Dreams of Nuclear Flight

The NEPA and ANP programs

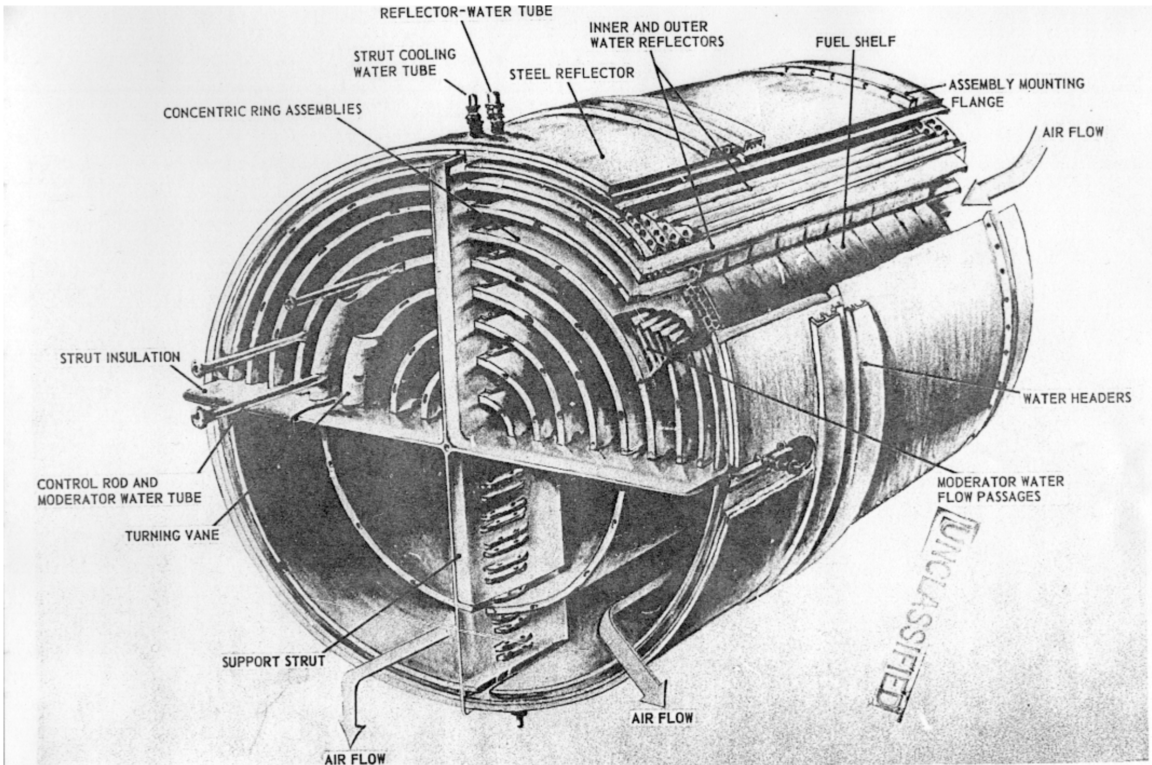

Fig. 2.2 – P-1 reactor structural arrangement

Jesse Stoffel
NEEP 602
University of Wisconsin- Madison
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Introduction

"…the potentialities of nuclear-powered flight are so great that its continued development…is mandatory in the interest of national defense", stated the final report of the Nuclear Energy for the Propulsion of Aircraft program.

Practically since the splitting of the atom, scientists and engineers dreamed of limitless, durationless nuclear flight. From 1946 to 1961, America poured a billion dollars into this dream. This paper will discuss the timeline of those years, the major successes and projects of those years and possible reasons while those dreams were not achieved.

Timeline

Visions of the apparently unlimited potential of nuclear power led the U.S. Army Air Force to award a contract to the Fairchild Engine and Airplane Corporation on May 26, 1946. Barely 6 months after the first atomic explosions and the end of World War II, Fairchild became the directing agency in charge of the Nuclear Energy for Propulsion of Aircraft (NEPA) Project. NEPA would perform feasibility investigations of and begin research toward the use of nuclear power for aircraft. Secondly, NEPA would educate the aircraft engine industry in such.

Fairchild was the only agency working on nuclear flight until 1948, when the Atomic Energy Commission contracted a group of MIT scientists to review the work completed and evaluate the possibilities. This group of scientist, known as the "Lexington Project", concluded that although success could not be guaranteed, Nuclear Flight could probably be achieved "in approximately 15 years at a cost well in excess of one billion dollars". The group recommended an expanded evaluation program and recommended that a strong development program be established, if national policy makers felt the high costs could be justified. The group also concluded that Manned Nuclear Aircraft would be the least difficult engineering problem concerning nuclear flight, the Ramjet and Rocket being judged as more difficult.

In 1949 the AEC, USAF, Navy and NACA (precursor to NASA) all took active roles in the program as feasibility studies continued at Fairchild and began at Oak Ridge National Laboratory (ORNL). By May of 1951 the NEPA project concluded nuclear flight was feasible. Having completed the primary mission, the program was closed, and the Aircraft Nuclear Propulsion Program (ANP) was born.

On March 21, 1951 the Aircraft Gas Turbine Division of General Electric came under contract with the Air Force to undertake active development of a nuclear turbojet engine. A second contract with the AEC for reactor development became effective June 29, 1951. That two separate agencies would contract with GE was indicative of future problems. Other companies, Lockheed, the Martin Company and Pratt-Whitney among them, would sign similar contracts to encompass other areas of research and development. This timeline will focus primarily on work at GE.

