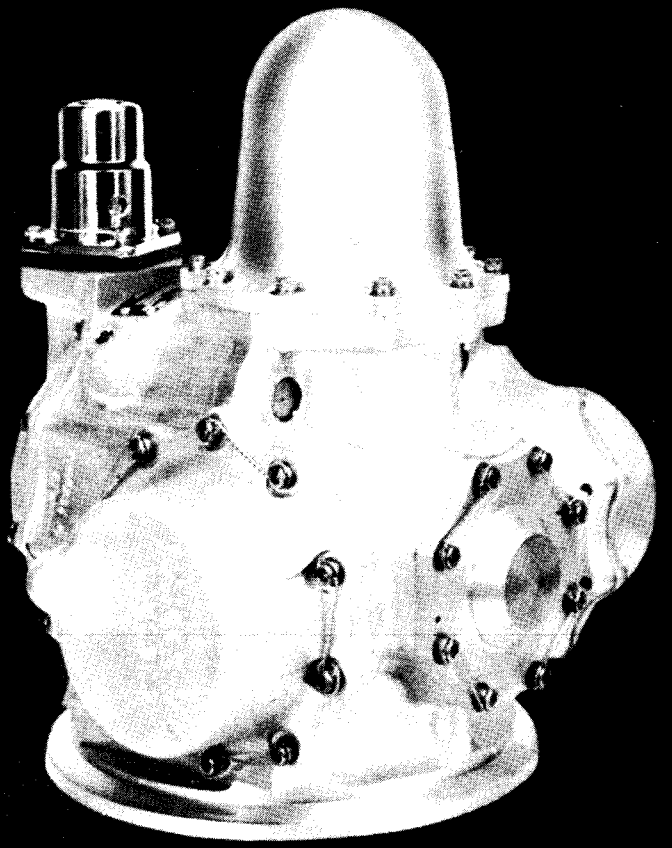
NASA NPO 65-1930
12-14-65

Fig 32

ELECTRO-PNEUMATIC ENGINE SYSTEM ACTUATORS



TURBINE-POWER CONTROL VALVE ACTUATOR



REACTOR CONTROL-DRUM ACTUATOR

NASA NPO 65-1914
REV. 1-24-66

Fig 33

PRESSURE, ACCELERATION, AND TEMPERATURE MEASUREMENT TRANSDUCERS TESTED FOR NUCLEAR ROCKET PROGRAM APPLICATION

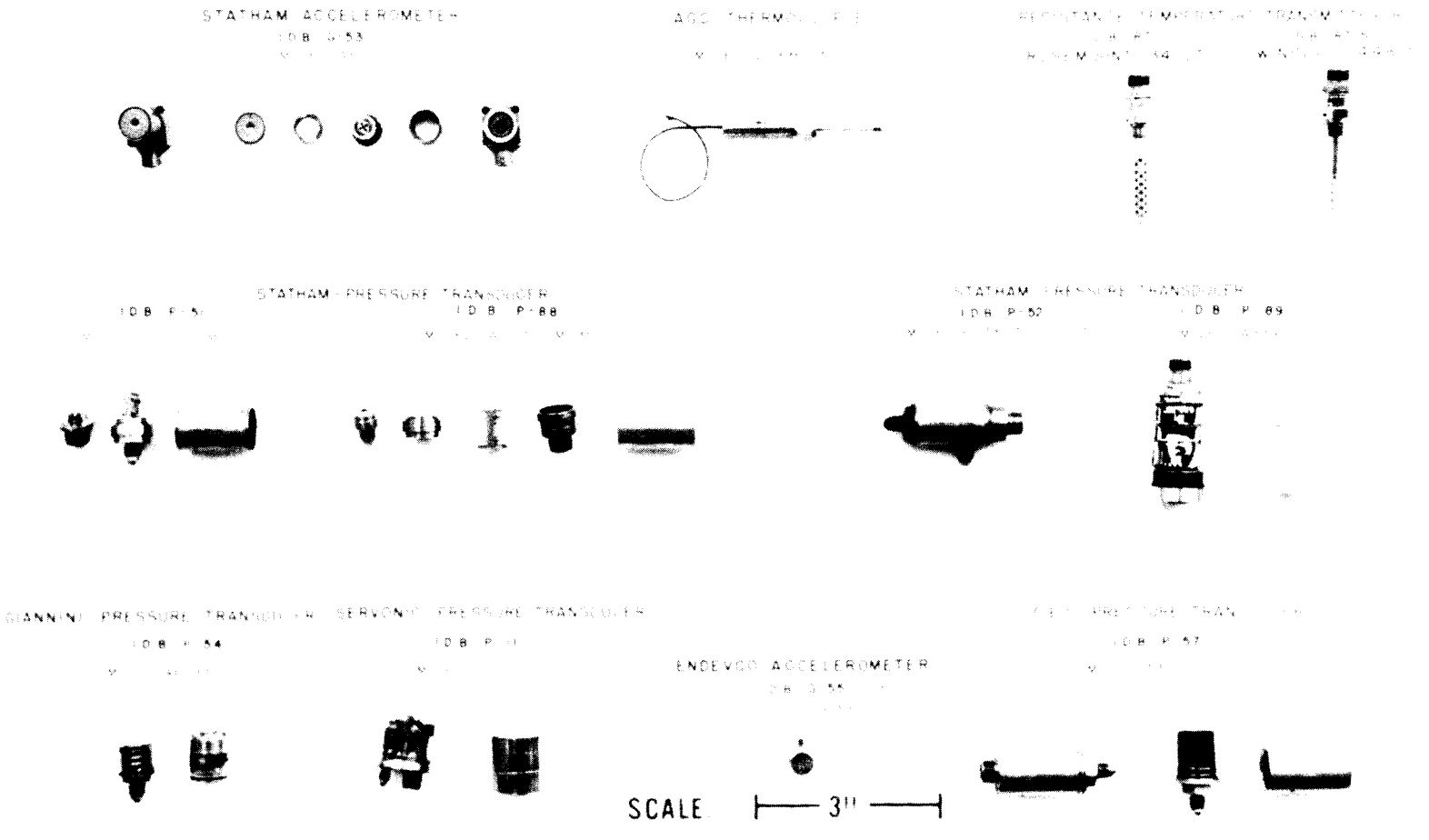


Fig 34

CABLE AND CABLE ASSEMBLIES TESTED FOR NUCLEAR ROCKET PROGRAM APPLICATION

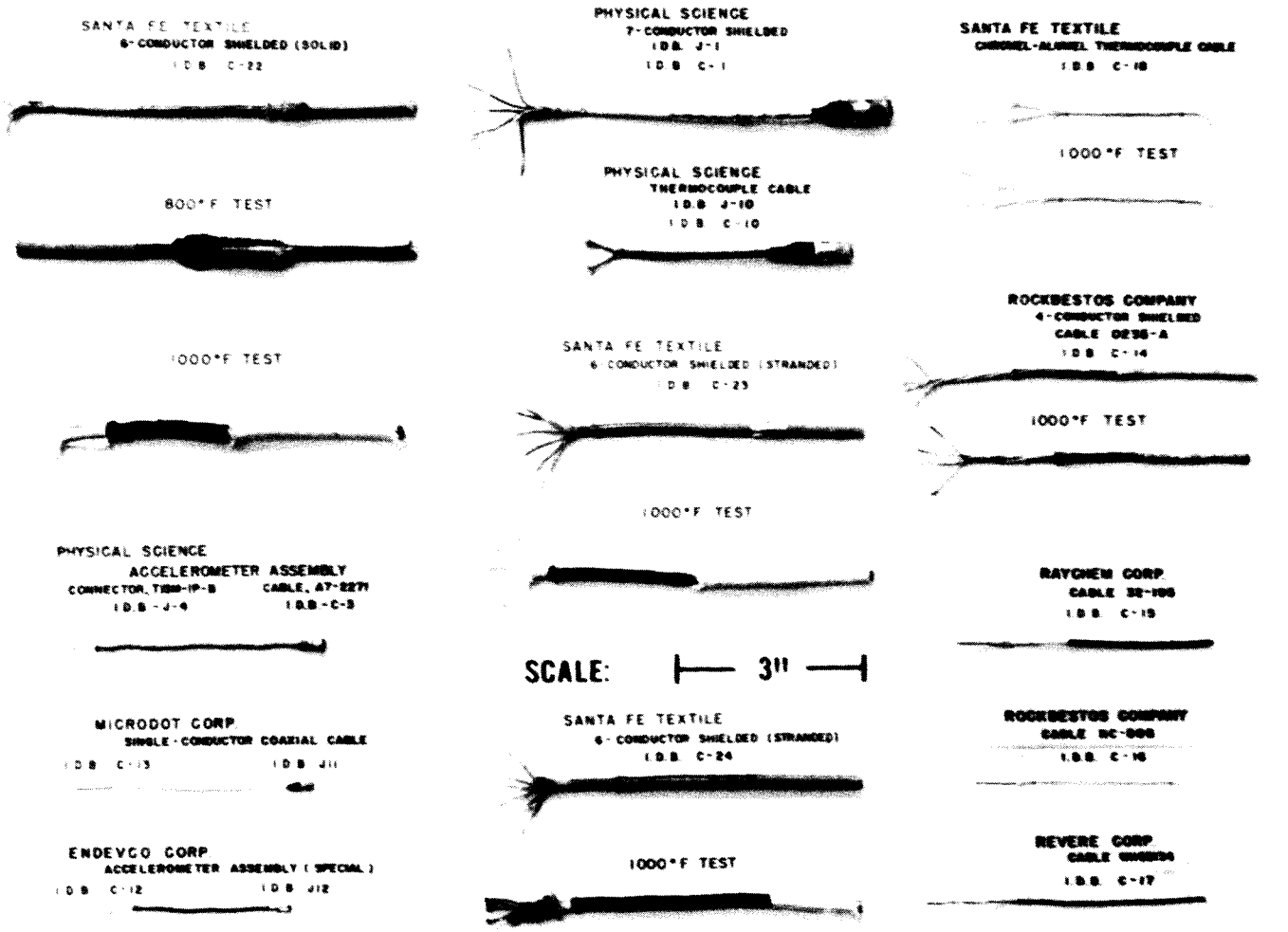
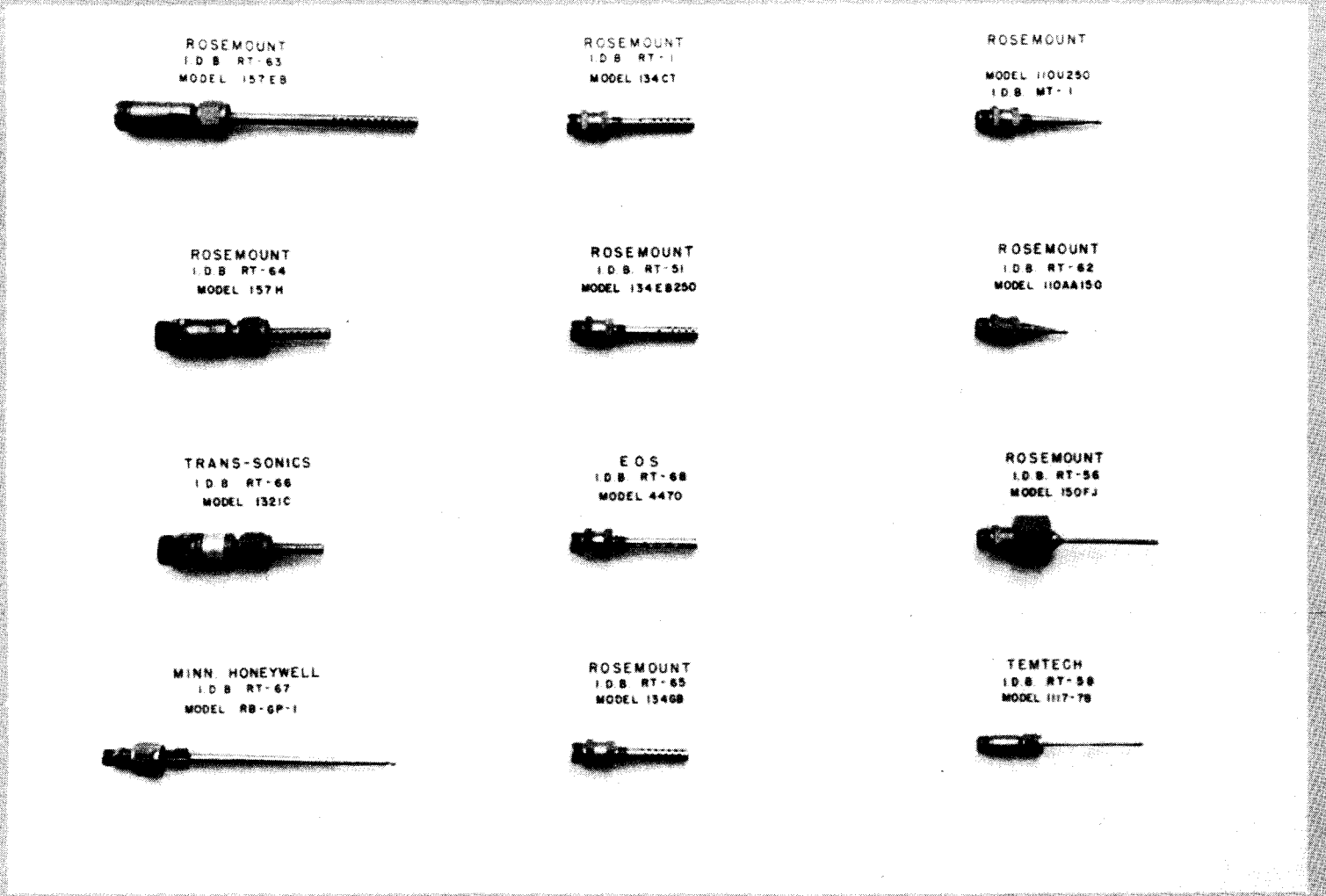


Fig 35

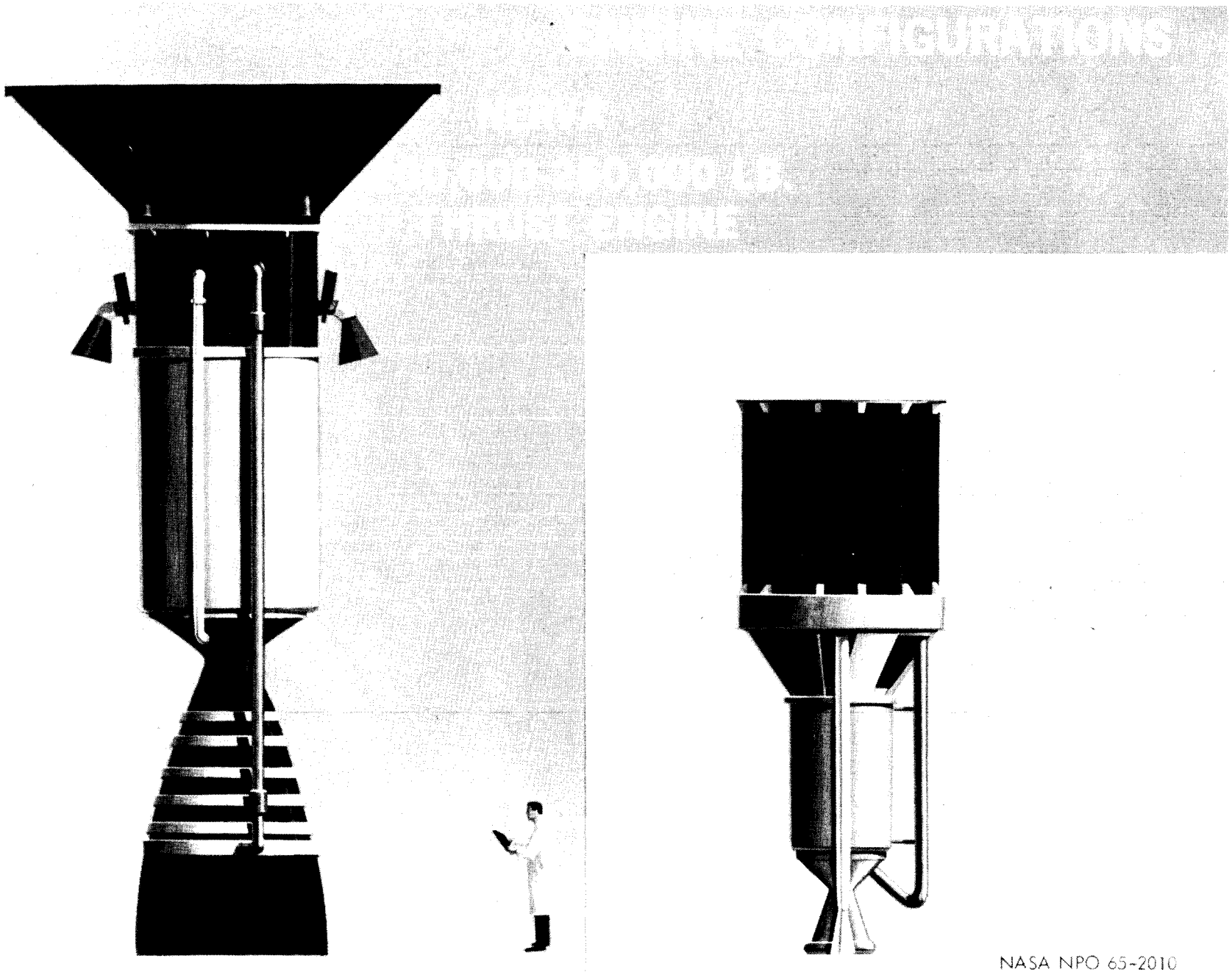
PLATINUM RESISTANCE TEMPERATURE TRANDUCERS TESTED FOR NUCLEAR ROCKET PROGRAM APPLICATION



SCALE: 5'

NASA NPO 66-348
2-1-66

Fig 36

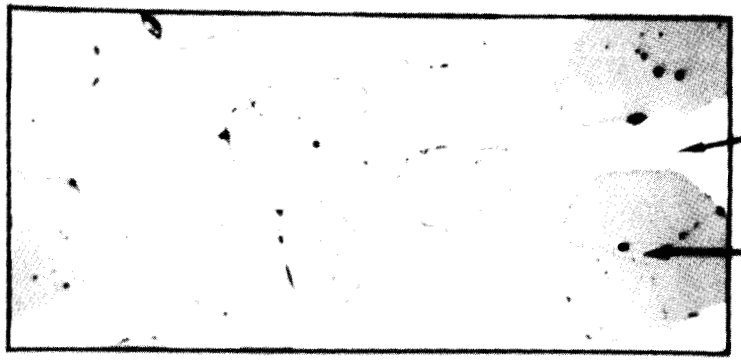


NASA NPO 65-2010
12-14-65

Fig 37

THERMAL CYCLE FAILURE OF TUNGSTEN URANIUM-DIOXIDE FUEL IN HYDROGEN

AS FABRICATED



AFTER THERMAL CYCLING IN HYDROGEN

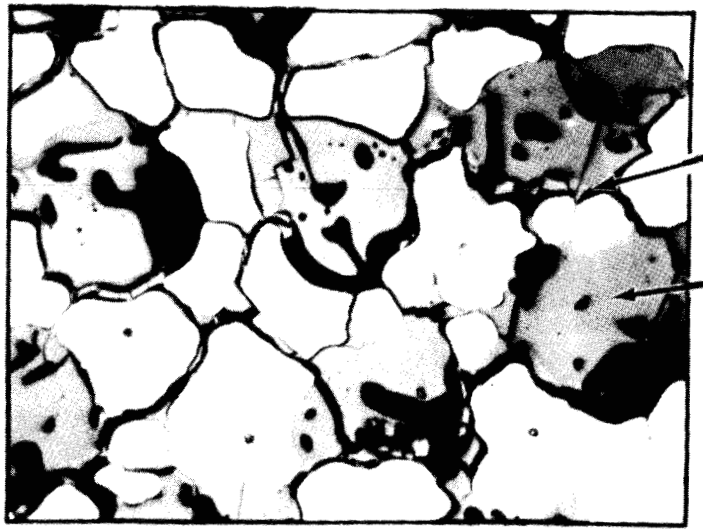
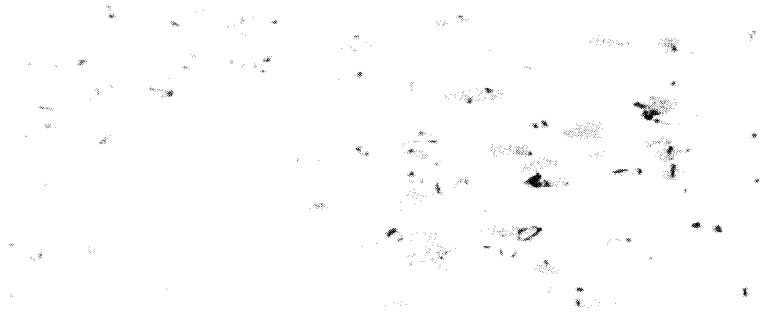


