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Nuclear Propulsion and Aerospace Power

General Thomas D. White

Chief of Staff, United States Air Force

PRE-EMINENCE in air power has been the goal of American airmen since the military potential of air operations was first recognized. This goal has unquestionably been realized throughout the years since World War II. The leadership of the United States in the field of air power has been evident in the continued superiority of our equipment and in the unsurpassed skill of those who have designed, developed, operated, and commanded this equipment.

Today, however, as air power evolves into aerospace power, our position is being seriously challenged—and challenged in an area in which we have been supreme for years: technology. As a result, we are being hard pressed to retain leadership. The rate at which we advance is no longer completely of our own choosing. Rather it must meet the demands of a deadly serious competition—a competition in which the security of our nation is at stake. If we are to continue to be secure, we cannot allow ourselves to be surpassed in any technical field—particularly the field of aerospace technology.

In order to hold our lead, we must constantly explore new concepts and advanced techniques. We must always be on the alert for new and radical methods to break through barriers which impose limitations on the employment of our aerospace forces. One major step in this direction would be the successful achievement of airborne nuclear propulsion. The development of this capability would open wide the door to new concepts—and would provide our country with a substantial additional measure of military security. Bold opportunities will be on hand for those nations which exploit this new technology.

Although I will not attempt to forecast specific configurations of future aerospace weapons, I am convinced that the Air Force of the future will always be comprised of mixed forces, that is, forces of both manned and unmanned vehicles. We must always have weapon systems available which can selectively attack and destroy all types of military targets. Manned systems provide the versatility needed to perform many of these tasks. The capability for essentially unlimited endurance, which is characteristic of airborne nuclear propulsion, will provide aerospacecraft with the long-sought objective of unlimited range. With the conquest of the range barrier, manned systems will gain a new and vastly improved flexibility. For example, a breakthrough in this area would allow the creation of a mobile strategic strike force capable of penetrating hostile territory from any direction at a choice of altitudes and unencumbered by staging or refueling operations. This force could rapidly be directed to selected targets anywhere in the world from airborne nomadic patrol stations. Armed with air-to-surface missiles, nuclear-powered aircraft could perform airborne alert duty for days—perhaps weeks—at a time. By maintaining a substantial portion of this force on constant airborne patrol, this force would be immune from enemy surprise attack.

The technological effort required to develop nuclear propulsion for manned aerospacecraft has been under way for more than a decade. In the mid-Forties the Air Force recognized the potential of nuclear propulsion for aerospace vehicles. Since then it has supported programs of research and development and has monitored their progress with interest and anticipation. At this time our greatest emphasis is on the manned-aircraft portion of this program, since its present technological position is far in advance of other nuclear-propelled aerospace systems. Our present development work is oriented toward an early attainment of this vital military capability.