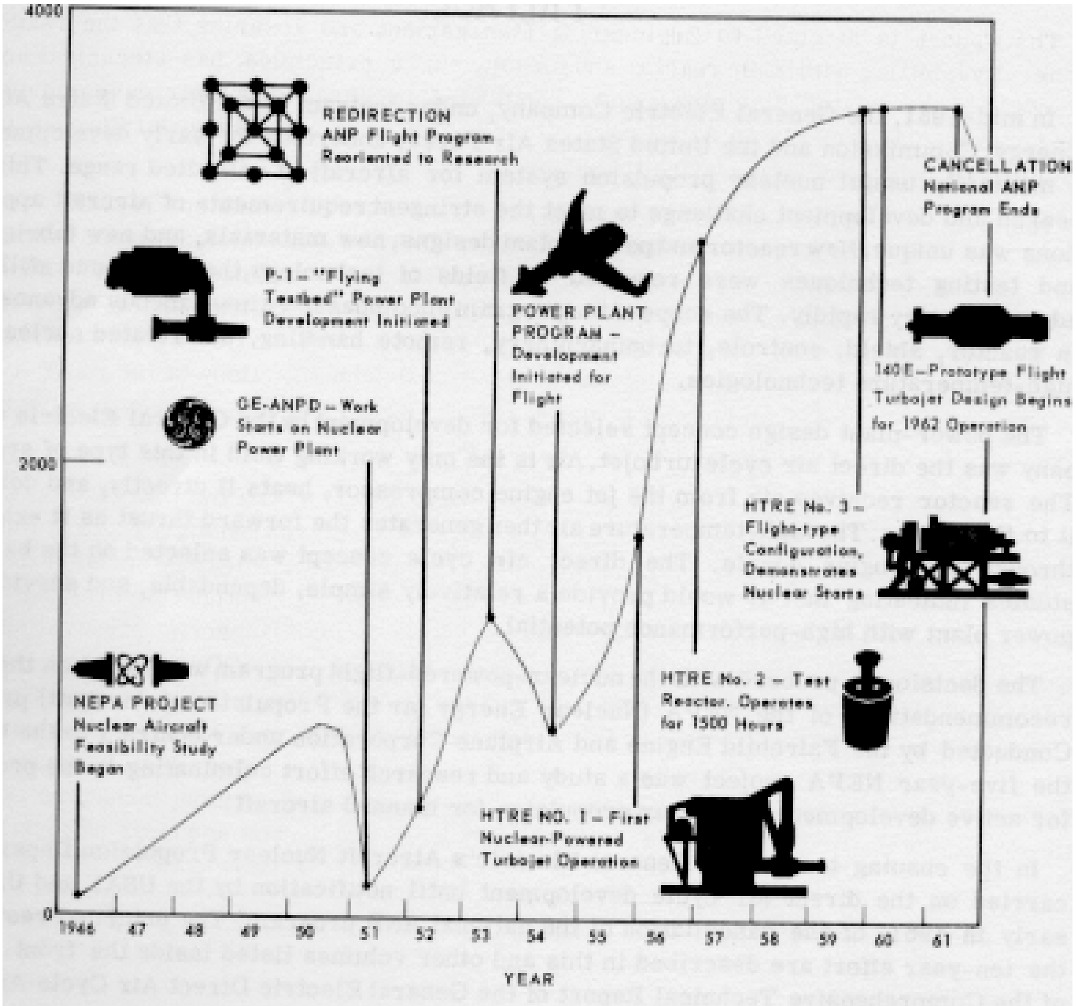
The first several months were spent selecting the type of system for initial development. On August 28, 1951, GE recommended pursuing a direct-air-cycle, air-cooled, metallic fueled, hydrogenous-moderated system. This was the system the engineers believed would fastest lead to nuclear flight. The power plant, the P-1, would not be capable of powering military craft but at this time the Air Force objective was ground and flight operations at the earliest date possible to gain experience. Development was approved in 1952, ground tests scheduled for 1954 with flight in 1957. P-1 was discontinued in May 1953 when the Air Force decided that an early flight without military applications was not desirable.

After cancellation of the P-1 development GE changed direction, since it no longer had a specified power plant objective, towards research that would advance materials research and engineering methods. It was decided that the efforts would be focused on performing nuclear reactor experiments utilizing reactor designs that had potential for use in nuclear aircraft propulsion. This series of experiments was known as the Heat Transfer Reactor Experiments (HTREs). Design and development began in 1953 and HTRE-1 became the first nuclear reactor to power a turbo jet engine in January of 1956. Three HTREs were utilized from 1956 to 1961. They were invaluable tools in advancing the Aircraft Nuclear Propulsion program.

In 1955, the ANP program received a power plant objective again when the air force proposed the 125A Weapons System. This would be a "Piloted Nuclear-Powered Intercontinental Strategic Bombardment Weapons System" capable of continuous cruise for 40 hours at Mach 0.9 and 20,000 feet, a 2000 nautical mile sprint at Mach 2.5 at 55,000 feet, and a low-level penetration at mach 0.9 and 500 feet. GE commenced development of the XMA-1 power plant (power plant encompasses the reactor, turbo jet, shielding and necessary other systems) to meet these objectives. The ground test was scheduled for 1959 and first flight for 1960.

Work continued on the XMA-1 and the HTREs, and in 1958, the Air Force changed Weapon System objectives to the "Continuous Airborne Missile Launcher and Low Level Weapons System" (CAMAL). Work was redirected, the XMA-1A would utilize the reactor design being successfully operated in HTRE-3, and XMA-1C would eventually meet the military objectives. Flight tests were now set for 1963.

The Department of Defense then elected in 1959 to eliminate the early flight option, and instead focus on improving potential performance. Work was halted on the XMA-1 and design begun on the XNJ140E power plant. Work on the XNJ140E was on schedule when the ANP program was terminated. Below is a graphical representation of manpower associated with the ANP project by year and phase.