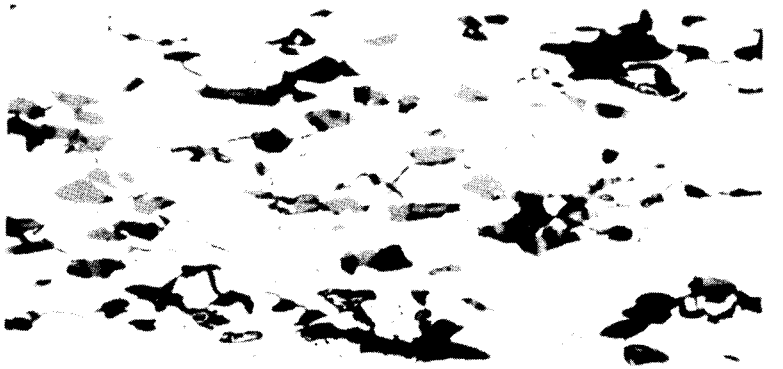
Fig 33

IMPROVED TUNGSTEN URANIUM-DIOXIDE FUEL

IMPROVED PROCESS CONTROL



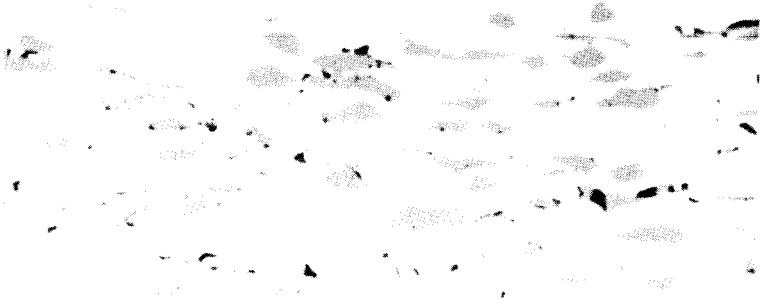
BEFORE TEST



AFTER TEST

IMPROVED PROCESS CONTROL PLUS OXIDE ADDITIVES

BEFORE TEST



AFTER TEST

NASA NPO 65-1999
12-18-65

TUNGSTEN URANIUM-DIOXIDE FUEL

FABRICATION STATUS 1962-1963

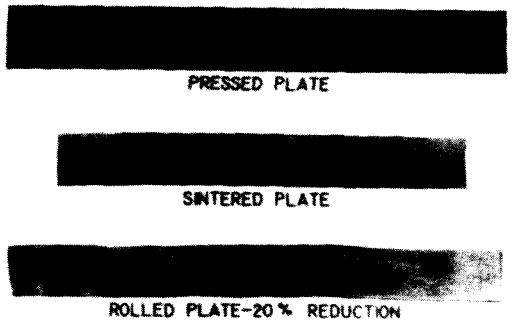
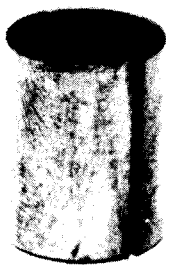


PLATE FABRICATION



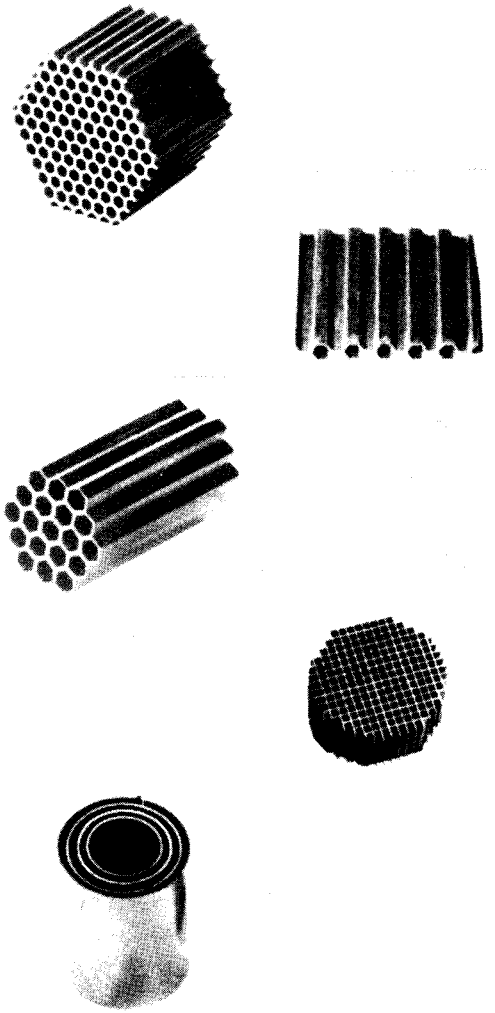
HOT FORMING

NASA NPO 65-1990
12-14-65

126

Fig 40

TUNGSTEN URANIUM DIOXIDE FUEL
FABRICATION SURVEY 1963-1964



- PNEUMATIC IMPACTION
- CO-EXTRUSION
- COLD-ROLLED WITH BINDERS
- ROLL FORMING
- SWAGING
- MAGNETIC FORMING
- ISOSTATIC COMPACTION
- PRESSING AND SINTERING
- DIFFUSION BONDING
- VAPOR CEMENTATION

NASA NPO 65-2000
REV. 1-24-66

Fig 41

COMPARISON BETWEEN SOLID–CORE REACTORS AND CAVITY REACTOR CONCEPTS

CONCEPT	SPECIFIC IMPULSE SECONDS	PROPELLANT CONDITIONS		NUCLEAR FUEL TEMPERATURE °R
		TEMP. °R	PRESS., psi	
SOLID CORE REACTORS	850 - 900	5000	< 1000	5500
CAVITY REACTORS				
DUST BED	1100	6200	1000	6500
LIQUID NUCLEAR FUEL	1500	10, 000	4000	15, 000
GASEOUS NUCLEAR FUEL	2500	30, 000	15, 000	140, 000

NASA NPO 65-1996
Rev. 2-23-66

Fig 42

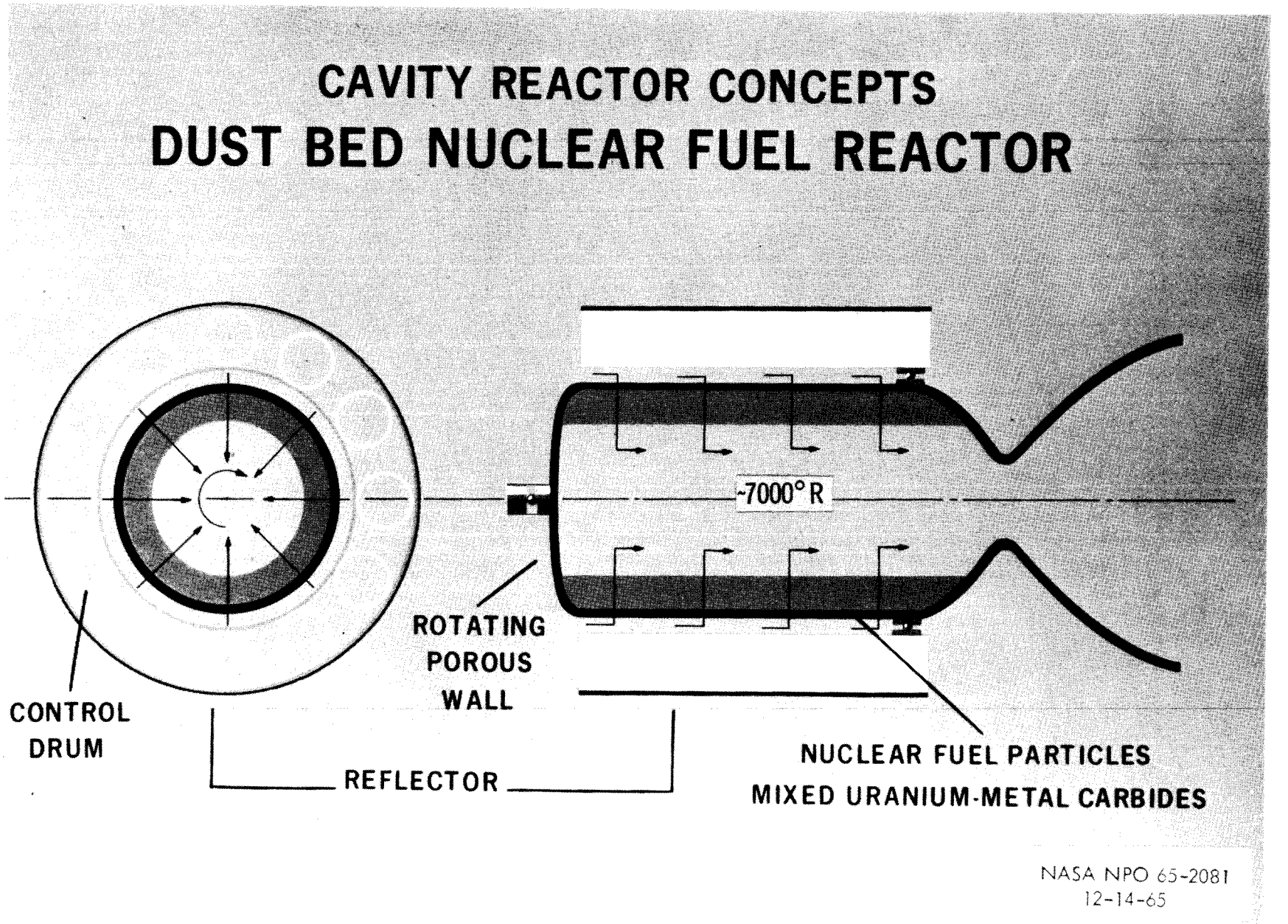

CAVITY REACTOR CONCEPTS
DUST BED NUCLEAR FUEL REACTOR
~7000° R
ROTATING
POROUS
WALL
CONTROL
DRUM
REFLECTOR
NUCLEAR FUEL PARTICLES
MIXED URANIUM-METAL CARBIDES
NASA NPO 65-2081
12-14-65

Fig 43

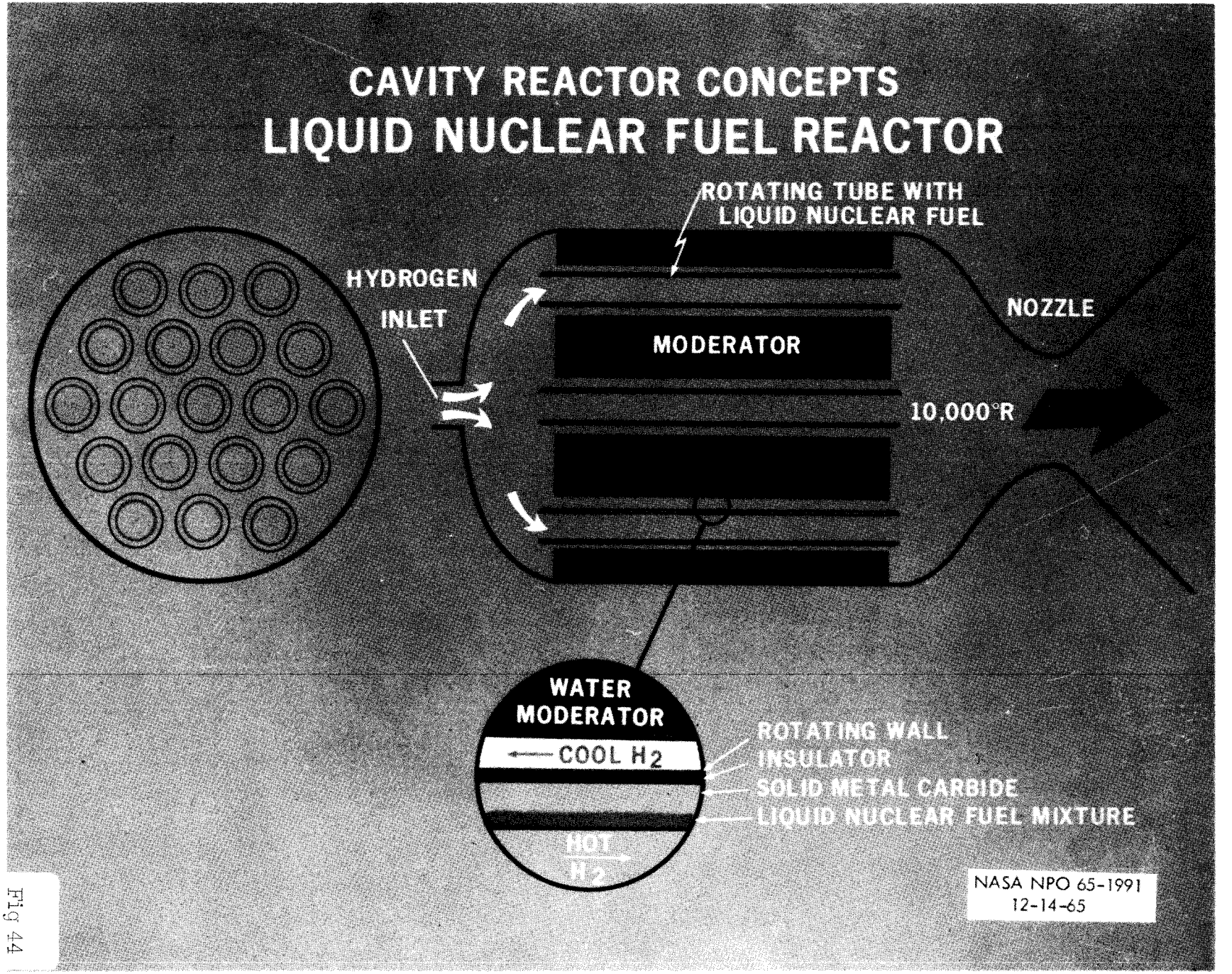
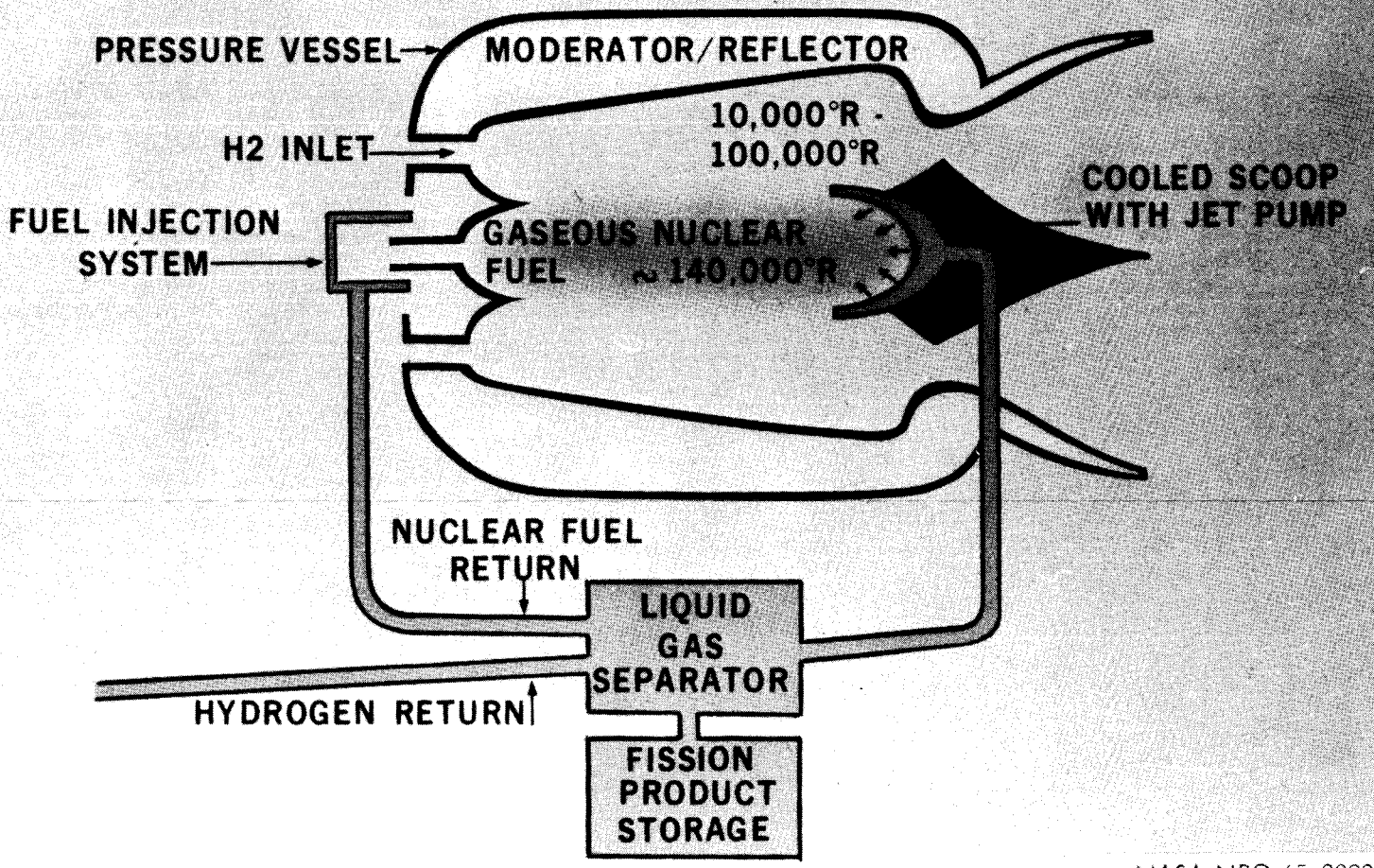

CAVITY REACTOR CONCEPTS
LIQUID NUCLEAR FUEL REACTOR
ROTATING TUBE WITH LIQUID NUCLEAR FUEL
HYDROGEN INLET
MODERATOR
NOZZLE
10,000°R
WATER MODERATOR
COOL H2
HOT H2
ROTATING WALL
INSULATOR
SOLID METAL CARBIDE
LIQUID NUCLEAR FUEL MIXTURE
NASA NPO 65-1991
12-14-65

Fig 44

CAVITY REACTOR CONCEPTS
COAXIAL FLOW GASEOUS NUCLEAR FUEL REACTOR WITH FUEL SCOOP



NASA NPO 65-2092
12-14-65

Fig 45

CAVITY REACTOR CONCEPTS RESEARCH TASKS

PART A

- LEWIS RESEARCH CENTER
  - CONCEPT STUDIES
  - COAXIAL FLOW FLUID MECHANICS
  - HYDROGEN OPACITY ($\longrightarrow$ 20,000^{0}R)
  - RADIATIVE HEAT TRANSFER
  - CAVITY REACTOR NEUTRONICS