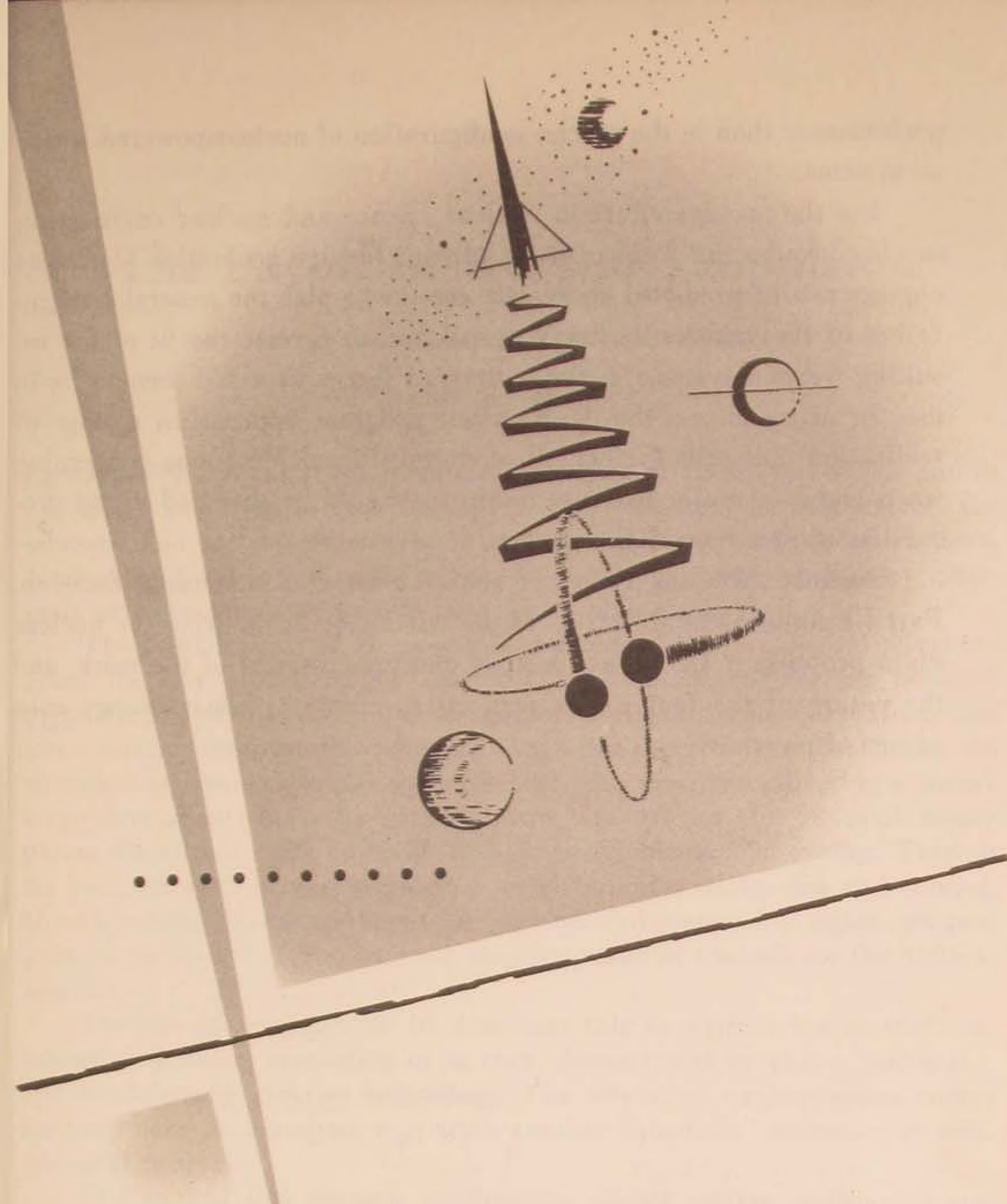
Although our nuclear-missile propulsion programs have only been under way a few years, nuclear rockets and nuclear ramjets already appear to offer greatly increased performance over their chemical counterparts. Nuclear rockets will possess tremendously increased thrust, which will make possible the launching of high-payload military satellites and surface-to-surface missiles. Thus our efforts toward operations farther out in aerospace can be greatly expanded through the use of nuclear propulsion. The large vehicles which are required to support practical, manned space exploration will also be possible.

Studies completed on nuclear-ramjet proposals offer promise of low-altitude, high-speed, long-range missiles that can augment our strategic ballistic missile forces. These missiles could operate from mobile sites on instant readiness. Unlike the current ballistic missiles they would be capable of weaving, feinting, and dodging while seeking out selected targets. The existing programs in development of nuclear-missile propulsion are now in proof-of-principle status. It is reasonable to presume that in due course these programs will approach the stage where they too may be applied to future aerospace weapon systems.

We have achieved our current position in nuclear propulsion through great technological effort. The concentrated endeavor of many highly competent people has been devoted to this task over a number of years. Despite frequent disappointments, they have experienced many significant successes and have now arrived at the threshold of manned flight under nuclear power. Similar successes are anticipated in the near future in our missile propulsion programs.