Summary of events – General Electric Aircraft Nuclear Propulsion Program*

*Detailed history and chronology is provided in Program Summary, APEX-901. Chronology information extracted from: Aircraft Nuclear Propulsion Program hearing before the Subcommittee on Research and Development of the Joint Committee on Atomic Energy, 86th Congress of The United States, First Session, July 23, 1959, United States Government Printing Office, Washington 1959.

General Electric was by no means the only group working on the ANP project. Convair modified a B-36 bomber to carry a 3 MW air-cooled reactor. The reactor was operated during flight to measure the effects on ground level radiation and contamination, and flew across the southwestern states from July 1955 to March 1957. Pratt-Whitney was designing and analyzing the liquid metal cooled indirect reactor. The reactor would transfer heat to a metal coolant, which would be used to heat the air. This design effort began at the same time as GE was developing the direct, air-cooled reactor, and continued on after cancellation of the ANP program, but never resulted in any testing of actual systems. And the UW Nuclear Reactor Directors, Richard Cashwell, was hired by Lockheed in 1958 to do irradiation testing of structural components utilized in the ANP program. Many different groups were involved, but the efforts in Idaho by GE were the most directly related to nuclear flight.

The Aircraft Nuclear Propulsion program was canceled on March 28,1961. President Kennedy recommended the omission of additional funds, stating "Nearly 15 years and about one billion dollars have been devoted to the attempted development of a nuclear-powered aircraft; but the possibility of achieving a military useful aircraft in the foreseeable future is still very remote." The General Electric post-mortem report disagrees with this prognosis claiming, "the program termination was based primarily on the fact that there was not considered to be a specific military requirement for a manned aircraft with the characteristics of the subsonic, long endurance system that was under development." Whatever the reason, the program was terminated, although limited development continued on the indirect, liquid metal-cooled design and the liquid-fueled design.

Nuclear Energy for the Propulsion of Aircraft (NEPA) project

On May 26, 1946, Fairchild Engine and Airplane Corporation was awarded the contract to head up the Nuclear Energy for the Propulsion of Aircraft (NEPA) project. The project had two major goals:

1) To perform feasibility investigations and research leading toward the adaptation of nuclear energy to the propulsion of aircraft.

2) To educate the aircraft engine industry in the field of nuclear science and its adaptation to aeronautical propulsion.

The NEPA project considered several options for a nuclear propulsion system over its existence. A direct-cycle system intakes compressed air, allows that air to come into direct contact with the fuel elements for heat transfer, and expels the heated air for thrust. Concerns with this system included neutron and radiation leakage through the air inlets and outlets, and retention of fission products within the fuel elements. An indirect-cycle, solid core model would pass a primary coolant (a liquid metal to achieve maximum temperatures) through the reactor core and then transfer that heat from the metal coolant to the air using a heat exchanger of some design. Problems were lack of experience working with metal coolants, possible coolant leakage and system unreliability. The liquid fueled design was also contemplated, uranium bearing metal coolant would pass through a critical cavity, of sufficient size and dimensions to cause criticality and produce heat. The heated fueled-metal would be then pass through a heat exchanger to heat the air required for propulsion. Again experience was lacking in this field. The NEPA project concluded, "Choice of any cycle for exclusive or even major development at this time would be arbitrary", explaining that too little was yet known. However, if early nuclear flight was an objective, the direct cycle approach would probably be easier to develop.

Early studies conducted by NEPA focused on uranium-bearing ceramics (graphite, beryllium oxides and carbides) due to the moderating properties (low neutron cross-sections and masses). These were focused on because the supply of uranium was so limited that maintaining a minimum uranium inventory was a major factor in material selection. Most high temperature metal fuels available at the time had higher neutron absorption levels, which would increase required uranium inventory. Beryllium and carbon moderators were eventually removed from contention due to high sensitivity to foreign materials. Instead a hydrogenous moderator would be used due to a low sensitivity to such. A new reactor design concept evolved that would utilize the moderating properties of the hydrogenous materials, while minimizing the negative side effects of most hydrogenous materials poor high temperature properties. A vessel was penetrated by many insulated air passages containing the air-cooled uranium fuel elements. The vessel then would be filled with water or a liquid hydrocarbon to serve as moderator and structural coolant. A radiator of some type could then remove the structural heat. NEPA concluded that an early flight program could be adopted and a direct air cycle, hydrogenous moderated reactor could be developed quite rapidly.

The NEPA project began as a United States Army Air Force venture in 1946 and remained a sole Air Force venture until 1948 when the AEC contracted with the Massachusetts Institute of Technology for a group of prominent scientists, known as the "Lexington Project", to review the work being conducted in the field of aircraft nuclear propulsion. The "Lexington Project" spent the summer of 1948 reviewing the existing knowledge, the foreseeable engineering problems, and the chances for success and reported:

"…although success cannot be guaranteed, there is a strong possibility that some version of nuclear flight can be achieved if adequate resources and competent manpower are put into the development; that intensive effort will be needed if a nuclear powered aircraft is to fly within 15 years…"

With this assessment in hand, the Atomic Energy Commission joined in the effort with the Air Force, the Navy, and the National Advisory Committee for Aeronautics. Work was progressing both at NEPA and at Oak Ridge National Labs, cooperative efforts between both groups, NEPA headed primarily under direction of the Air Force and ORNL primarily under direction of the AEC increased until there were joint programs in all fields. In May 1951, the NEPA project was deemed to have proven the general feasibility of nuclear flight and the project was closed in favor of the joint Aircraft Nuclear Propulsion (ANP) program.