- UNITED AIRCRAFT RESEARCH LABORATORY
  - VORTEX FLOW FLUID MECHANICS
  - RADIATIVE HEAT TRANSFER

NASA NPO 65-1993
12-14-65

Fig 46

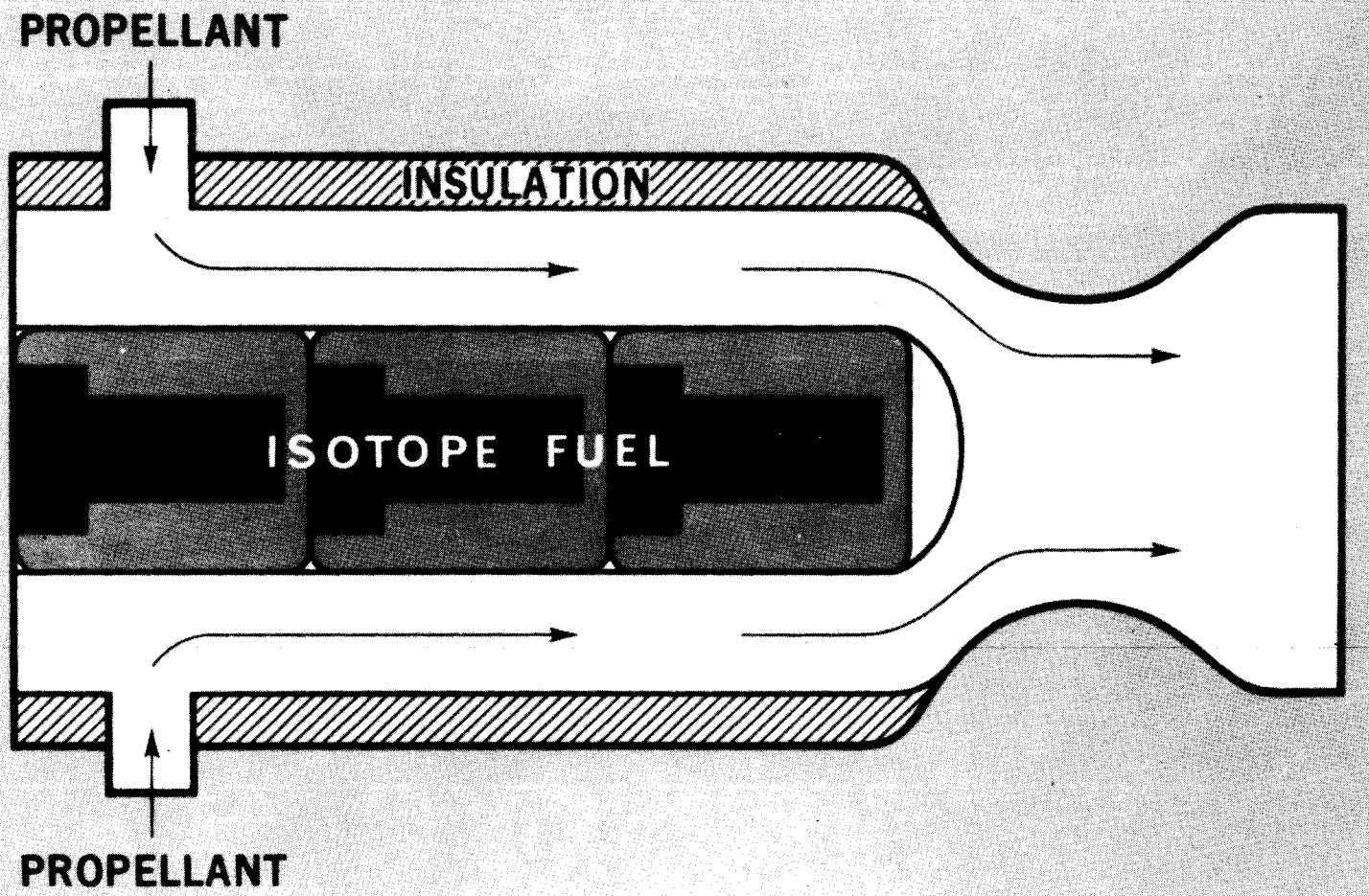
CAVITY REACTOR CONCEPTS RESEARCH TASKS
PART B

- TRW SYSTEMS - CONCEPT STUDY
- DOUGLAS AIRCRAFT - FLASH HEATING TESTS
- G. E. NMPO - CAVITY REACTOR CRITICAL TESTS
- BROOKHAVEN NATIONAL LABORATORY - DUST BED CONCEPT RESEARCH
- ILLINOIS INSTITUTE OF TECHNOLOGY- VORTEX FLUID MECHANICS
- GEORGIA INSTITUTE OF TECHNOLOGY - RADIATIVE GAS HEAT TRANSFER
- CASE INSTITUTE OF TECHNOLOGY - CAVITY REACTOR SUBCRITICAL TESTS
- CATHOLIC UNIVERSITY OF AMERICA - VORTEX FLUID MECHANICS
- PRINCETON UNIVERSITY - HIGH TEMPERATURE CO-AXIAL FLOW
- TEMPLE UNIVERSITY - LIQUID CARBIDE TESTS

NASA NPO 65-2001
12-14-65

Fig 46a

ISOTOPIC THRUSTER

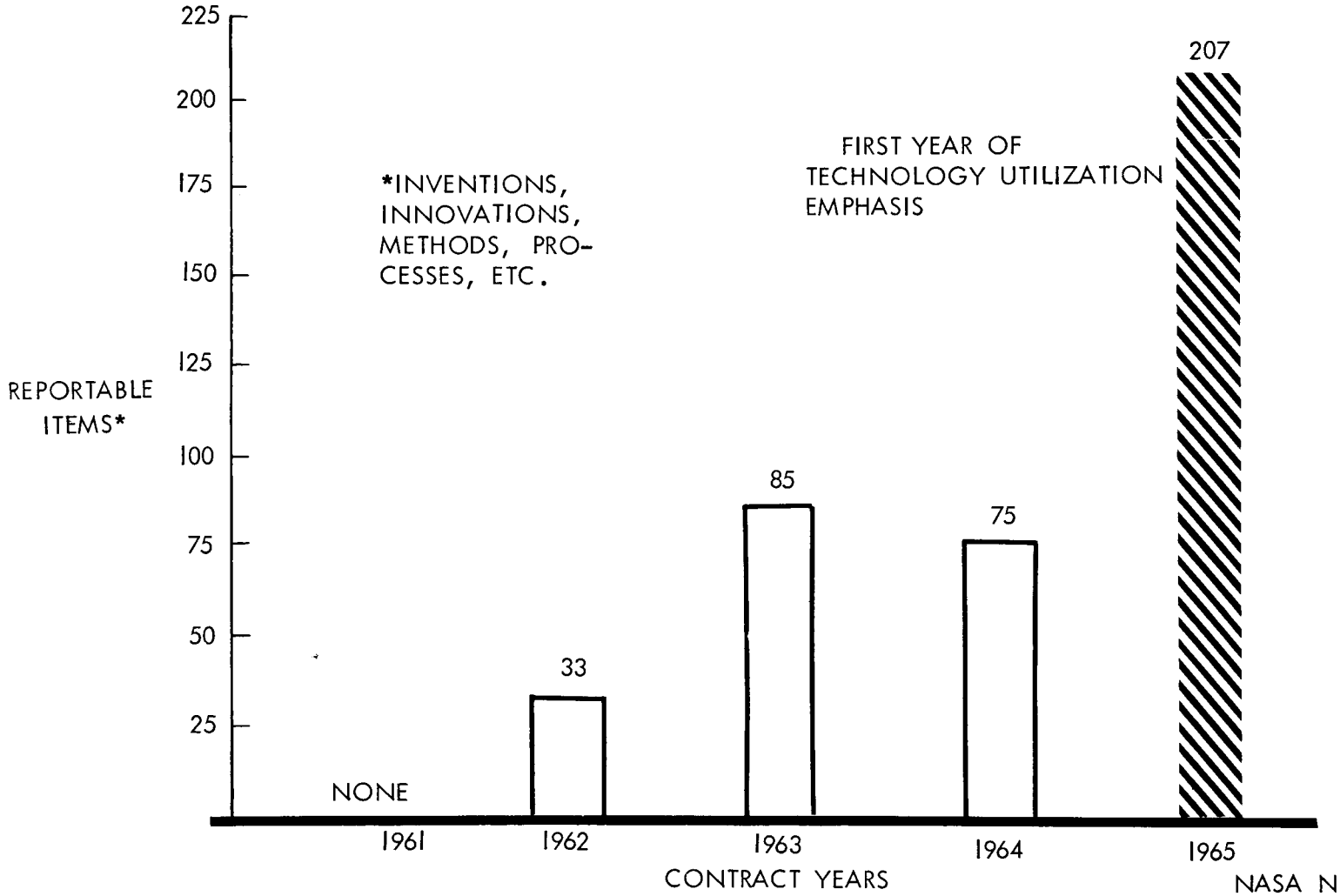


NASA NPO 66-607
2-15-66

Fig 47

NUCLEAR ROCKET PROGRAM

TECHNOLOGY UTILIZATION SUBMISSIONS UNDER NERVA CONTRACT

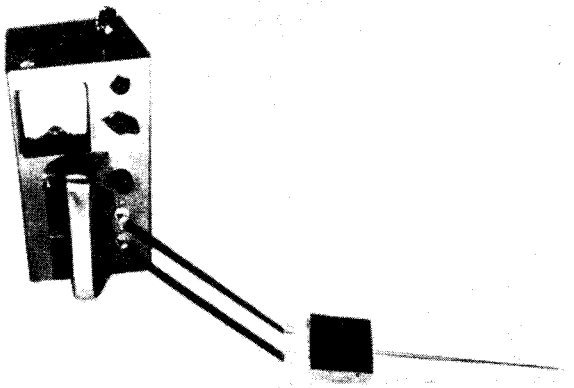


AEROJET - GENERAL CORP. AND WESTINGHOUSE ASTRONUCLEAR LAB.

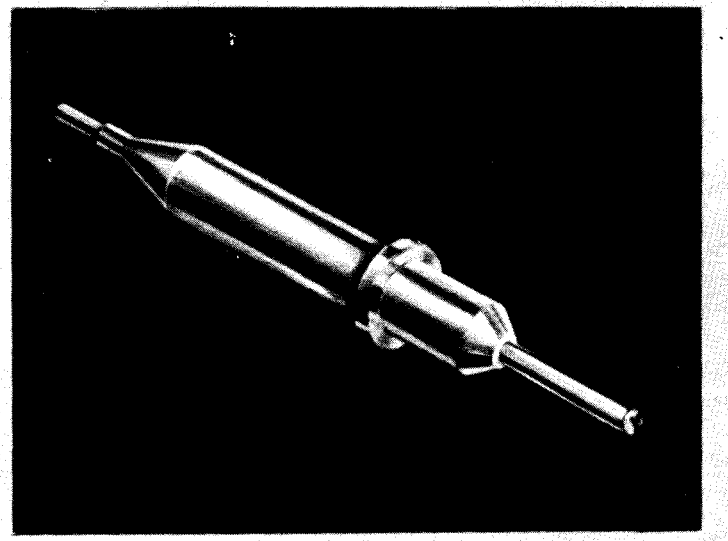
NASA NPO 65-2188
Rev. 2-23-66

Fig 48

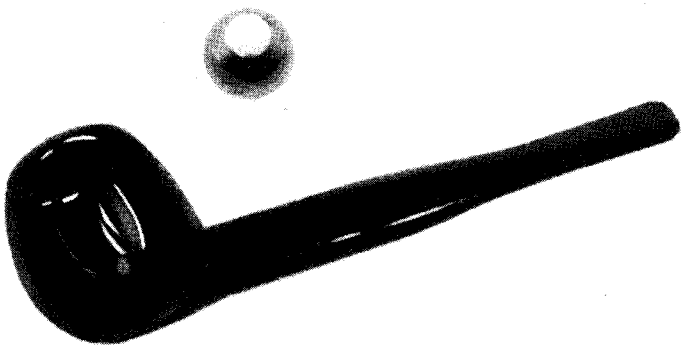
NUCLEAR ROCKET
TECHNOLOGY UTILIZATION PROGRAM
TYPICAL REPORTED ITEMS 1964 - 1965



EDDY CURRENT PROBE DETECTS CRACKS IN TUBING



HIGH TEMPERATURE THERMOCOUPLE

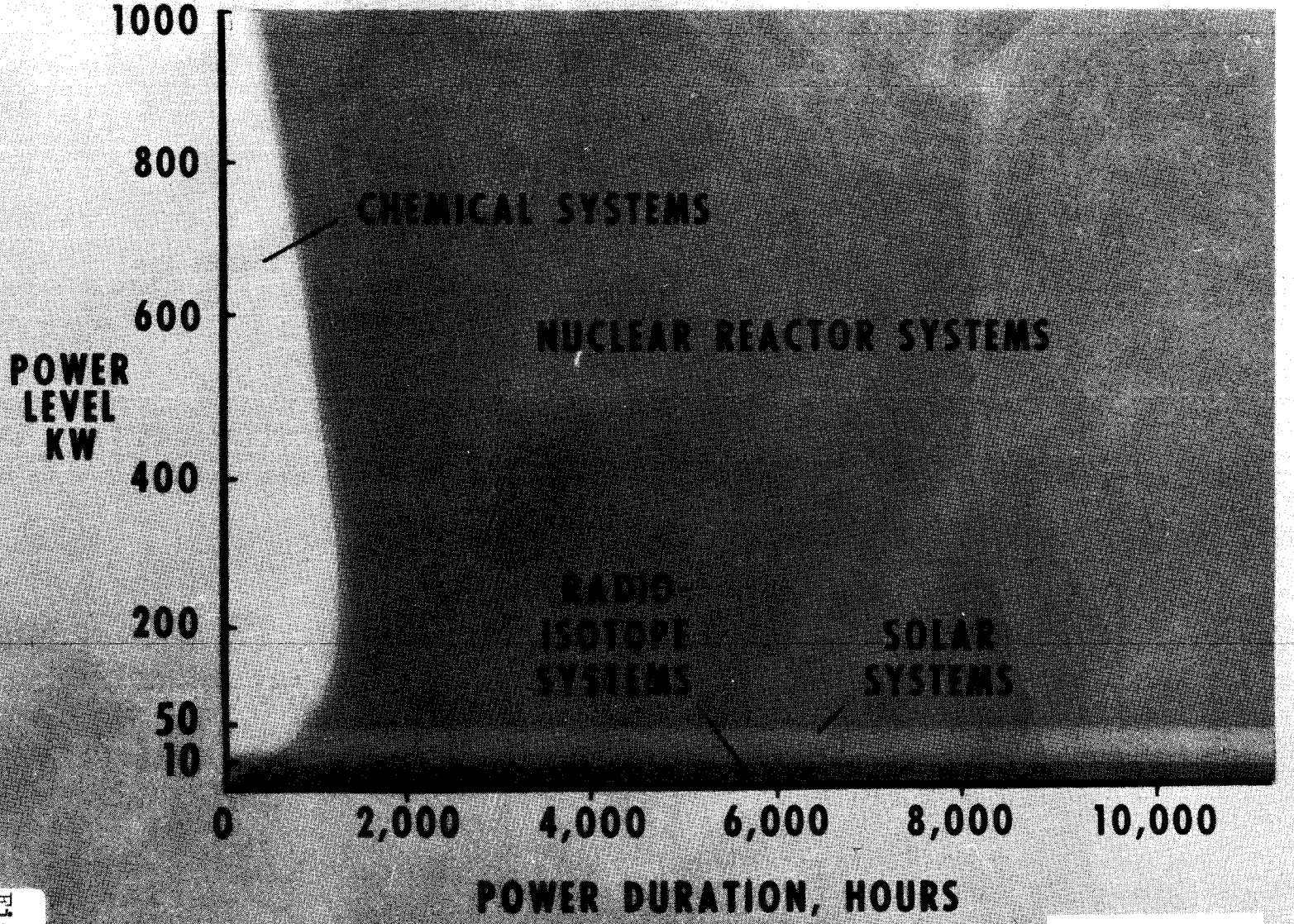


SMOKING PIPE LINED WITH PYROLITIC GRAPHITE

Fig 49

NASA NPO 61-2083

OPERATING RANGE OF POWER SOURCES



NASA RN64-350
REV. 2-12-66

Fig 50

SPACE POWER SYSTEMS UNDER INVESTIGATION

CHEMICAL

PRIMARY BATTERIES*

SECONDARY BATTERIES*

FUEL CELLS*

ENGINES

SOLAR

PHOTOVOLTAIC*

BRAYTON

THERMIONIC

NUCLEAR

RADIOISOTOPE

THERMOELECTRIC*

BRAYTON

THERMIONIC

RANKINE

REACTOR

BRAYTON

RANKINE

THERMIONIC

MAGNETOHYRDODYNAMIC CONVERSION (MHD)

* OPERATIONAL SYSTEMS

NASA RN 65-1942
REV. 2-1-66

Fig 51

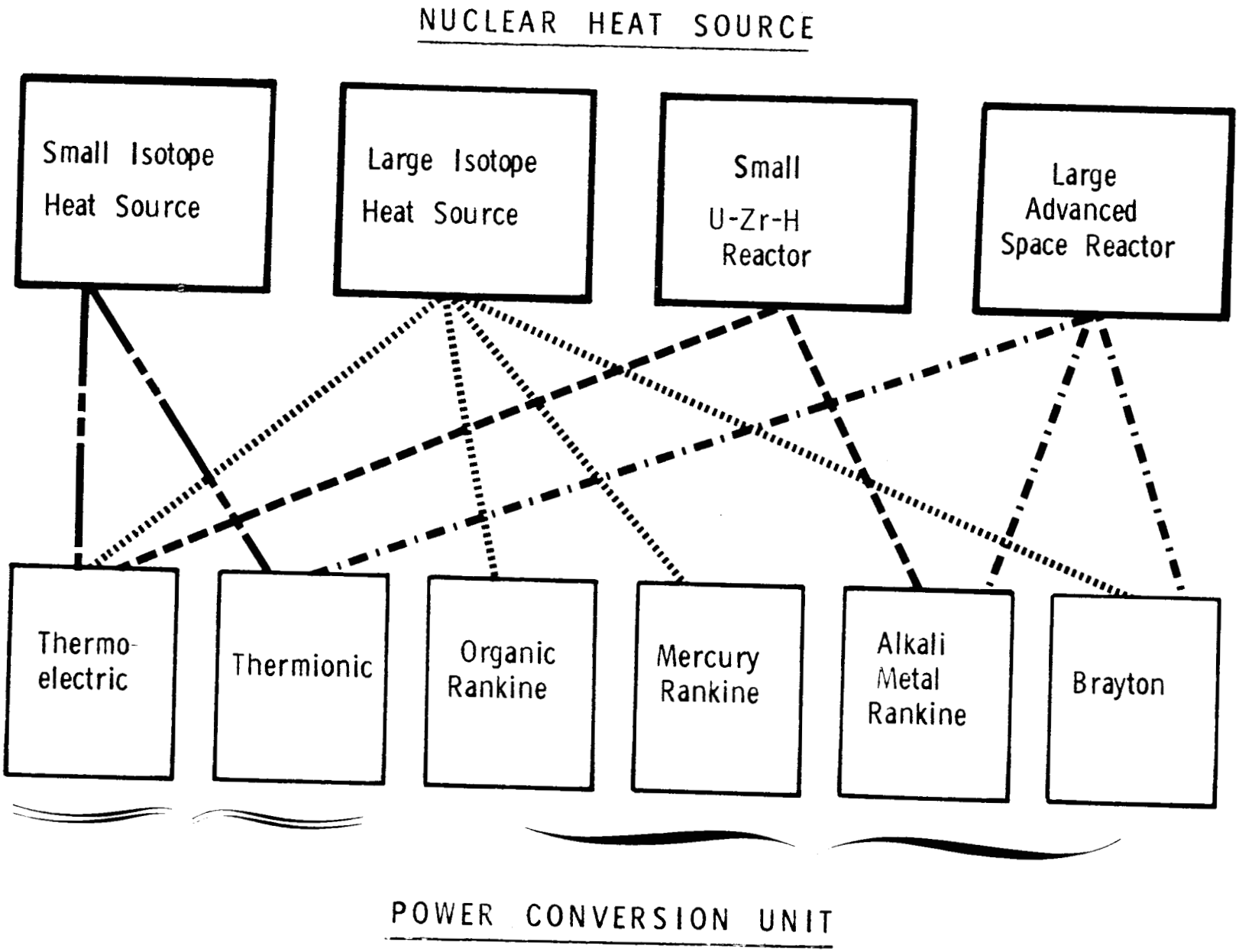

NUCLEAR HEAT SOURCE
Small Isotope Heat Source
Large Isotope Heat Source
Small U-Zr-H Reactor
Large Advanced Space Reactor
Thermo-electric
Thermionic
Organic Rankine
Mercury Rankine
Alkali Metal Rankine
Brayton
POWER CONVERSION UNIT