The military exploitation of airborne nuclear propulsion will provide a significant increase in our future deterrent capability—an increase which must be realized if this capability is to remain effective. Thus the support of this effort by the United States Air Force is in keeping with our constant goal—the preservation of peace through the unquestioned pre-eminence of this nation's aerospace power.

Headquarters United States Air Force



PART I

The Prospect for Nuclear-Powered Flight

THE promise of nuclear propulsion for vehicles and missiles in the aerospace extends to a broad spectrum of military and nonmilitary applications. Their attainment, as with other objectives that compel large departures from earlier technology, demands first the penetration of a maze of scientific and technological obstacles that lie across the way to the engineered, working systems. Because of this needful broadening of theoretical and technical bases, the military accrual from nuclear propulsion is defined more clearly at this time in the prospect of improved performance than in the precise configuration of nuclear-powered weapon systems.

But the massive effort in nuclear science and nuclear engineering steadily invades the problem areas. Already the first generation of nuclear engines can be predicted accurately enough to plan the general configuration of the vehicles they will propel and to foresee the fit of the resulting weapon systéms in the pattern of forces expected then to be in use. In many phases the development program approaches a stage of realization that calls for complicated and difficult decisions concerning when and how major national resources should be allocated to the production of prototype flight systems.

Against this background of achievement and impending decision, Part I examines the objectives of the Air Force in its drive for nuclear flight propulsion, the unique history and management of the work, and the nature of the four major projects to employ nuclear energy as a source of power.

The Payoff in Nuclear Propulsion

LIEUTENANT GENERAL ROSCOE C. WILSON

DCS/Development, Headquarters USAF

TODAY WE stand at the threshold of nuclear propulsion in the air and in space, an advance in technology which will immeasurably extend the strategic and tactical potentials of aircraft and missiles as we know them. Nuclear propulsion will open the way to the development of military spacecraft of types which we can visualize only dimly now.

The brief history of air power is studded with technological advances. From the day of the fragile craft that introduced man-bearing powered flight the tempo of progress has accelerated. A list of the new departures and trend-making innovations would be long: the supercharger that broke old altitude barriers, the monocoque fuselage, the cantilever wing, new metallurgy that swept away the stick-and-wire biplanes for the all-metal monoplane, the retractable landing gear, the controllable-pitch propeller. Then as the pace stepped up, the precision bombsight, radar navigation and control, blind-bombing devices, powered gun turrets and computing sights, jet propulsion, the rocket engine, and the complex realm of controls for the ballistic missile.

The rise of air power to its dominant role in warfare has in truth exhibited a technical revolution of its own, characterized by vision, conviction, and hard-driving, creative technology. The advent of nuclear-fission energy for propulsion in aerospace represents another "quantum" milestone in technological progress.

The tactical and strategic employment of our current weapons is governed by the quality of their performance in speed, altitude, payload, and range, varied in emphasis to achieve an optimum effectiveness for their primary purposes. All these systems, from interceptor-aircraft types to intercontinental ballistic missile, are powered by chemical energy. Over the years we have seen the speed and altitude of manned aircraft increase sharply as a result of technological advances in chemical propulsion and in aerodynamic and structural efficiencies. Our fighters, as well as our new bombers, have maximum speeds well in excess of mach 2; altitudes have been pushed up toward 100,000 feet. Our gains in all areas have been great; but, as "Boss" Kettering used to say, the greatest gains of all have been in fuels.

We are now at a stage in technology where our gains in the energy of chemical fuels are of an asymptotic nature, approaching the maximum limit as governed by the physical laws of nature, even though there are still important gains to be made. Meanwhile, during the past score of years, significant progress has been made toward controlling the energy released by the fission of the atom. Noteworthy strides also have been made in the shielding which is necessary if nuclear power is to be practical in manned aircraft.