Early Work of the Aircraft Nuclear Propulsion Program

Selection of the power plant system to be developed was the first task undertaken by the newly formed ANP project.

On August 28, 1951 the ANP project recommended to the Air Force and the AEC to proceed with development of the direct-air-cycle system using a n air-cooled reactor with metallic fuel elements and a hydrogenous liquid as the moderator and structural coolant, as the best way to obtain early nuclear flight experience. Problems anticipated by the NEPA project were dismissed. Fission product release could be reduced or eliminated by using a clad metallic fuel element. Neutron and radiation leakage through air ducts appeared to be less of a problem than anticipated due to energy reductions due to scattering. The potential problems with the liquid metal reactor, reliability and control of system leakage still seemed to be quite challenging. Weights of the direct and indirect systems were comparable, even though the indirect core would be smaller, the required pumps and piping would almost even out the comparison. For these reasons and others, GE would remain staunchly in favor of air-cooled systems throughout the life of the reactor.

Research and development began on the P-1 power plant utilizing this system. Early availability would be much more important than high performance. It was hoped that the power plant would be sufficient to sustain low speed flight, but this was not a design requirement.

The P-1 power plant would consist of one large reactor and shield assembly powering four turbojet engines. The shield, reactor, and associated ducting required to power four turbo jets would weigh less than four separate reactors and shields. The reactor would be mounted in a converted B-36 bomber, designated the X-6. The four engines would be mounted under the fuselage.

The reactor, the R-1, was made up of nine annular concentric air passages that contained the fuel elements. Between these rings were rings of water to serve as the moderator and structure coolant. The fuel was uranium oxide disbursed in stainless steel, clad with unfueled stainless steel. Two stainless steel cylinders surrounded the reactor core and served as reflectors. The annular ring design was chosen due to ease of nucleonic calculations and analysis.

The Air Force discontinued the P-1 development program, deciding that to pursue a power plant with no military purpose would be useless. At the time of termination the reactor and power plant components were in the final design and development stages. An entire power plant had been built and had been tested using a chemical heat source in place of the reactor, proving that several turbojets could be run from the same heat source. Much of this equipment and the control rod systems would be used in later experiments.

The R-1 reactor

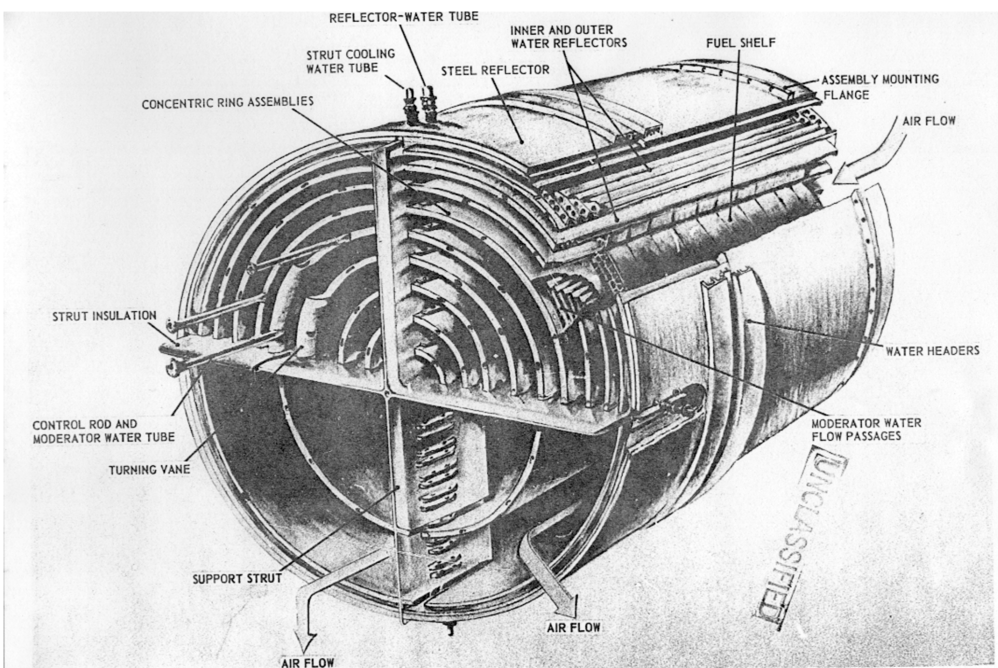


Fig. 2.2 – P-1 reactor structural arrangement

Heat Transfer Reactor Experiment One (HTRE-1)

With the removal of a distinct power plant objective, it was decided that the best way to provide direction for materials and component development would be a series of nuclear reactor experiments, which could have applications towards nuclear flight. This series of experiments were known as the Heat Transfer Reactor Experiments and were used to assist in development of a flight system from 1953 to the program termination.

The HTRE-1 was designed for higher performance than the P-1 but utilized many features of the R-1 reactor. The control rods and actuators were from the R-1 development, and water was used both as a moderator and structural coolant again. The reactor could be tubular instead of annular to provide better structural characteristics because nuclear analytical methods were now advanced enough to account for less homogeneous geometries.

Fuel was still manufactured the same way, but was made of a nickel-chromium alloy (80Ni-20Cr). Enriched UO2 was mixed with the Nickel-chromium to 40 to 42 percent UO2, and the element was clad with niobium-modified 80Ni-20Cr. The Niobium improved strength and oxidation resistance. The fuel was worked into concentric rings, which fit into the tubular air passages.