Fig 52

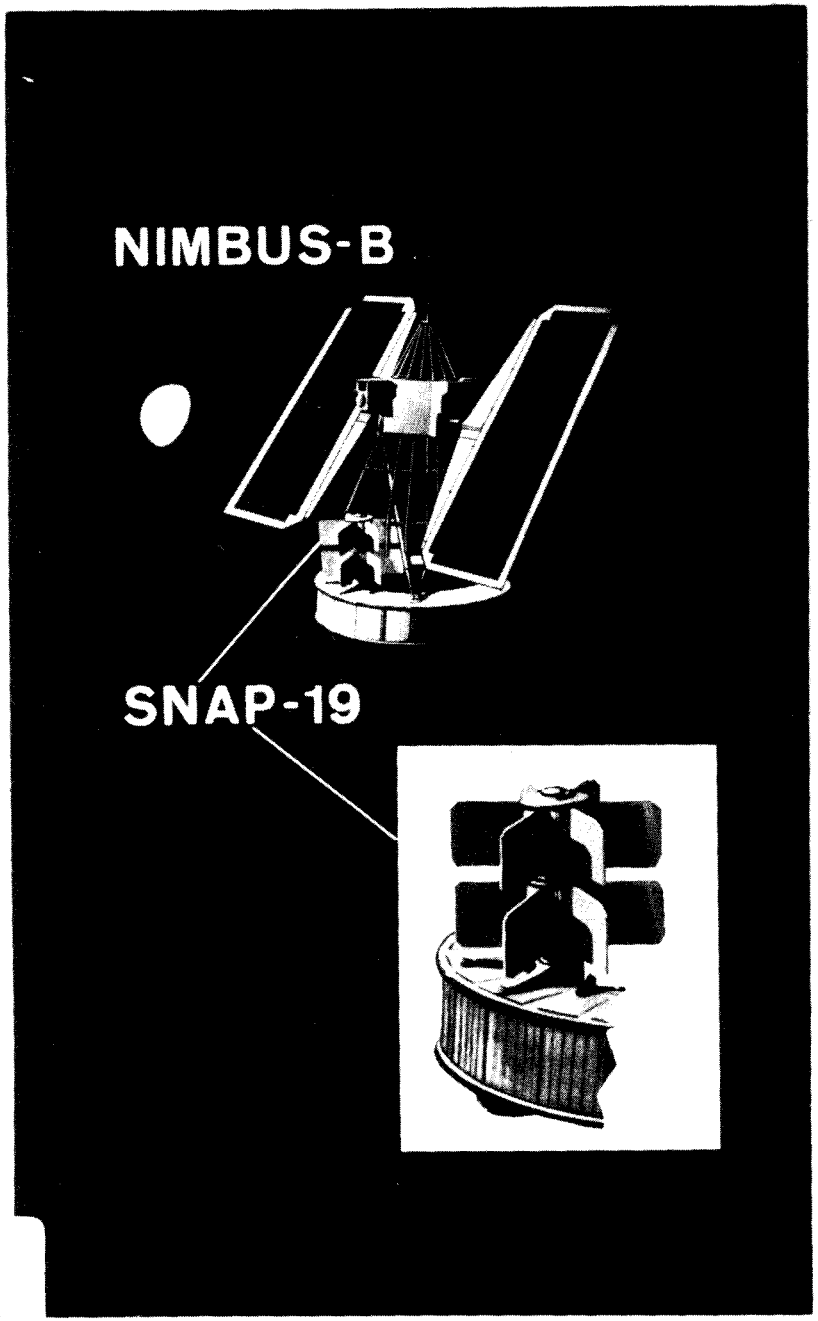
AEC THERMOELECTRIC GENERATORS

BEING TESTED AT NASA CENTERS

CENTER	GENERATOR	POWER (WATTS)
GODDARD SPACE FLIGHT CENTER	(2) SNAP-19	50
JET PROPULSION LABORATORY	SNAP-11	25
MANNED SPACECRAFT CENTER	SNAP-9	25
LANGLEY RESEARCH CENTER	SNAP-3	3
AMES RESEARCH CENTER (WITH LIVERMORE)	SNAP-19	25
MARSHALL SPACE FLIGHT CENTER	SNAP-19	25

NASA RN 65-2055
REV. 2-1-66

Fig 53



NIMBUS-B SNAP-19

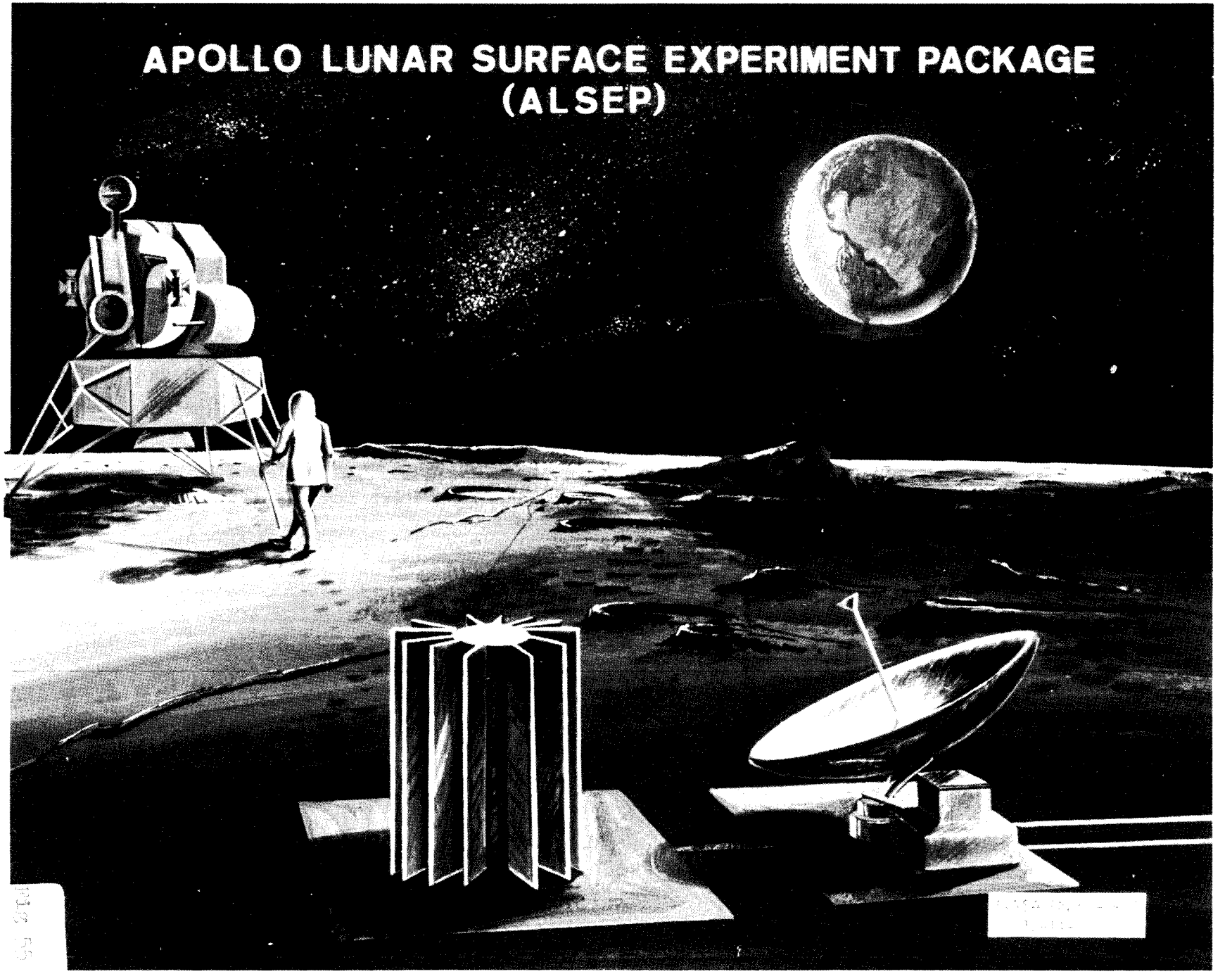
OBJECTIVES

- PROVIDE ADDITIONAL POWER FOR NIMBUS-B
- PROVIDE EXPERIENCE FOR USE OF RADIOISOTOPE POWER FOR METEOROLOGICAL SATELLITES

STATUS

- PRELIMINARY PROTOTYPES TESTED IN 1965
- ENGINEERING MODEL IN FABRICATION
- SPACECRAFT MODIFICATIONS IN DESIGN
- FUEL BEING PRODUCED
- INTERAGENCY AGREEMENT DRAFTED

NASA RN 65-2192
REV. 2-1-66


APOLLO LUNAR SURFACE EXPERIMENT PACKAGE
(ALSEP)

BRAYTON TURBOELECTRIC

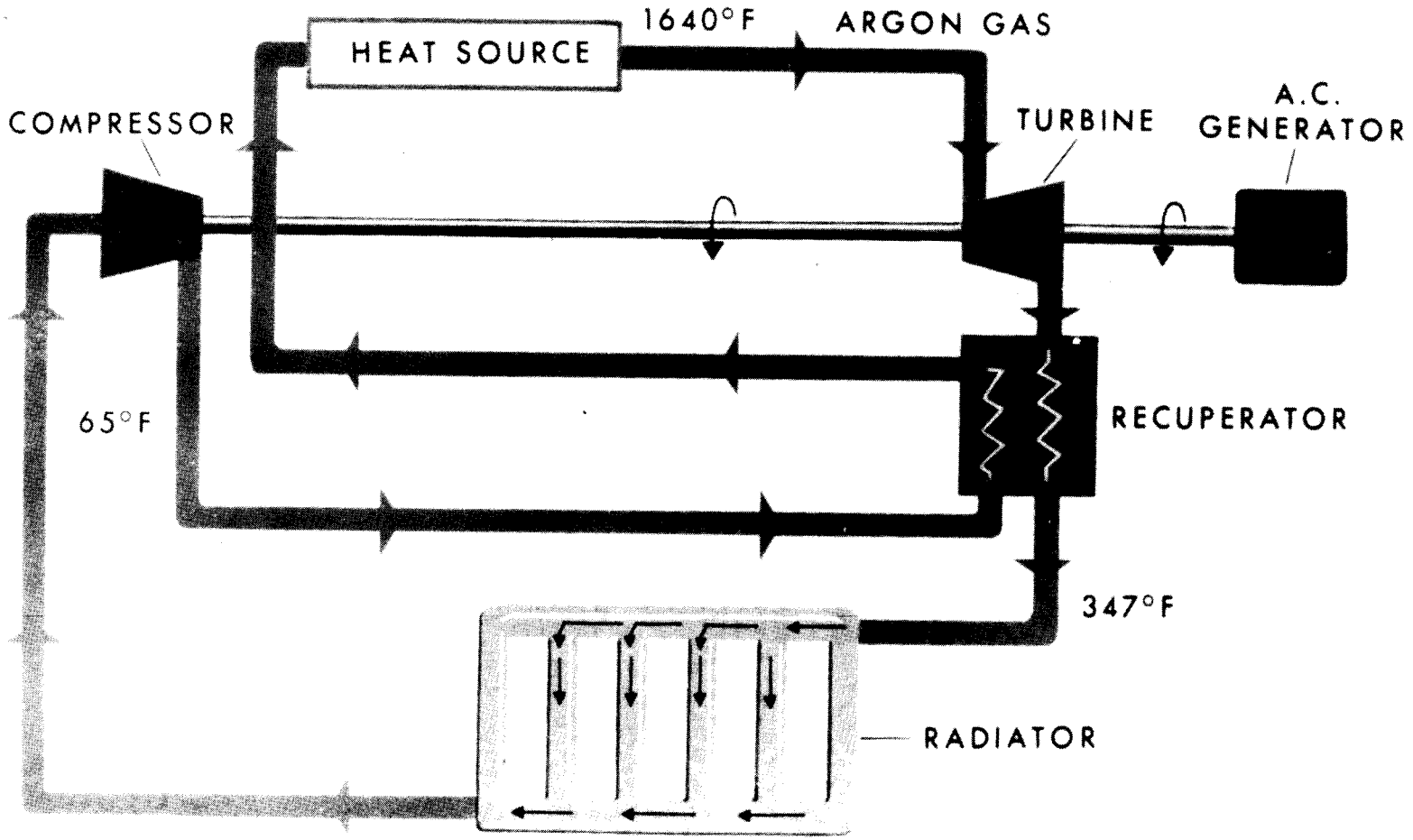
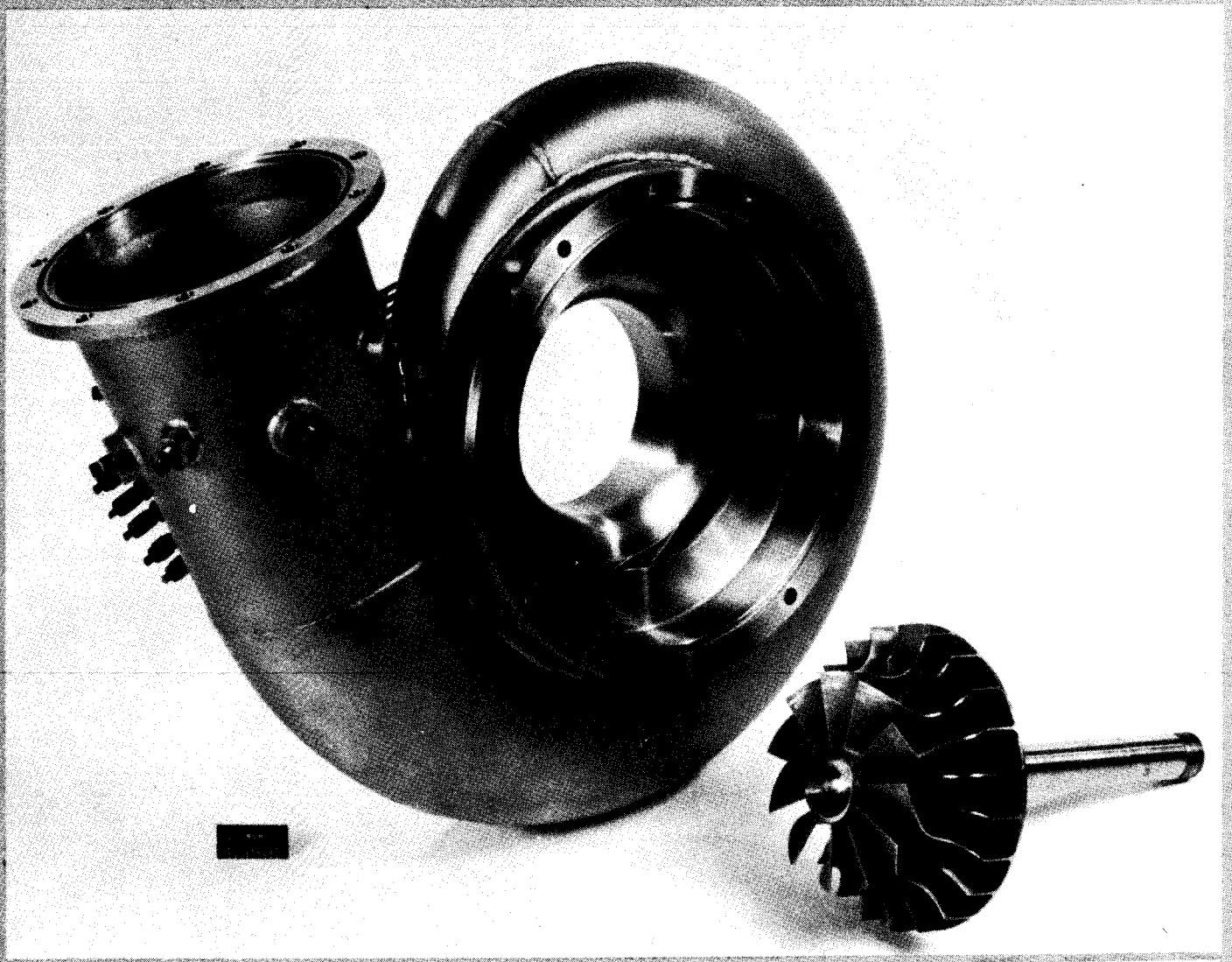