The taming of the atom, coupled with the technological advances in aerodynamic and structural efficiencies achieved over the past several decades, now brings atomic-powered aircraft and missiles within our grasp. Atomic-powered boosters can have enormous, controlled thrust; atomic-powered aircraft can have whatever endurance we care to give them.

Controlled thermonuclear energy from the fusion process is not yet with us but represents a goal that promises still greater power, less radiation, lower cost, and unlimited fuel supply.

The characteristics inherent in nuclear-fission power provide a new approach to propulsion. For a small amount of nuclear-fission fuel we can now run an engine for five days without landing. The figure of five days has been selected on the basis not of fuel consumption but of crew limitations. The amount of nuclear fuel consumed in five days is negligible, so that neither speed nor payload is affected by increased range. Speed will be governed largely by the temperature limitations of the materials used in the nuclear engine. It is generally conceded that manned aircraft speeds up to mach 0.9 are possible based on today's technology. In our very promising advanced nuclear-engine programs, speeds well in excess of mach 1 seem quite feasible. The broad ramifications of nuclear propulsion offer revolutionary improvements in all the performance yardsticks, creating new dimensions in the strategic employment of manned aircraft.

The essentially unlimited range of nuclear-propelled manned aircraft can be translated into distance, endurance, or both. The impact on operations is significant in several areas. Unlimited range permits zone-of-the-interior basing without the burdens imposed by tanker-aircraft inventories or overseas-base logistics, defenses, and political considerations. Routes of approach to mission areas are no longer restricted. Operational commanders are free to choose inbound and outbound routes of varying tracks around the globe. The possibility of missions of several days' duration permits the effective utilization of as high as 50 per cent of the force on air alert. Strategically placed around a sensitive area, the airborne alert would be invulnerable to attack and in its close proximity to the enemy heartland would constitute an ominous deterrent. Effective stationing of the air-alert forces would provide omnidirectional penetration routes which would tax the enemy defense effort severely, forcing him to defend his entire perimeter in strength. The use of the manned nuclear bomber in a high-endurance weapon system on air alert permits flexible and positive timing, control, and target assignment.

Low-altitude penetration is a fundamental capability of the nuclear-powered aircraft. Chemically powered aircraft are extremely limited in range at low altitude because of the tremendous increase in fuel consumption, even at moderate speeds. The nuclear engine will operate at low altitude by increasing slightly the power level of the reactor, causing only a negligible increase in fuel consumption.

Added to the operational gains made possible by nuclear propulsion are the desirable characteristics which will result from the growth potential in payload. Nuclear-powered aircraft can be designed for large weapon payloads at no sacrifice in range, and payload can be increased directly with improvements in thrust-to-weight ratio. Several noteworthy features arise. Especially interesting are the many combinations of weapons and military subsystems that can be carried. They offer versatility that can be quickly tailored to alternate mission requirements, particularly to various limited-war situations. More important, as technology improves our capability in guidance systems, air-launched missiles, bomber defense systems, penetration aids, and reconnaissance techniques, the large and versatile payload capacity will give a long inventory life to manned nuclear aircraft.

A second broad area for the application of nuclear propulsion lies in missiles. Nuclear propulsion looks extremely attractive in rockets, in ramjets for air-breathing missiles, and as auxiliary or secondary power sources for satellites and space vehicles. Although applications to these purposes have been under research and development for only a few years, the results to date have been most encouraging.

As in manned aircraft, truly remarkable progress has been made in the last ten years in the development of chemical rocket engines and fuels, but the next decade does not appear to offer similar growth because the limits imposed by the physical laws of nature are being reached. Specific engine performance well in excess of 90 per cent of theoretical values is already commonplace, and within the next few years engines will be available that burn chemical propellants of the highest performance known.