37 air passage tubes penetrated a cylindrical aluminum vessel. The vessel was filled with water to serves as a moderator and coolant. A beryllium reflector surrounded the tubes, and was cooled by the water. The fuel elements operated at 1700 degrees F, producing an outlet air temperature of 1350 degrees. A reactor operating life of 100 hours was the design goal. The reactor would be placed in a shielded Core Test Facility

consisting of a shield tank, two modified turbo jet engines (HTRE-1 and 2 would power only one turbo jet at a time though) and the accessory equipment. The entire CTF would be mounted on a train car to allow removal to the hot shop for maintenance and inspection.

The engine was started on chemical power, using the turbojet engine compressors to draw air through the reactor. Rods were withdrawn and the reactor brought to power. The rise in outlet air temperature would be sensed and less chemical fuel would be used until eventually the system was running on full nuclear power. Shut down could be done in the opposite manner or the reactor could be scrammed and engine coast down would provide enough airflow to remove the initial decay heat.

HTRE-1 reached full nuclear power in January of 1956 and reached power levels up to 20.2 megawatts. Fuel element damage occurred in 3 tubes within he first 6 hours due to thermal shock from faulty insulation. The elements were replaced and the core operated for 144 more hours at discharge temperature from 1280 to 1380 degrees F. Some small blisters were detected in the post operational analysis due to damage to the clad by weld splatter. Oxidation of the fuel had caused expansion which caused blistering.

HTRE-1 met or exceeded all objectives set for it. The feasibility of operating a high temperature gas turbine reactor was proven. The fuel was proven to have exceeded lifetime requirements. The analytical methods developed for analysis were proven and the reactor was proven stable. In fact, the fast response times in the control system were proven to be unnecessary. Additionally safe operational and maintenance procedures were developed. It was shown that after removing the fuel, the remainder of the system could be manually maintained after short decay times.

The reactor design utilized in the HTRE-1 could have been applied to a load-carrying airplane, allowing a range of 50,000 miles at subsonic speeds. However, for military applications, it was obvious improvements would have to be made in both performance and endurance. The decision was made to modify HTRE-1 to allow testing of new materials that may allow these necessary improvements. The modified reactor was Heat Transfer Reactor Experiment Two.

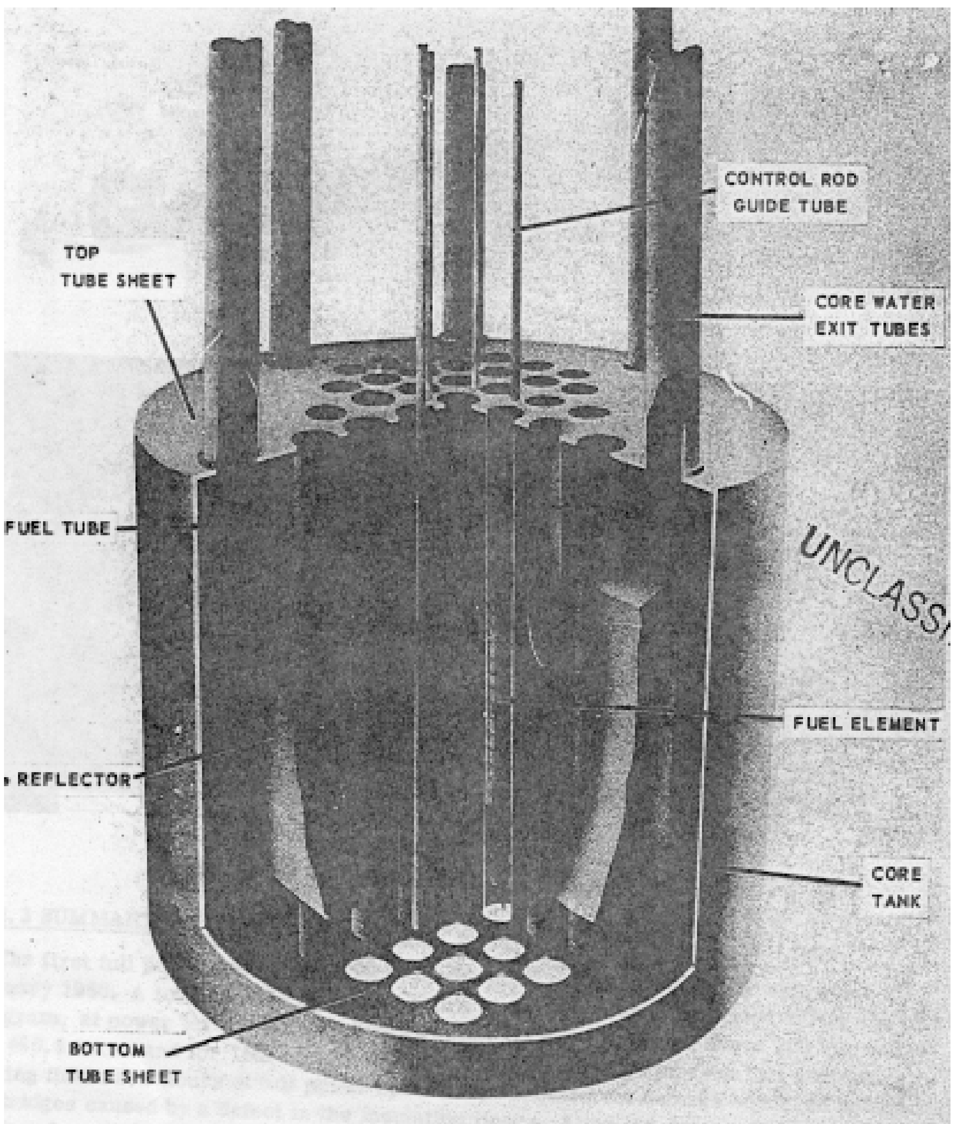


Fig. 3.4 – HTRE-1 reactor

HTRE-1

Heat Transfer Reactor Experiment Two (HTRE-2)

The central seven fuel/air tubes of HTRE-1 were removed and replaced with a hexagonal void 11 inches across. This void allowed insertion test materials. To compensate for the loss of reactivity due to the removal of the 7 fuel elements, an additional four inches of beryllium was added to the reflector.