Fig 56

(MORL) MANNED ORBITAL RESEARCH LABORATORY

LANGLEY RESEARCH CENTER CONCEPT

BRAYTON CYCLE RESEARCH TURBINE 6 INCH DIAMETER



NASA RN 66-285
2-1-66

Fig 58

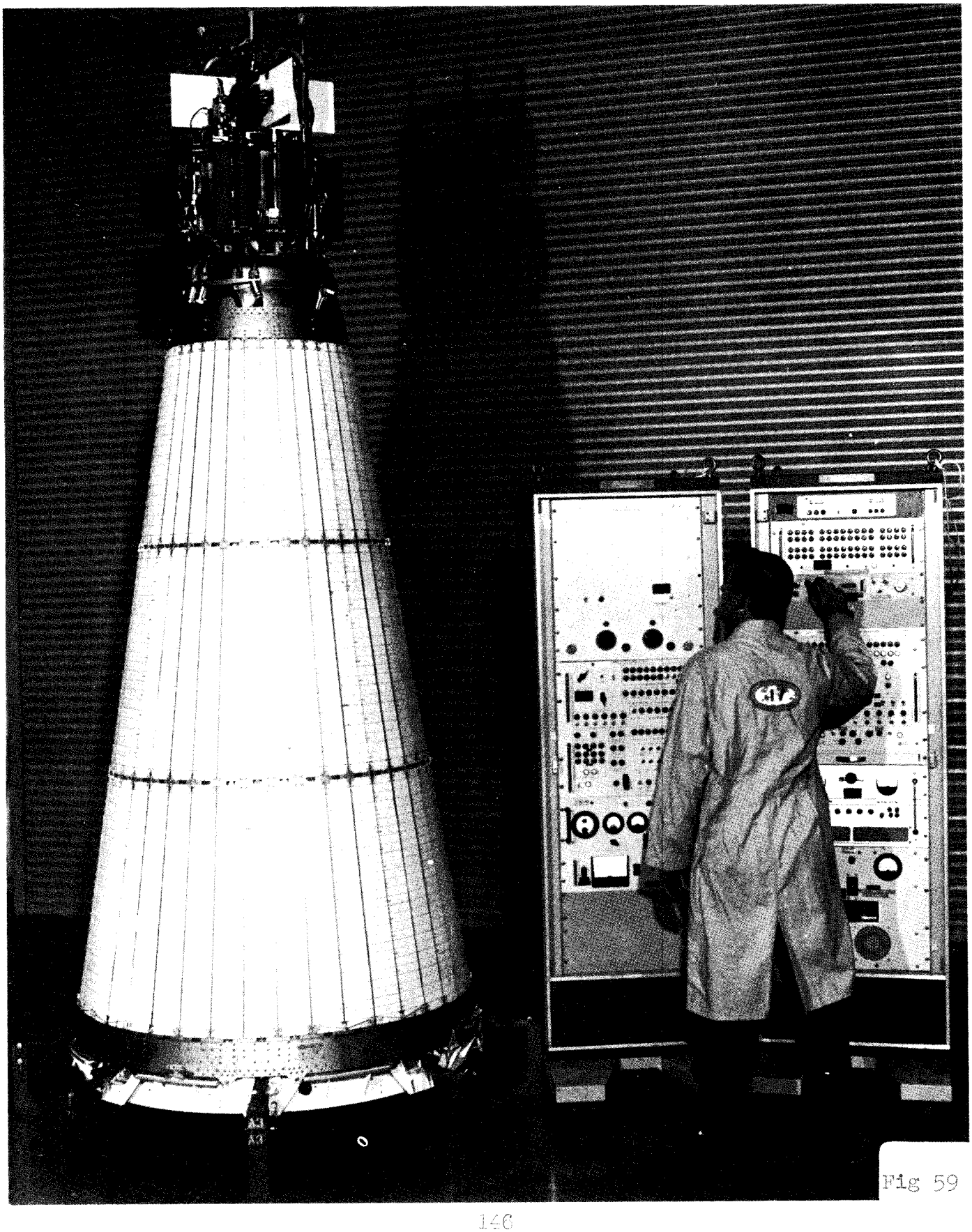


Fig 59

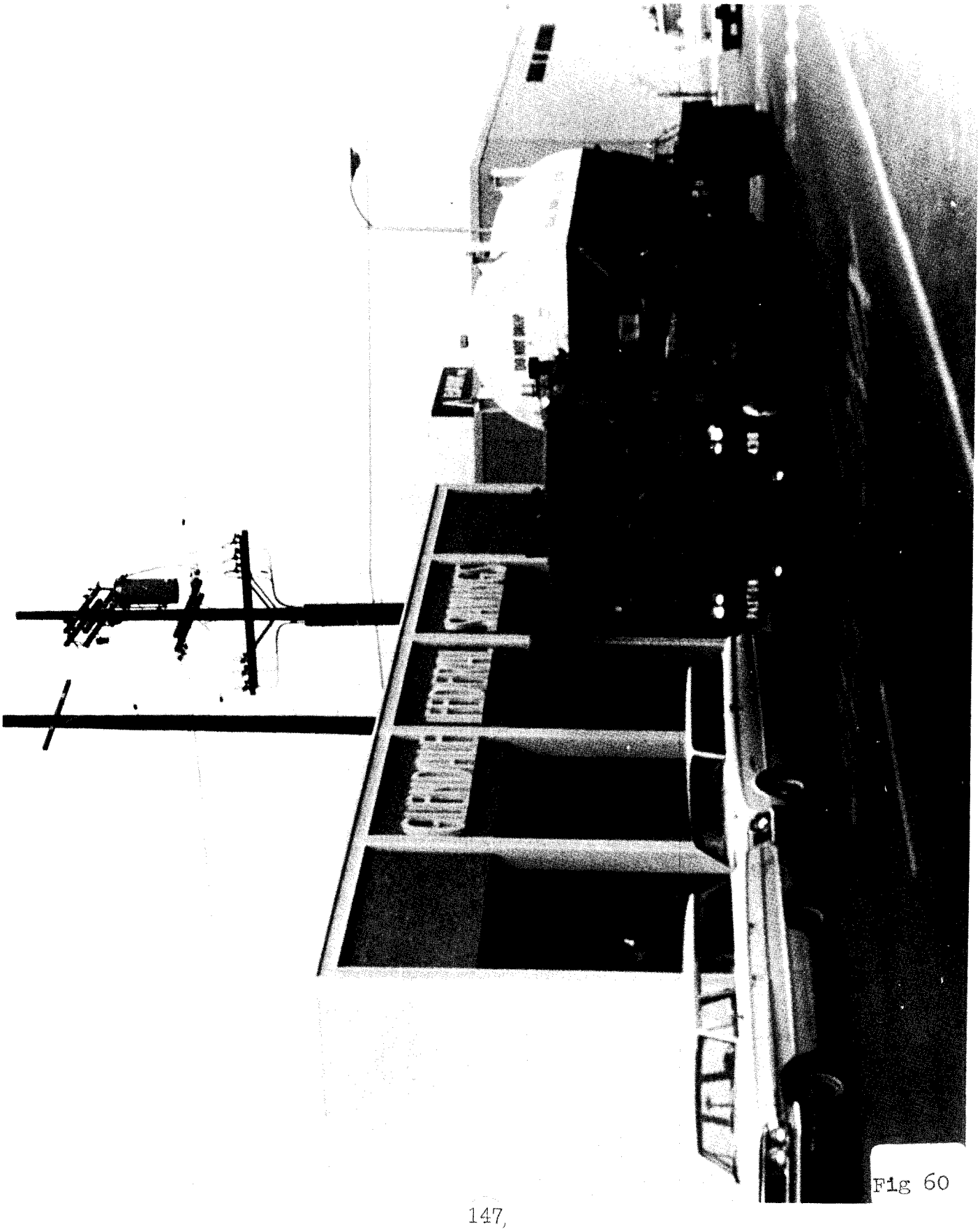


Fig 60

4-3-65
UNCLASSIFIED
PHOTOGRAPHIC DEPT. CANOGA PARK, CALIF.
AF 6751
7561-12230

Fig 61

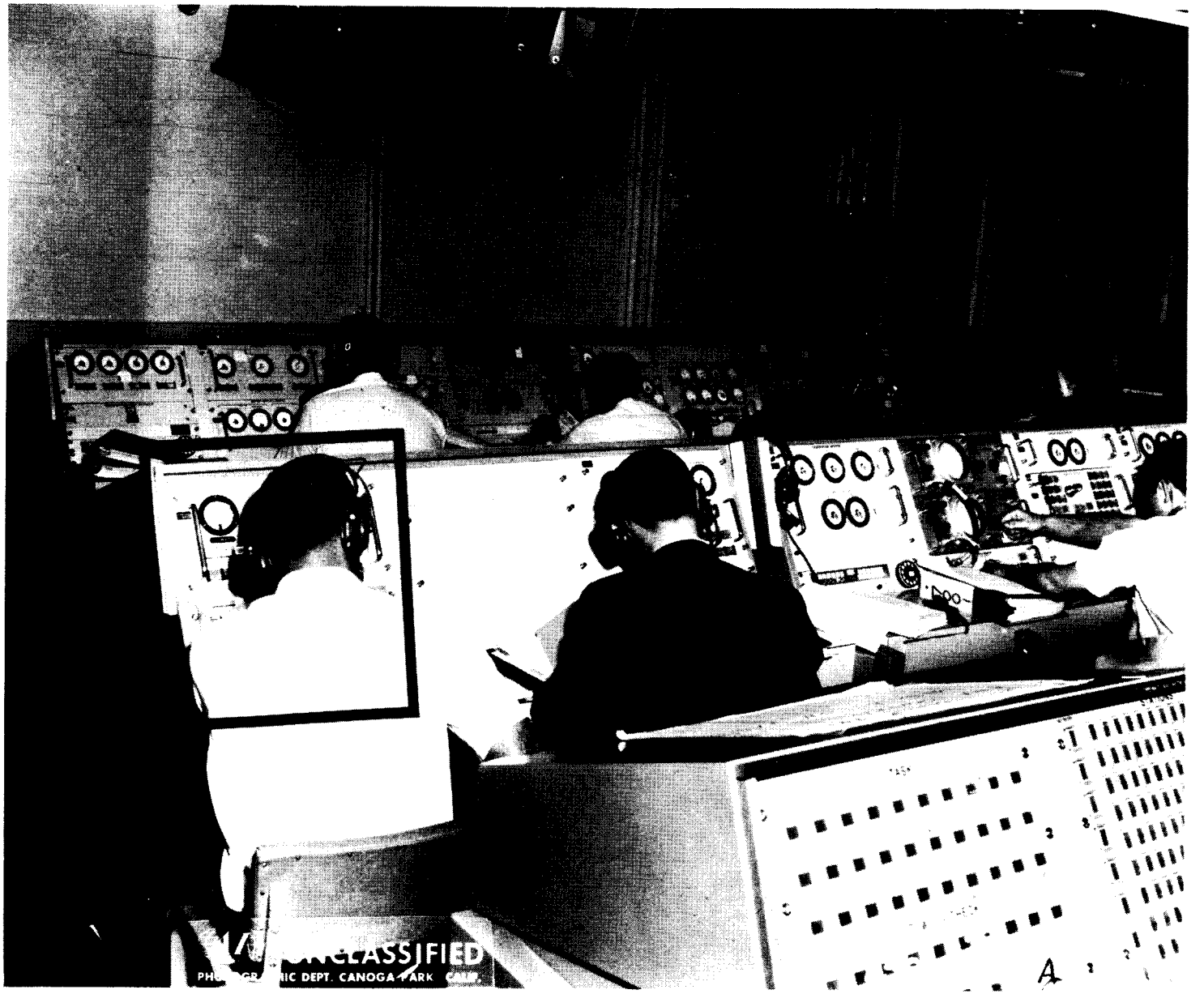


Fig 62

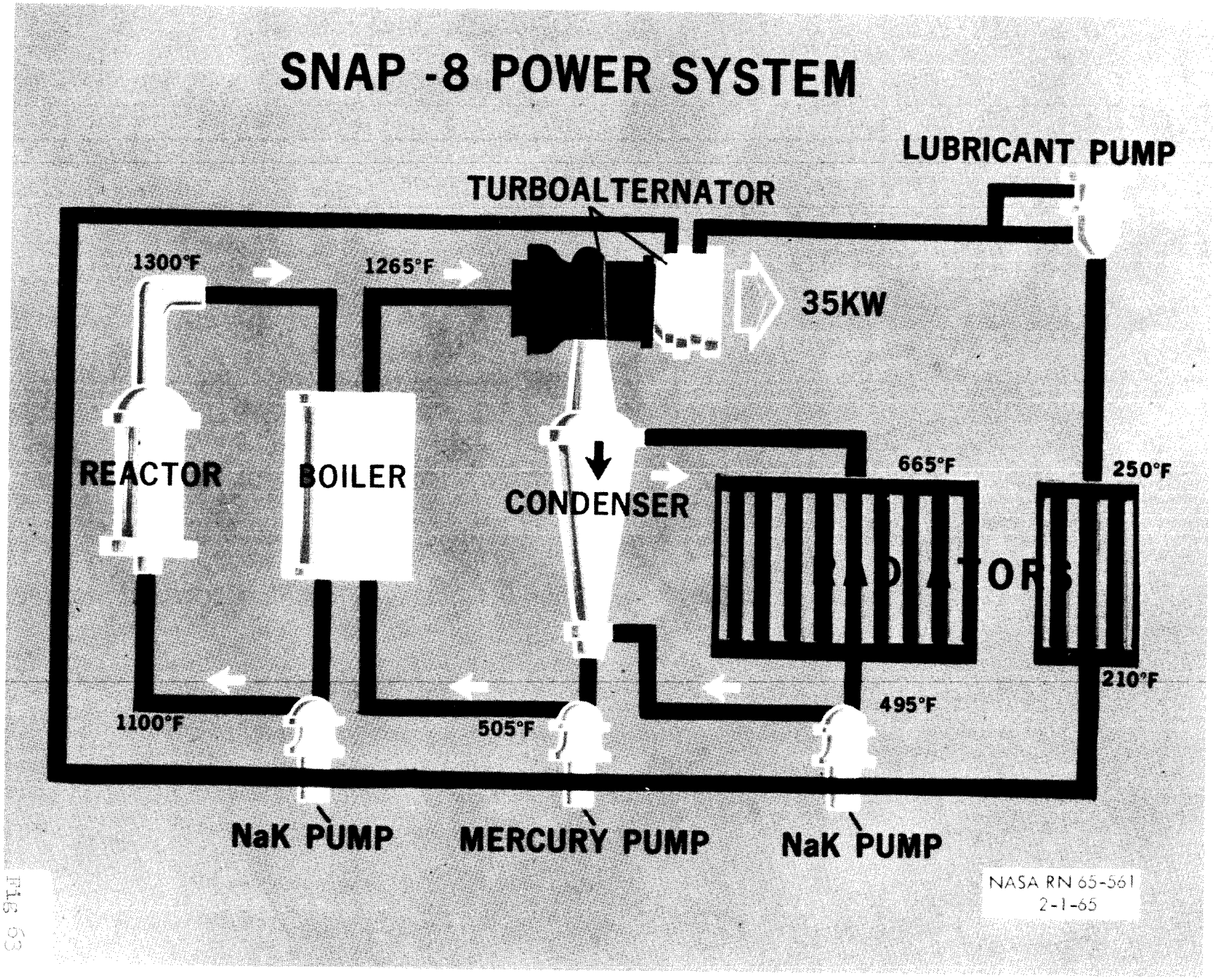
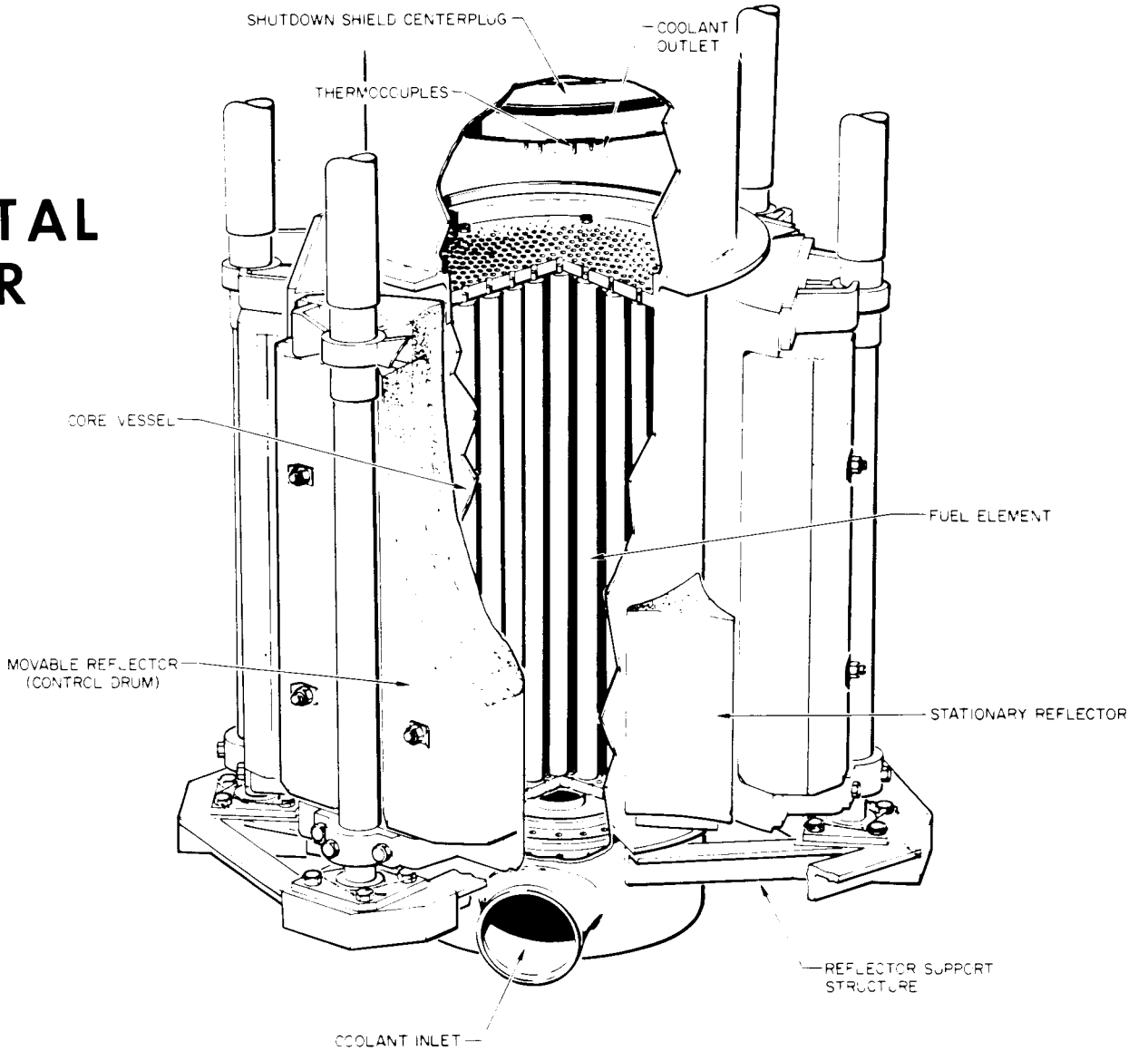

SNAP -8 POWER SYSTEM
LUBRICANT PUMP
TURBOALTERNATOR
1300°F
1265°F
35KW
REACTOR
BOILER
CONDENSER
665°F
250°F
RADIATORS
210°F
495°F
1100°F
505°F
NaK PUMP
MERCURY PUMP
NaK PUMP
NASA RN 65-561
2-1-65

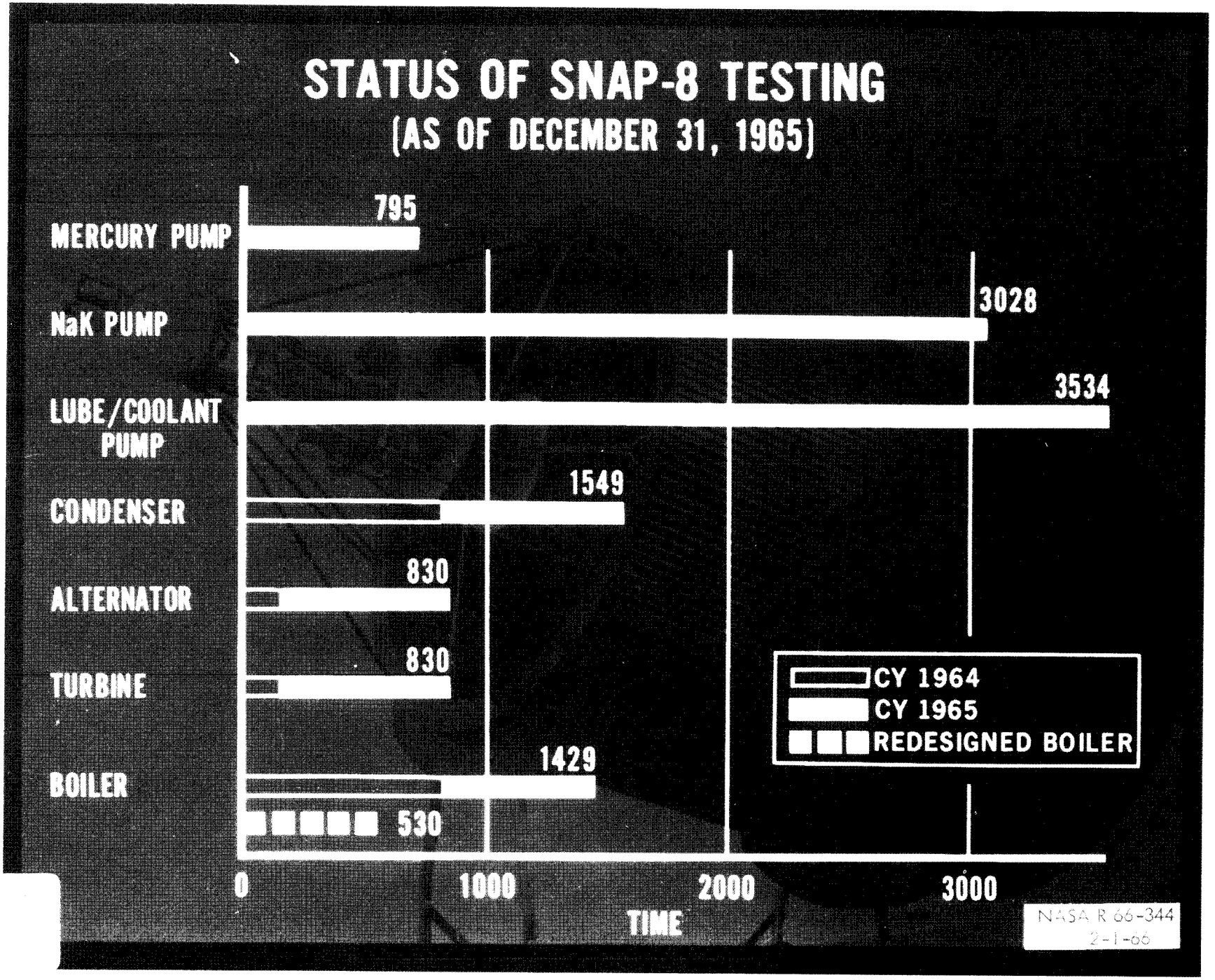
Fig 63

SNAP 8 EXPERIMENTAL REACTOR

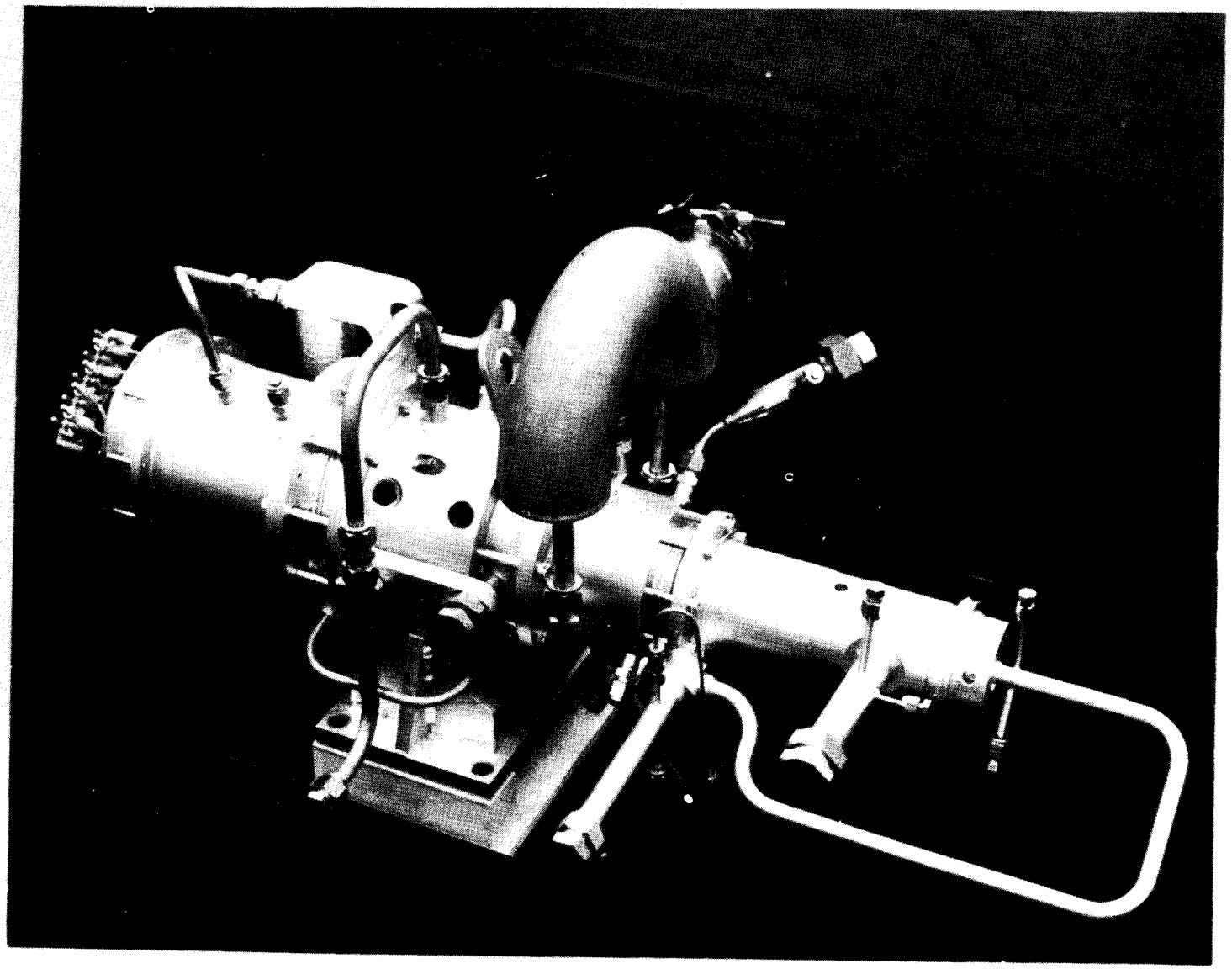


NASA RN 66-290
2-1-66

Fig 64


STATUS OF SNAP-8 TESTING
(AS OF DECEMBER 31, 1965)
MERCURY PUMP
NaK PUMP
LUBE/COOLANT PUMP
CONDENSER
ALTERNATOR
TURBINE
BOILER
795
3028
3534
1549
830
830
1429
530
0
1000
2000
3000
TIME
CY 1964
CY 1965
REDESIGNED BOILER
NASA R 66-344
2-1-66

SNAP-8 MERCURY PUMP



NASA RN 65-1946
12-14-65

SNAP-8 NaK PUMP

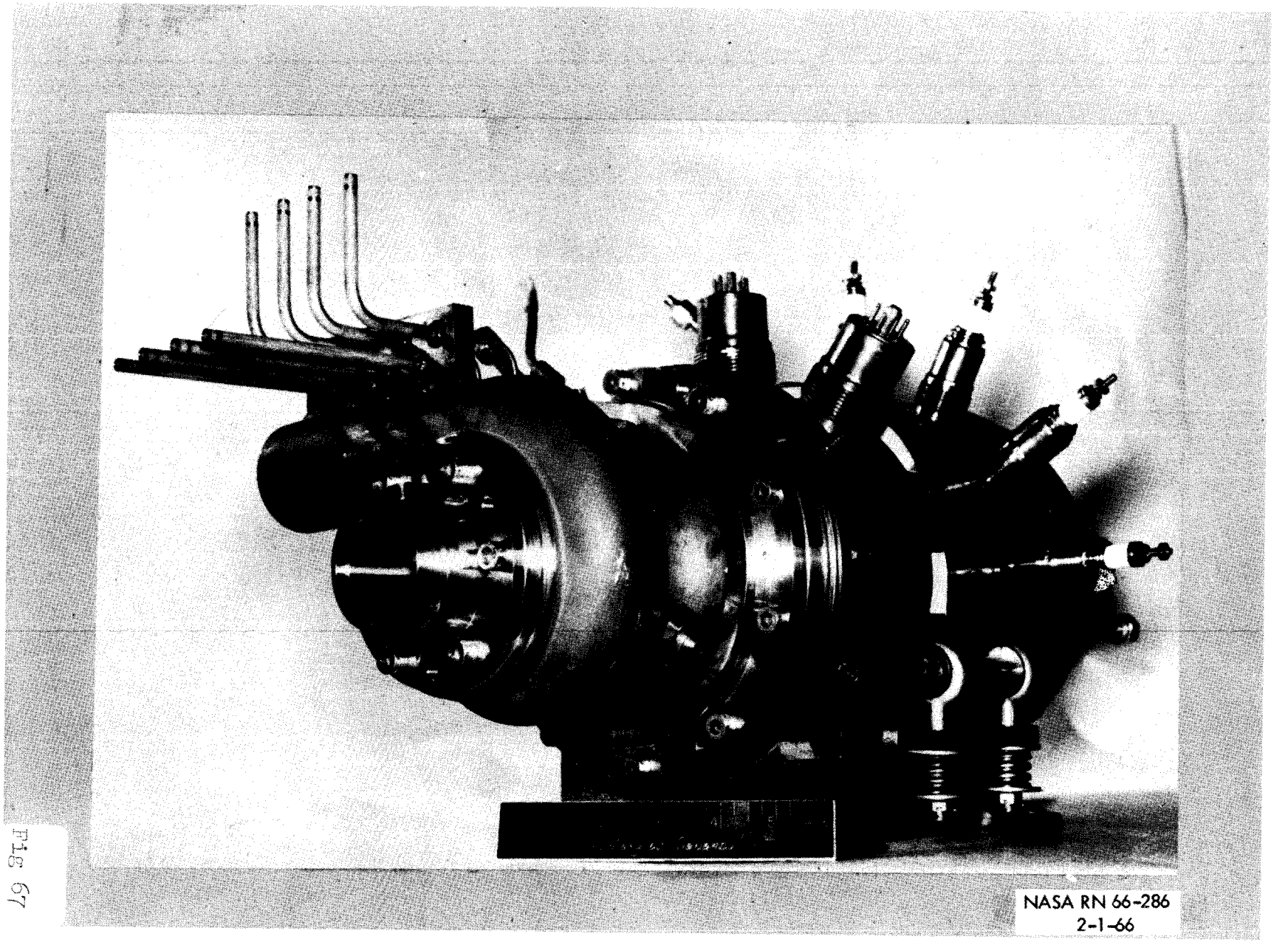
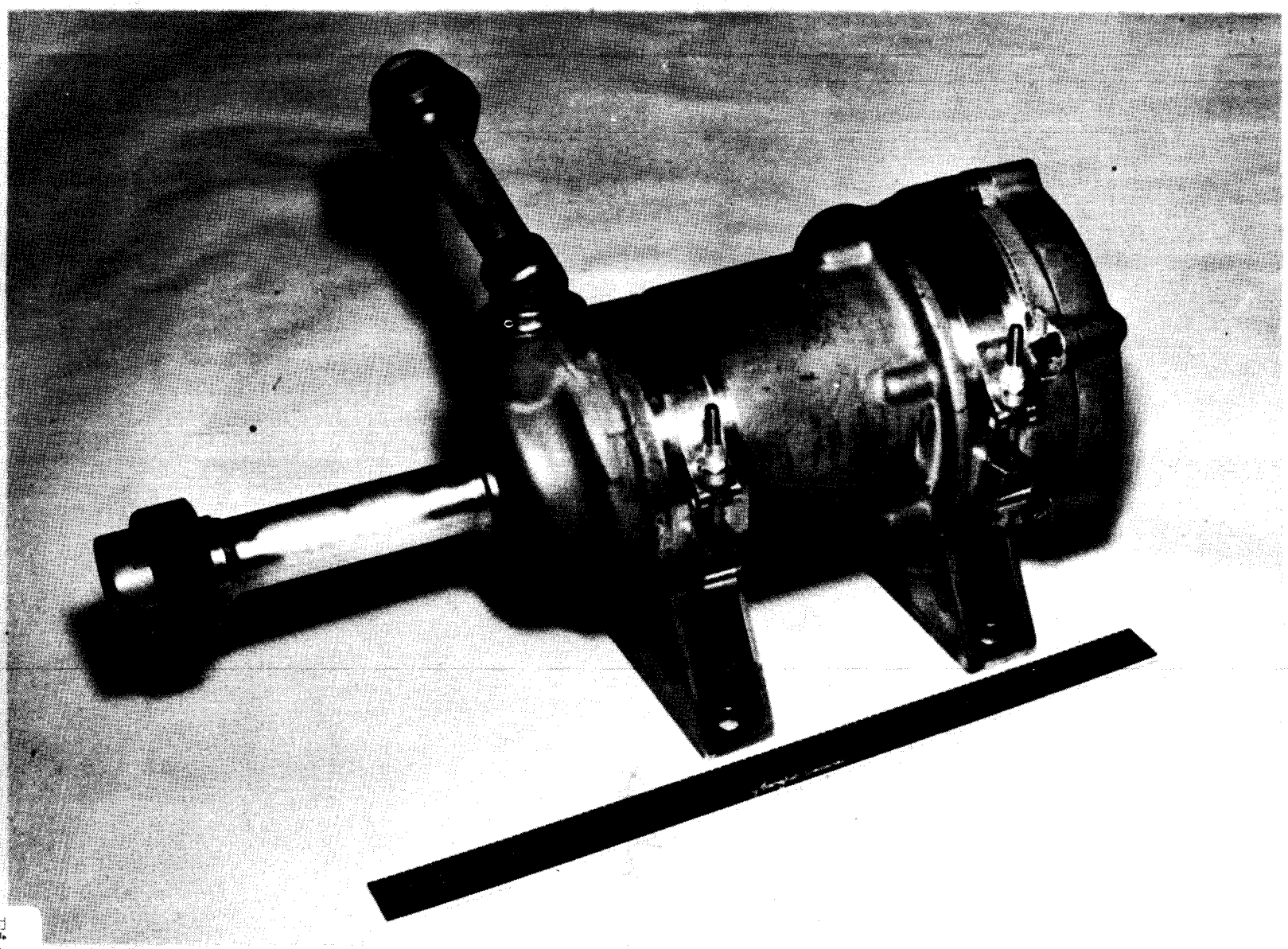