HTRE-2 was used for four metallic fuel element and moderator tests:

1. Insert 1B-Evaluated cladded hydrided zirconium as a potential solid moderator at temperatures up to 1600 degrees F. The moderator surrounded fuel elements similar to those used in HTRE-1. Operated for 36 hours.

2. Insert 1C-Tested uncladded hydrided zirconium for 100 hours. Proved successful at temperatures of 1200 degrees F.

3. Insert 1D-Similar to 1C, except two elements were purposely deprived of airflow to evaluate melt down behavior. Significant amounts broke away and some escaped through effluent, the moderator was essentially undamaged.

4. L2C1 Insert Cartridge- a fuel element of UO2 dispersed in chromium-titanium, surrounded by beryllium to peak the flux to allow more severe conditions. Satisfactorily tested for 80 hours at 2090 degrees F.

HTRE-2 was also operated for more than 1100 hours to test a variety of ceramic fuels being developed for the XNJ140E-1 power plant. Bare and clad inserts were tested in conditions up to 4400 degrees F for time periods as long as 193 hours.

The HTRE-2 core operated for a total of 1299 hours at power and was still in operation at the termination of the program. Five of the fuel elements had been operated for 997 hours with no signs of damage. It therefore not only helped form the basis for HTRE-3 and other planned cores, but also proved the steadfastness of the direct cycle air-cooled nuclear reactor.

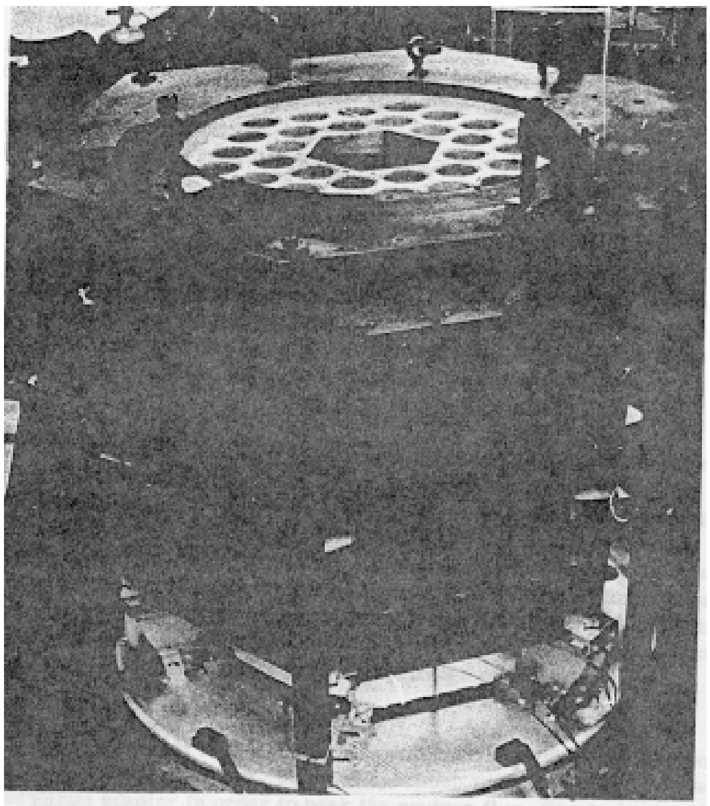


Fig. 3.8 – HTRE-2 reactor during construction, showing the hexagonal cavity used to test advanced reactor components (C-04013)

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HTRE-2

Heat Transfer Reactor Experiment Three (HTRE-3)

HTRE-3 differed from the previous two experiments in 3 major ways:

1) It had a solid moderator. This allowed air-cooling of the moderator, and increased the power to weight ratio. Hydrided Zirconium, tested in the HTRE-2, was used. Hydrogen content was varied to flatten the power distribution.

2) The reactor is horizontal. HTRE-3 and its components were built to be fit into an airframe, with the exception of the shield, which was water cooled and would be air cooled in an aircraft design.

3) HTRE-3 powered 2 turbo jets simultaneously. HTRE-3 was designed to operate at conditions approaching those reached in the proposed XMA-1 power plant, which would also power two engines.

HTRE-3 was dimensionally the size of a power plant providing flight propulsion, and was designing structurally to do so. HTRE-3 would operate up to power levels of 35 Megawatts, but was designed to provide propulsion levels of power when connected to larger turbojets. Power levels and airflows were chosen to be characteristic of flight service. HTRE-3 would prove that nuclear propulsion would be ready in the near future.

HTRE-3 was constructed of 150 cells. Each cell was made up of 19 stages of 12 concentric fuel rings. A hexagonal block of hydrided zirconium for moderation surrounded the entire cell. A beryllium reflector was once again incorporated, but this reflector, as well as the moderator and control elements, was air-cooled. Power flattening within the fuel elements was accomplished by variation of enrichment between concentric fuel rings.

HTRE-3 commenced initial power testing September 8, 1958. On November 18, the dynamic and shim rods were excessively withdrawn from the core due to an erroneous reactor power reading. The resultant power excursion melted and collapsed several fuel element rings. The high temperature scram and reduction in reactivity due to fuel melting and redistribution caused the reactor to shutdown. The core was returned to the hot shop for inspection and repair.