Fig 67

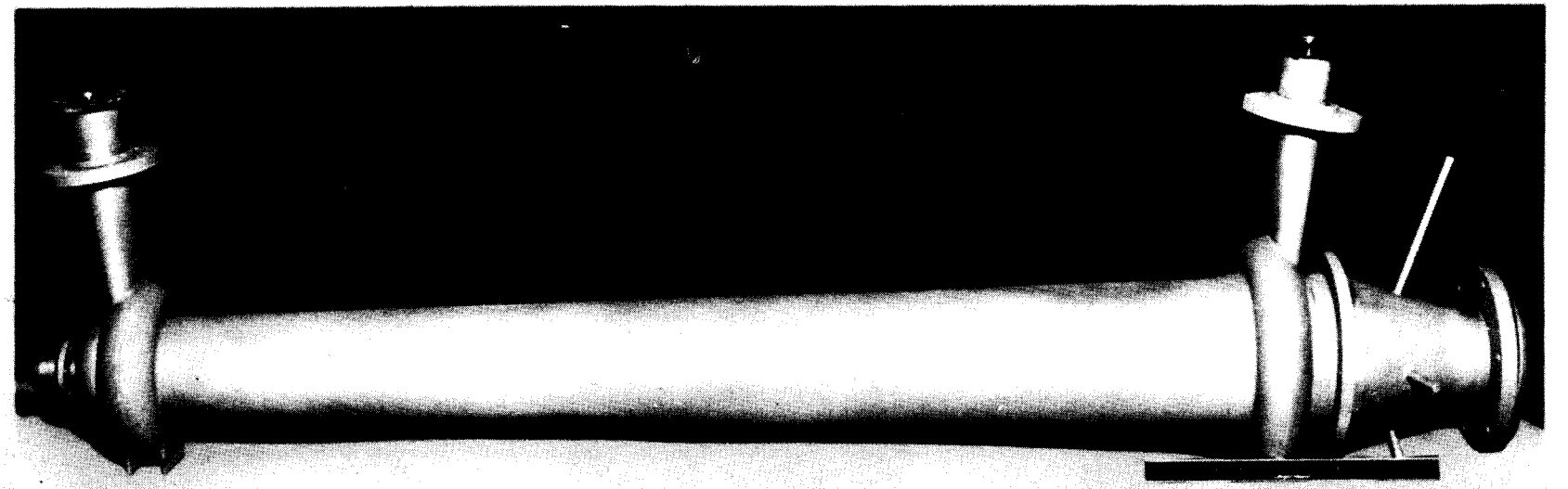
SNAP-8 LUBE/COOLANT PUMP



NASA RN 65-1944
12-14-65

Fig 68

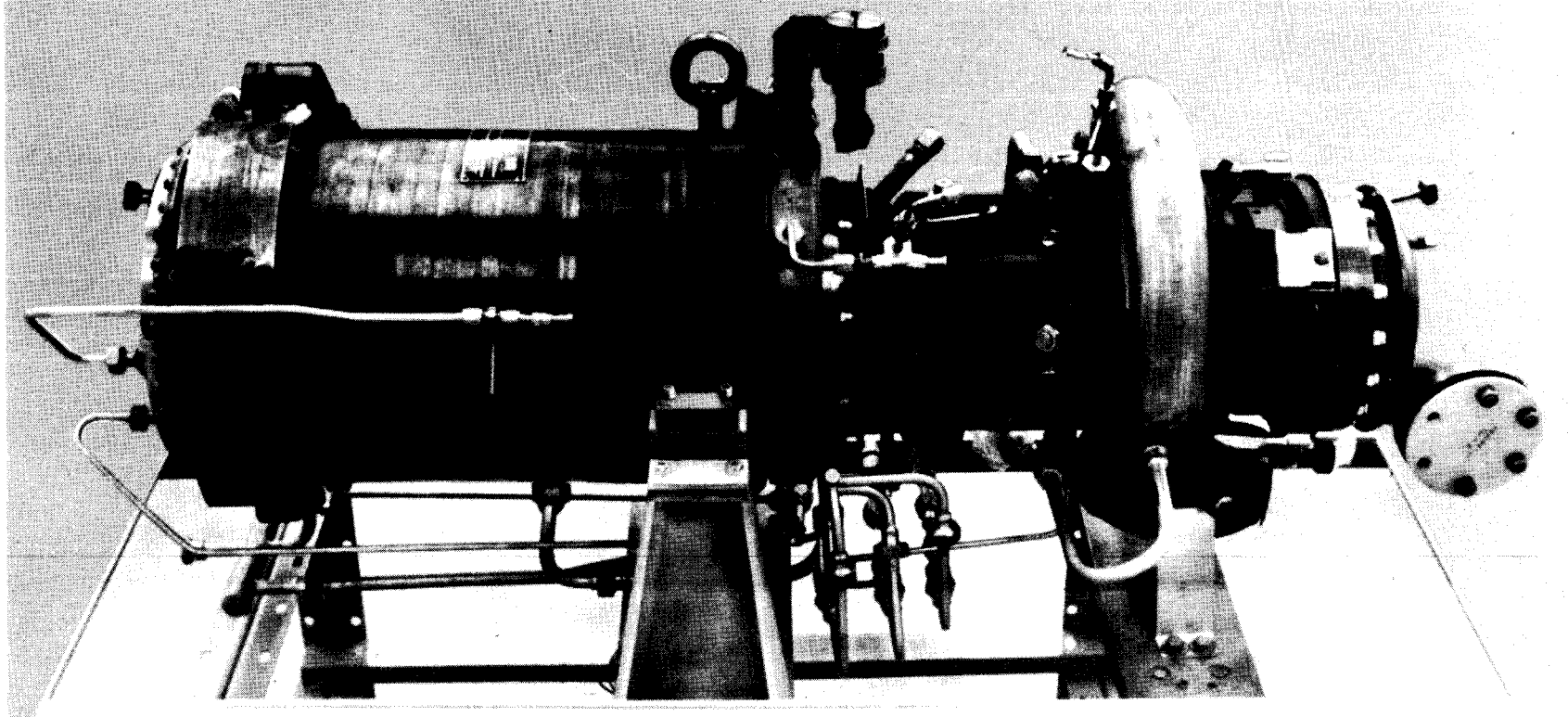
SNAP-8 CONDENSER



NASA RN 65-1945
12-14-65

Fig 69

SNAP-8 TURBINE ALTERNATOR

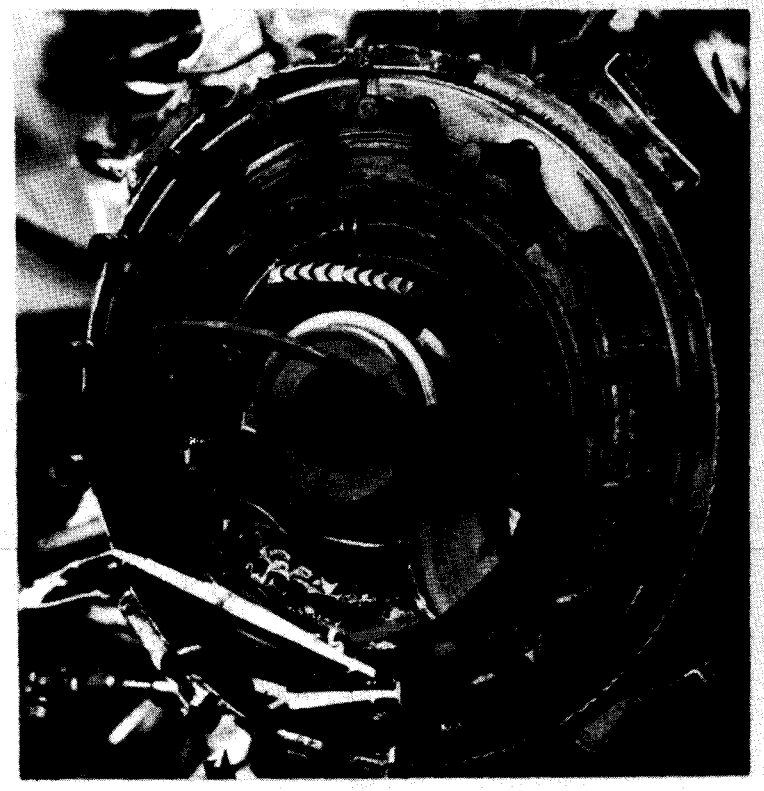


NASA RN 65-1947
12-14-65

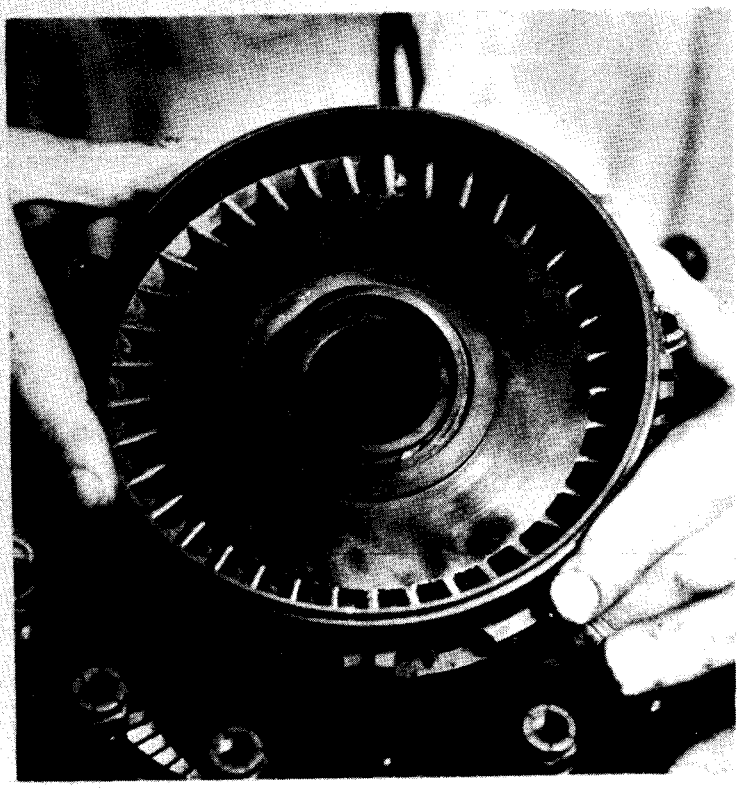
FIG 70

SNAP-8 TURBINE FAILURE

OCCURRED @ 830 HRS OF MERCURY OPERATION



FIRST STAGE DAMAGE

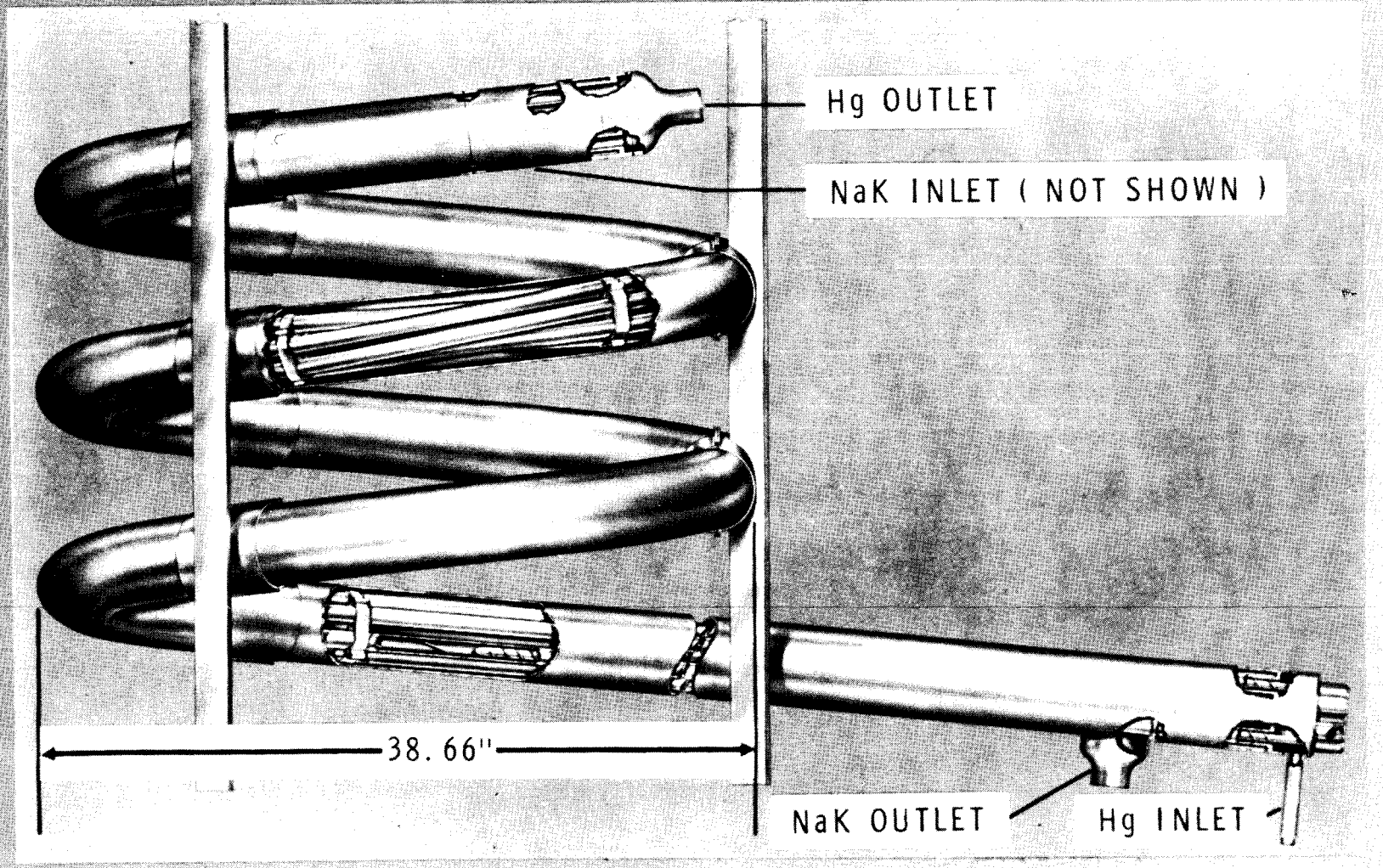


THIRD STAGE DIAPHRAM

NASA RN 65-2068
12-14-65

Fig 71

SNAP-8 BOILER



NASA RN 65-1939
12-14-65

Fig 72

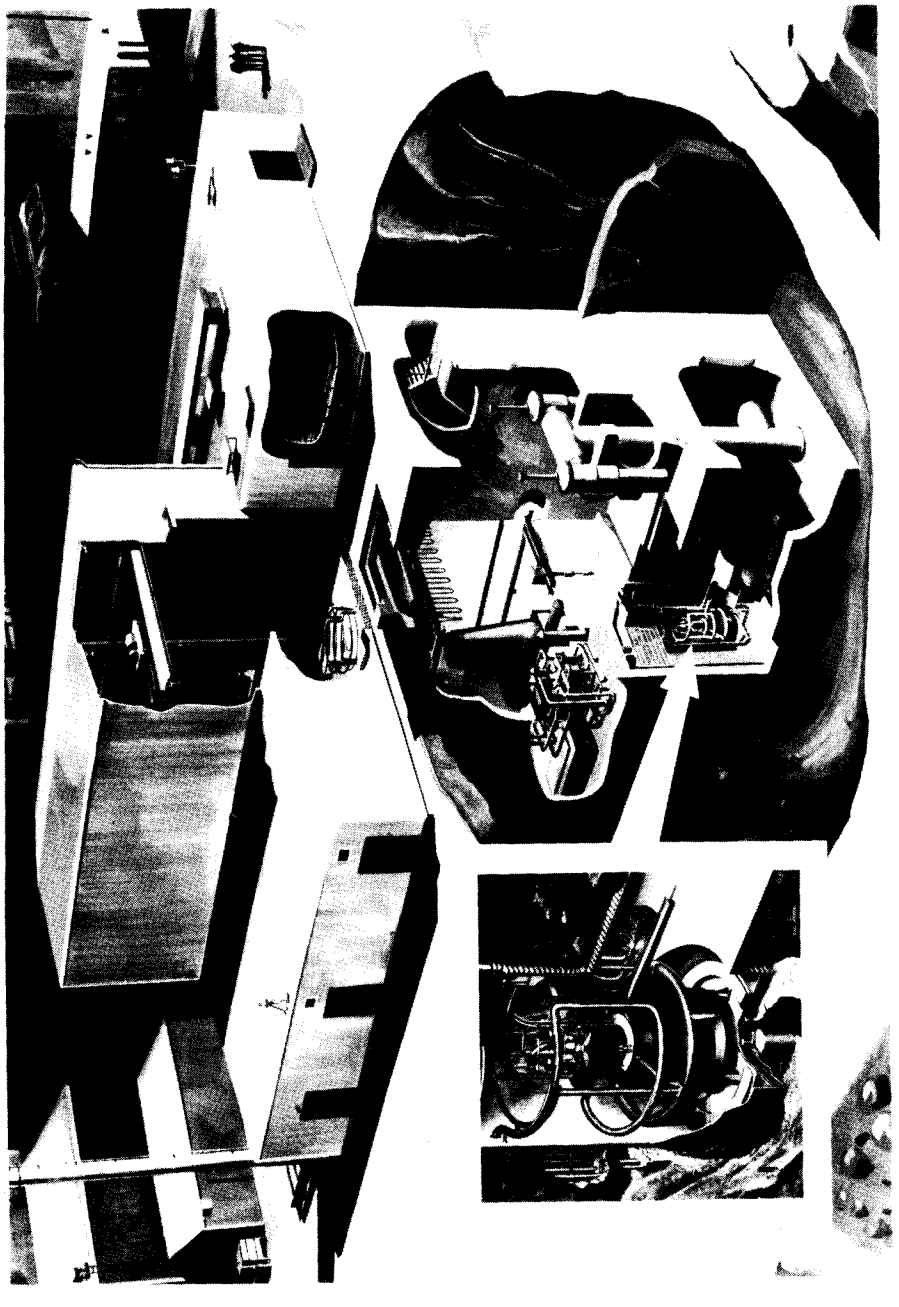


Fig 73

ADVANCED NUCLEAR POWER TECHNOLOGY

CONVERSION SYSTEM	STATUS
● LIQUID METAL RANKINE	COMPONENT TECHNOLOGY
● THERMIONIC DIRECT CONVERSION	COMPONENT TECHNOLOGY
● MAGNETOHYDRODYNAMIC CONVERSION	RESEARCH

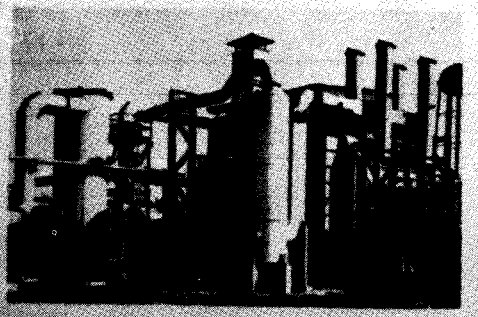
NASA RN 65-1948
12-14-65

Fig 74

ADVANCED SYSTEMS
CRITICAL PROBLEMS

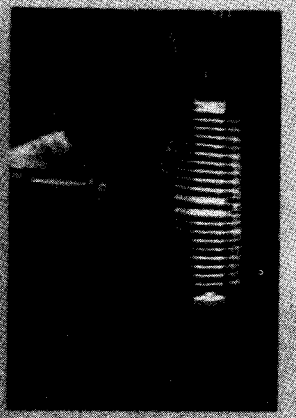
RANKINE

- TURBINE EROSION
- LIQUID METAL CORROSION IN BI-METAL SYSTEMS
- TEST FACILITIES



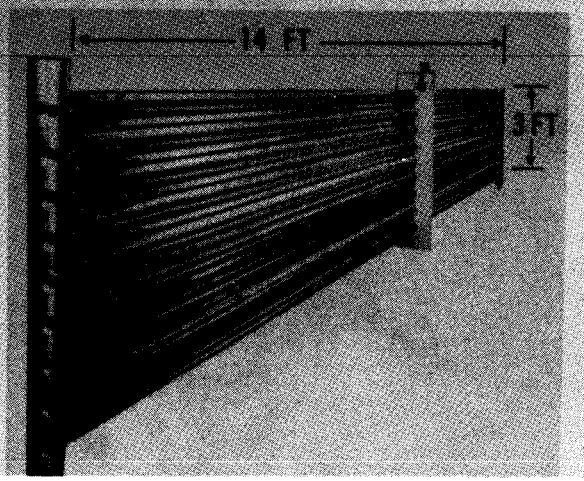
THERMIONIC

- HIGH TEMPERATURE MATERIALS
- CONVERTER PERFORMANCE



COMMON

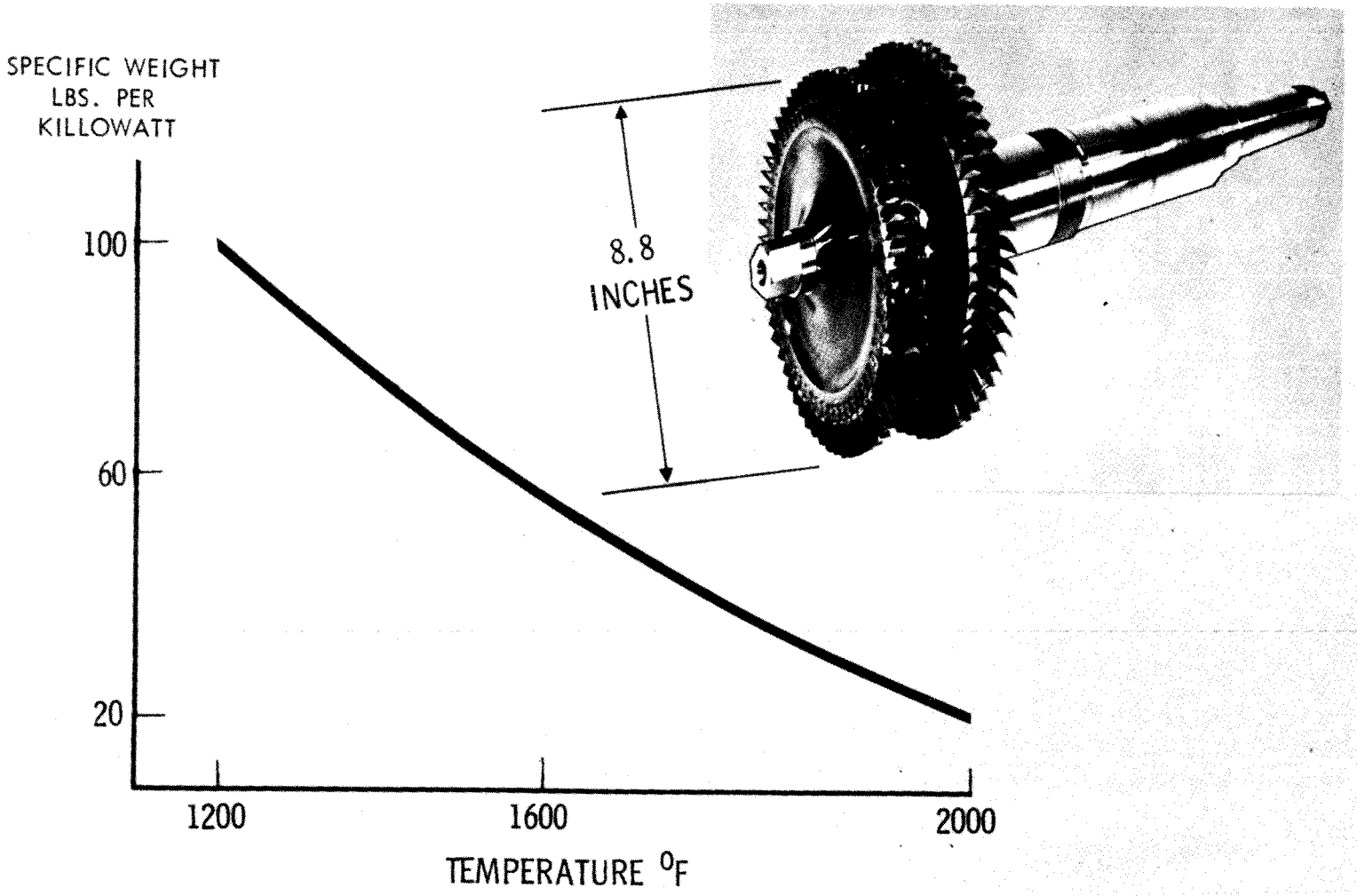
- RADIATOR TECHNOLOGY
- PUMP AND HEAT EXCHANGER TECHNOLOGY
- FAST REACTOR DESIGN



NASA RN 65-2181
REV. 2-1-66

Fig 75

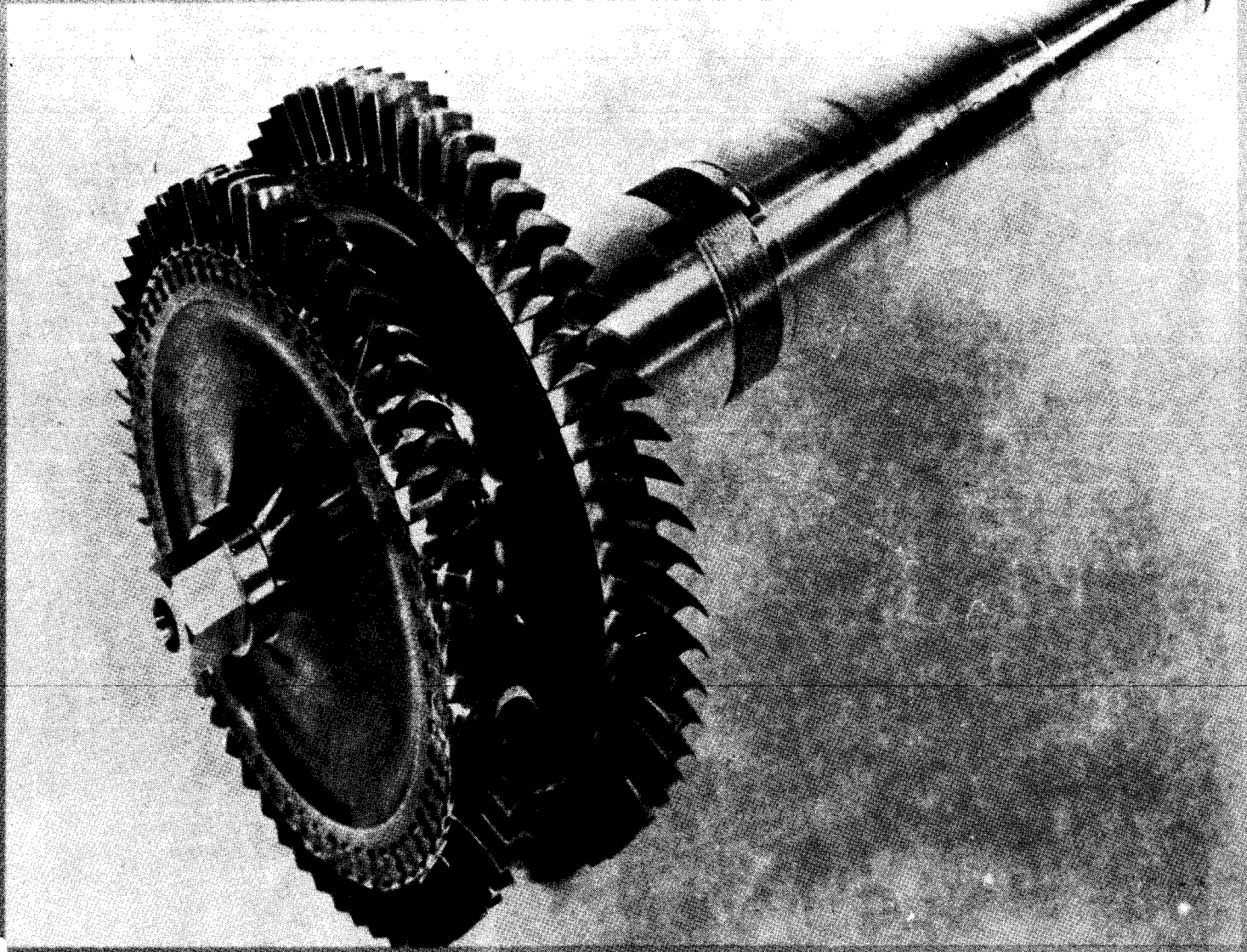
SYSTEM WEIGHT
VS.
TURBINE INLET TEMPERATURE



NASA RN 65-2171
REV. 2-15-66

Fig 76

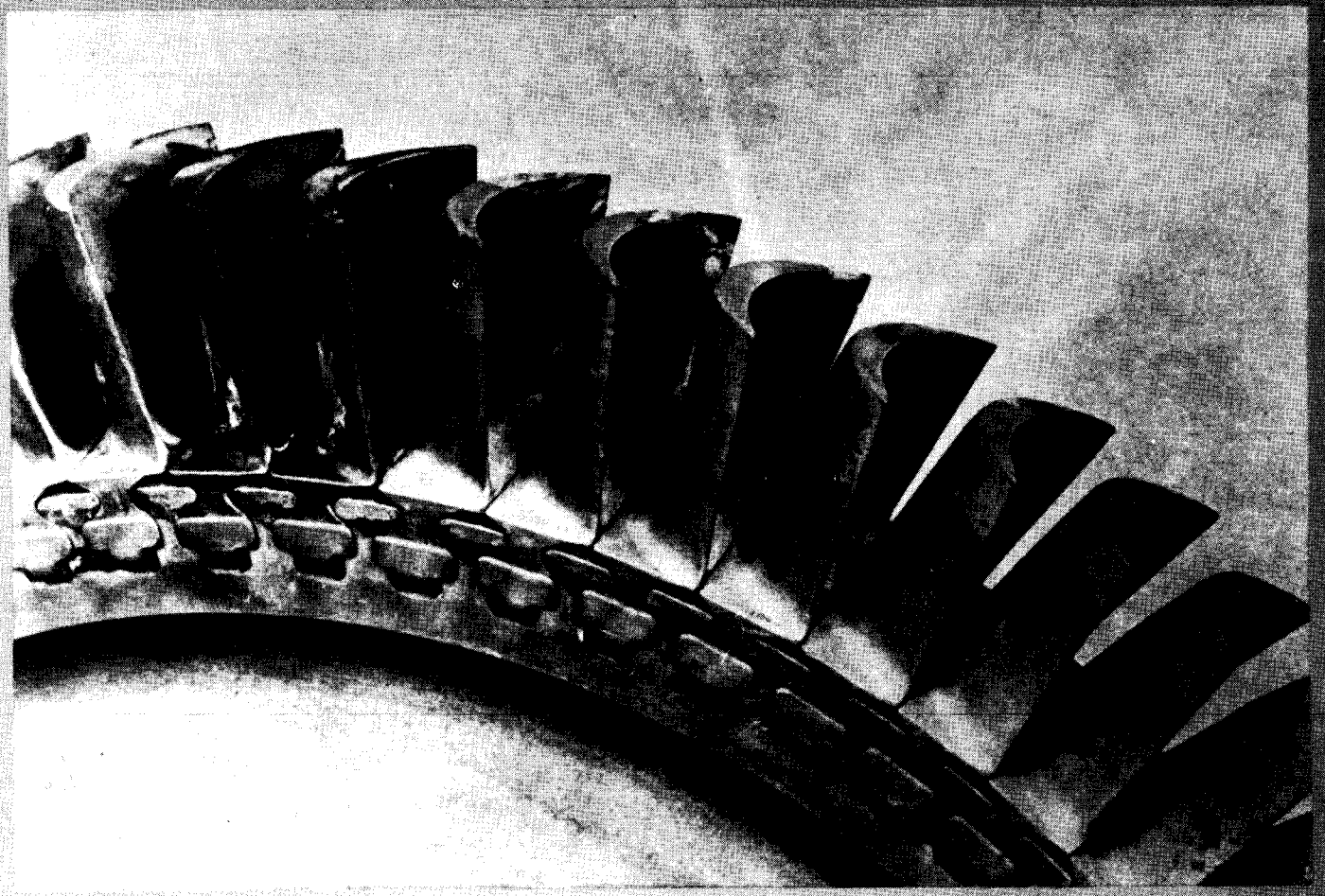
TWO STAGE POTASSIUM TURBINE ROTOR



NASA RN 66-605
2-15-66

Fig 77

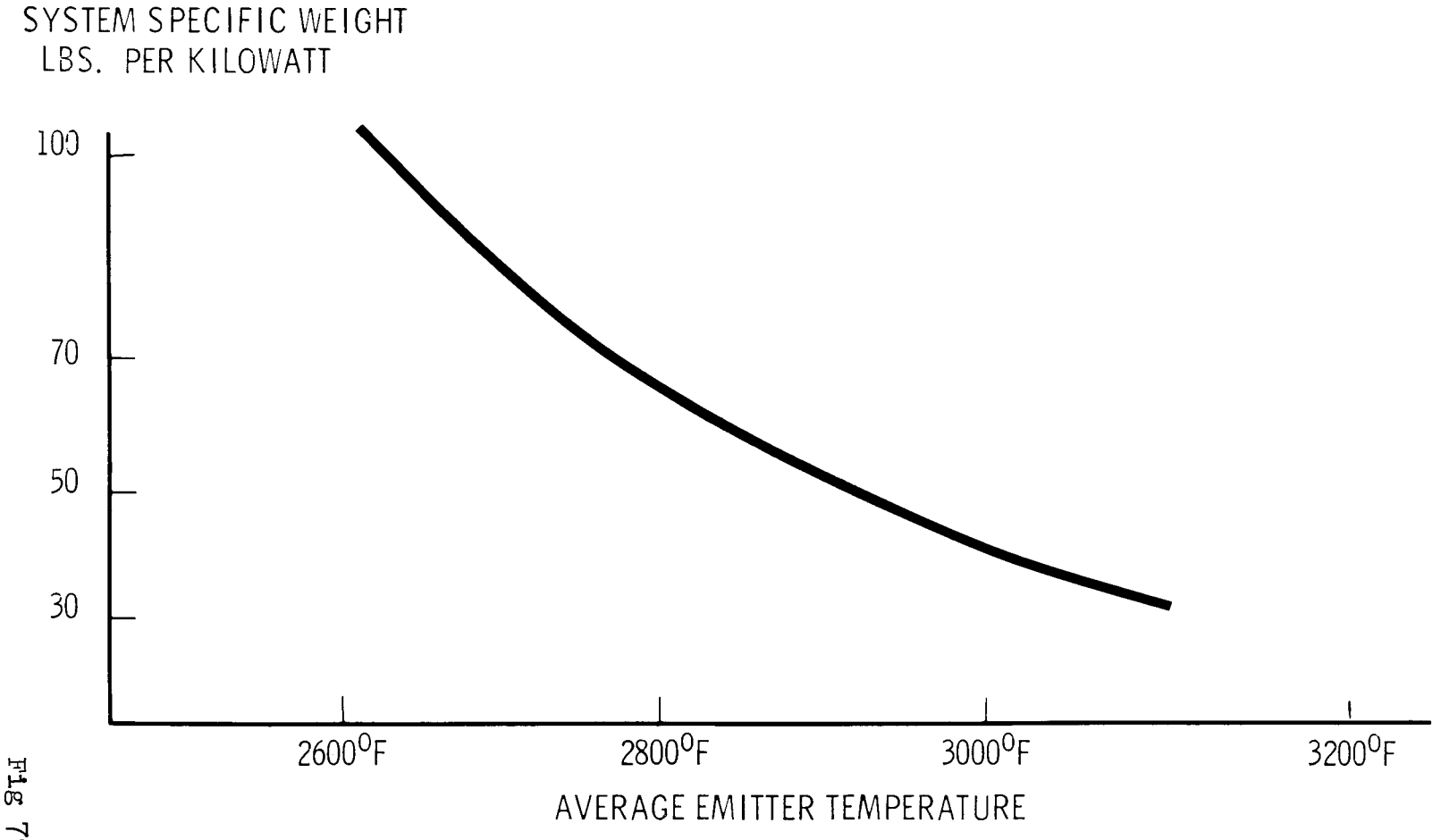
POTASSIUM TURBINE AFTER 2000 HOUR ENDURANCE TEST-SECOND STAGE TURBINE BLADES



NASA RN 66-604
2-15-66

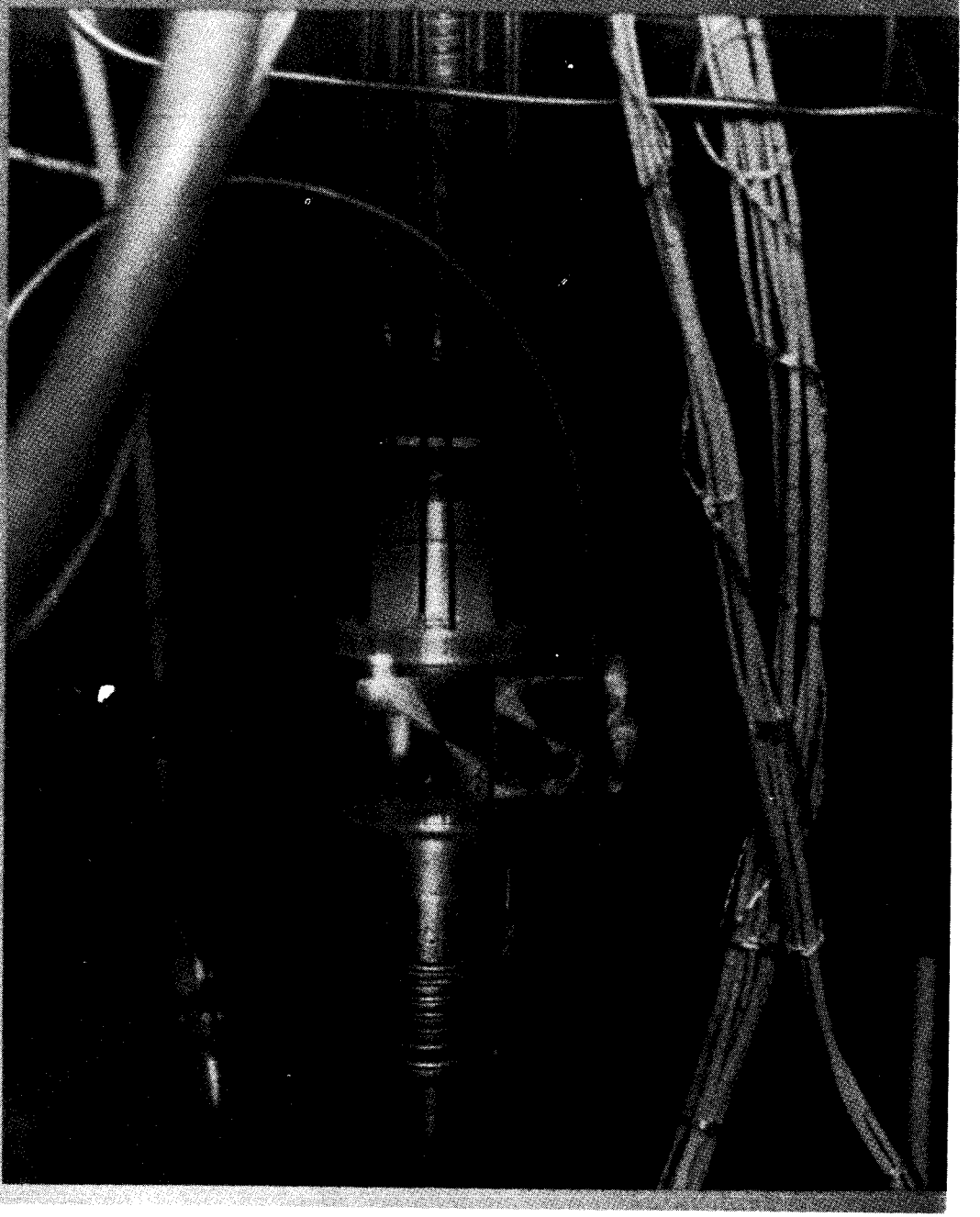
Fig 78

THERMIONIC SYSTEM WEIGHT
VS
OPERATING TEMPERATURE



NASA RN 65-1937
12-14-65

Fig 79

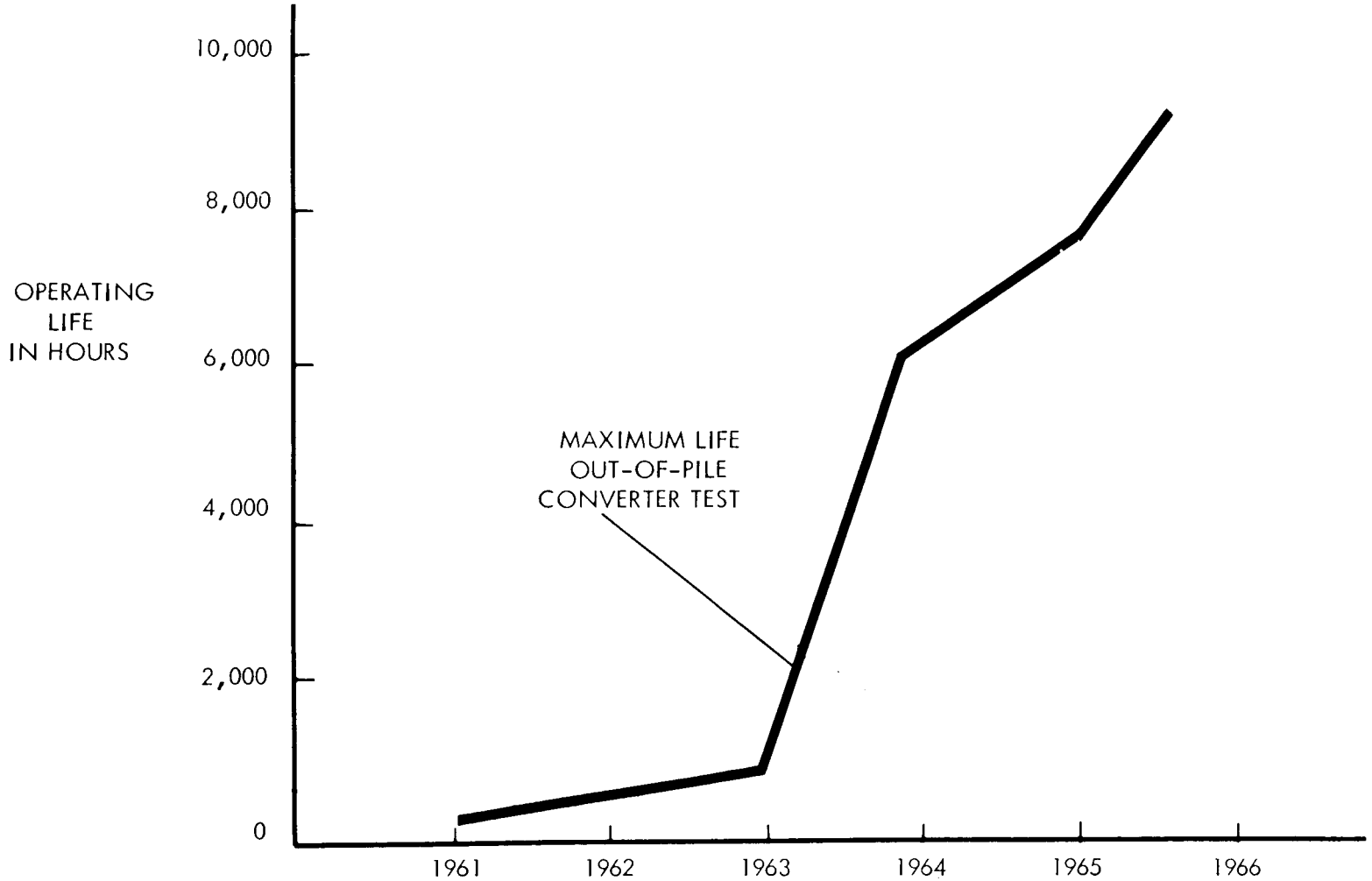


THERMIONIC DIODE
IN OPERATION
AT 1800°C

NASA RN 66-606
2-15-66

Mar 80

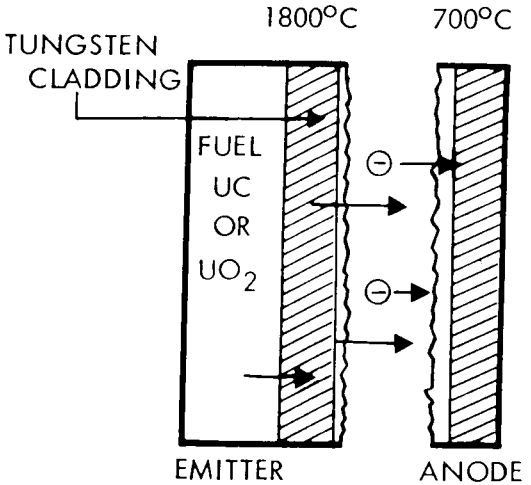
NUCLEAR REACTOR THERMIONIC CONVERTER EXPERIENCE



NASA RN 65-1934
REV. 2-15-66

Fig 81

THERMIONIC FUEL TRANSPORT



FUEL DIFFUSION RATE = 1 ATOMIC LAYER PER HOUR
= 0.0001 CM PER YEAR

NASA RN 65-2152
REV. 2-15-66

Fig 82