Upon repair, HTRE-3 was subjected to an endurance test. It operated at full power nearly continuously for 126 hours. It was the first time a reactor had ever powered two turbojets simultaneously. After the endurance test, the fuel elements were inspected, and appeared to be in excellent condition. Upon reassembly, HTRE-3 became the first reactor to start a turbojet solely on nuclear power. All previous experiments had begun with the turbojets operating on chemical power and shifted to nuclear. A total of three nuclear starts were performed prior to commencing an elevated performance test run, which subjected the core to more extreme conditions for 20.3 hours.

The HTRE-3 accomplished many objectives. It demonstrated the solid moderator concept. It exceeded its 100-hour design life significantly, while powering multiple turbo jets. It demonstrated full nuclear starts and progressed reactor design toward the totally air-cooled concept (HTRE-3's shield was still water cooled, an aspect that would be changed prior to flight). The advances made in HTRE-s were to be utilized in the XMA-1A power plant design.

HTRE-3

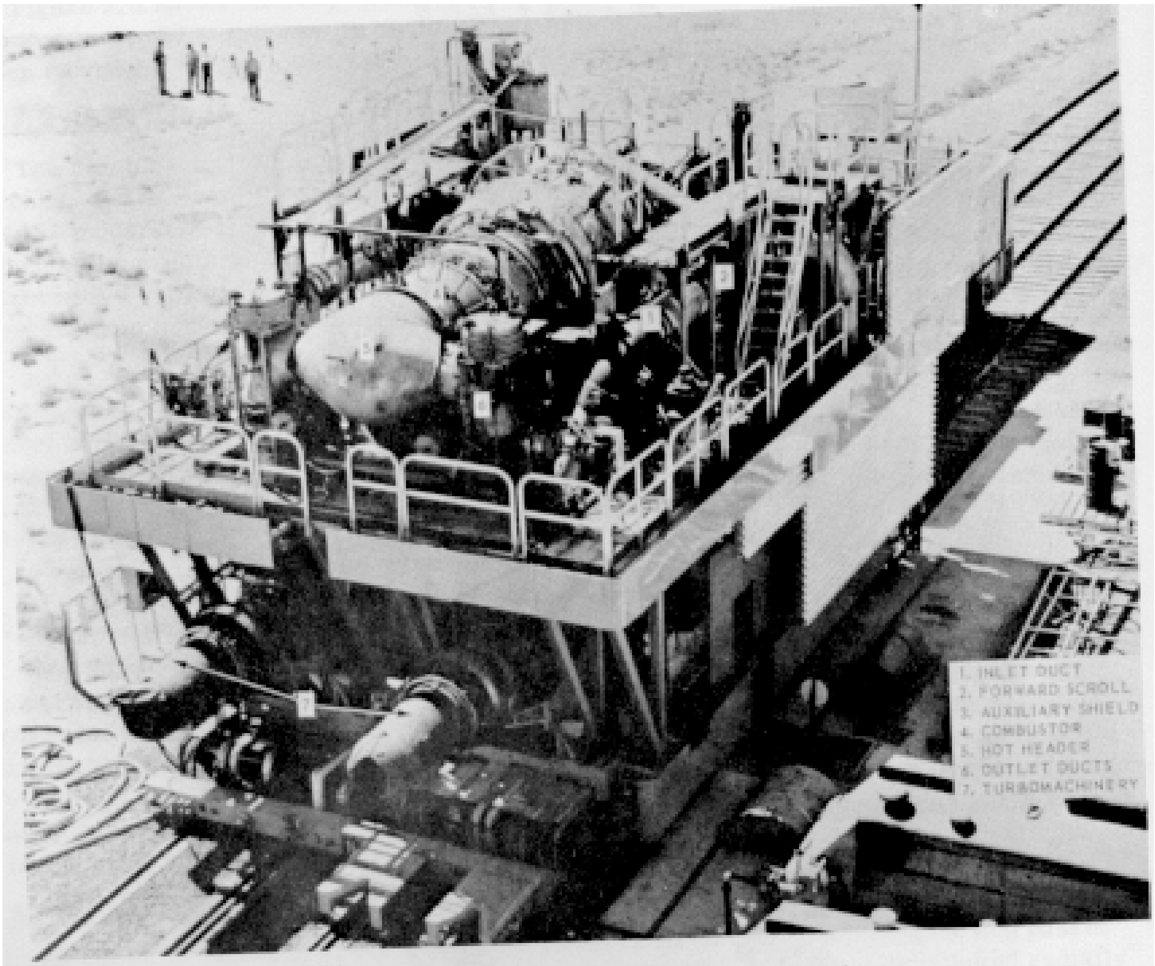


Fig. 2.2 – HTRE No. 3 test assembly (Neg. U-2700-11)

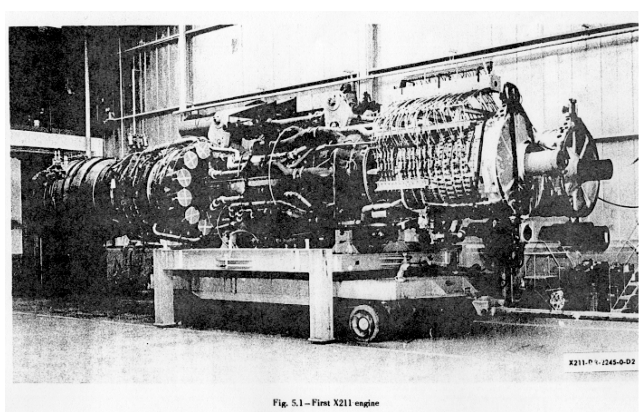
XMA-1 Power Plant

In 1955, three years after the cancellation of the P-1 project, GE again had a specific military objective. The 125A weapons system needed to have an extended cruising range, be capable of penetrating enemy defenses at high altitudes and speeds, and attack at very low altitudes. Development of the XMA-1 power plant began to meet those goals.

The XMA-1 would utilize two X211 turbo machines coupled to one reactor and shield assembly. Utilizing one larger reactor would require less than shielding than two smaller reactors, it was reasoned, and the two engines would also help serve to shield the core.

The initial XMA-1 reactor design called for 151 cylindrical fuel elements with unclad hydrided zirconium bars placed in the interstitial points and in the center of all fuel assemblies for moderation. The XMA-1A, anticipated to be in use earlier would have an identical core design as HTRE-3. The XMA-1C would greatly improve the performance of the final weapon system and would utilize the ceramic fuels being tested in the HTRE-2 inserts.

Reactor development was underway and the X211 turbo machines had been completed and tested at simulated XMA-1 operating conditions when the project was cancelled in lieu of the more advanced XNJ140E power plant.



The X211 Turbo jet

XNJ140E Power Plant

Early flight objectives were canceled by the Air Force for the XMA-1 in 1959. With the objective cancelled, the work on the XMA-1 was discontinued. GE commenced the "Advanced Configuration Study" to determine which type of power plant, Dual-Engine, Integral Single-Engine, or Separable Single-Engine, would best meet future objectives. Eventually the Integral Single-Engine was selected for compactness, reliability and maintainability. Despite requiring extra shielding for two reactors, the Integral Single-Reactor concept was found to be comparable weight-wise to the Dual-Engine concept due to the reduction in external ducting.

The XNJ140E was then designated as the power plant to be designed. The reactor would be made of ceramic materials to allow higher operating temperatures. Fuel was Berylia containing dispersed uranium oxide. The reflector was beryllium oxide. The turbine shaft pierced the center reflector annulus region.

According to GE, work was on schedule on the XNJ140E when the ANP program was terminated. Manufacturing drawings had been released and long lead-time materials had been ordered. Critical experiments had been performed and permission to proceed with fabrication and assembly had been requested.

The XNJ140E Reactor

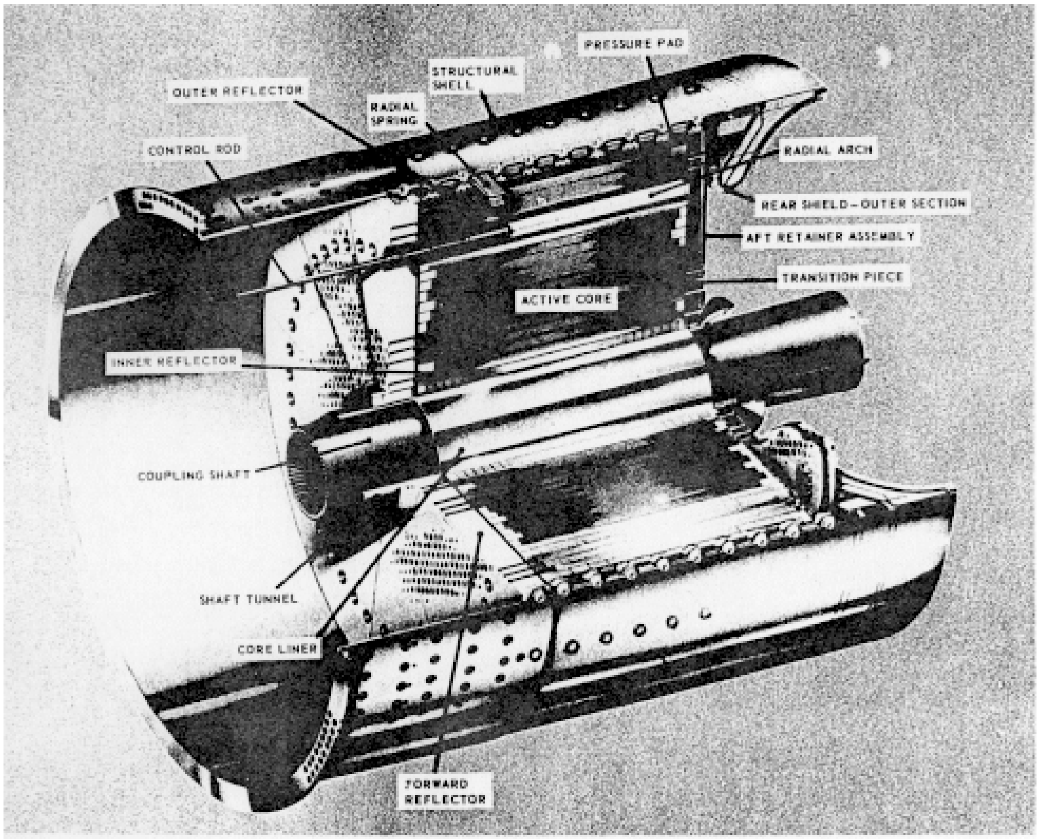


Fig. 4.1 – Cutaway view of XNJ140E-1 reactor

Project Cancellation

President Kennedy canceled the ANP project in 1961. In his written statement, the President recounted the 15 years and 1 billion dollars spent on the program and claimed nuclear flight was still in the distant future.

It is ironic that those values, 15 years and a billion dollars, match exactly the numbers predicted by the "Lexington Project" to have some limited nuclear flight capability. If the project had been run more effectively and had not constantly changed objectives, or if it had seen the value of early flight to maintain interest in the program, nuclear flight would have occurred. The P-1 was scheduled for flight testing in 1957, four years before the program was terminated, and the success of the HTRE experiments showed that nuclear flight would likely have occurred if project objectives had not switched almost at random. Surely the development of the Polaris A-1 missile system in 1960 removed most of the drive from the ANP program, but it seems strange that a President, who presented such a challenge to the American people as manned exploration of the moon, would cancel the ANP project.