In the ballistic missile the ratio of payload weight to gross weight, which encompasses both engine and airframe effects, serves as an index of mission capability. For rocket vehicles relying on chemical combustion, progressively smaller improvements in this ratio can be expected. And while theoretically no limit exists to the thrust level that can be achieved by clustering chemical rocket engines or to the size of the vehicle that results, practical limits are being rapidly approached. A new, more powerful source of energy that yields a breakout beyond these limits would mean a major advance. The potential of nuclear energy is one possible solution. If nuclear energy can be utilized, significant increases in performance will result. It is notable that the advantage of nuclear propulsion increases rapidly for the larger-payload and longer-range missions. Nuclear-rocket propulsion offers our best hope for future high-payload rocket missions in orbit or beyond in space.

A second missile area in which significant advantages of nuclear propulsion seem to exist is in application to the ramjet. The ramjet is a high-performance engine in which forward speed compresses air in the engine intake to be heated to high temperature and exhausted with jet force through a rear nozzle. The chemical-powered system is penalized by the problems of finding fuel space and of obtaining the additional thrust not only to overcome the added weight of the fuel but to improve performance. A nuclear ramjet uses air as the working fluid and a nuclear reactor in place of the chemical-fuel combustion chamber. This eliminates the heavy, complex chemical-fuel transportation and consumption system. Reduction in the weight and size of the energy source correspondingly reduces the weight and size of the missile and increases its range. Some recent studies have revealed that application of nuclear power to the ramjet engine would make possible a strategic low-altitude missile, endowed with global range, supersonic speed, and multiple-warhead payload.

Because nuclear energy can be converted into electrical energy in sufficient amounts and for extended periods of time, it offers advantages for use in meeting the internal power requirements of space vehicles. Satellites depend on power sources of light weight and long duration to operate the instrumentation designed to collect and transmit data back to earth. Radioisotope devices and small nuclear reactors offer successful answers. Research in these fields has been under way for some years, and as recently as January 1959, Snap-3, a proof-of-principle radioisotope power device, was successfully demonstrated to President Eisenhower. Potentially such lightweight power packages, unencumbered by enormous quantities of chemical fuel or by storage batteries, can offer sustained, dependable service not only in satellites but in space platforms and space probes.

Our success in weaving the benefits of nuclear propulsion into our present air power concepts and operational forces will in large measure determine the extent to which the United States Air Force will maintain its dominant role in future years.

Headquarters United States Air Force

The USAF
Nuclear Propulsion Programs

Major General Donald J. Keirn
Chief, Aircraft Nuclear Propulsion Office

To grasp the portent of nuclear power within the Air Force, visualize a fleet of nuclear-powered bombers continuously airborne around the periphery of a would-be aggressor or a force of supersonic, low-altitude ramjet missiles on ceaseless mobile ground alert within the borders of the United States. In this day of advanced technology these concepts are just being fully understood. Yet as far back as 1944 there were men in the Air Force who foresaw these possibilities.

Six months before the first nuclear explosion near Alamogordo, New Mexico, the Air Force entered into discussions with Dr. Vannevar Bush, Director of the Office of Scientific Research and Development, on the possibilities of nuclear-powered flight. Later discussions with Maj. Gen. Leslie Groves, head of the Manhattan Project, led to a study contract in May 1946 between the Army Air Forces and the Fairchild Engine and Airplane Corporation. The purpose of this study was to determine the feasibility of nuclear energy for the propulsion of aircraft (NEPA). Although the Manhattan Engineer District, now the Atomic Energy Commission (AEC), did not actively participate in this project, it did make space available for NEPA study in an isolated area of Oak Ridge. Later, in 1948, the AEC established at the Massachusetts Institute of Technology a separate study group designated as the Lexington Project, whose purpose was to determine for the AEC the feasibility of nuclear propulsion for aircraft. The Lexington group concluded that, if the national interest warranted the expenditure in manpower, material, and money, a strong development program should be undertaken. It was estimated that the program leading to a nuclear-powered aircraft would take fifteen years and cost well over one billion dollars.

In result of these conclusions NEPA was phased out, and the AEC joined the Air Force in a more dynamic effort called the Aircraft Nuclear Propulsion program (ANP). This was in 1950. The main objective of the ANP program was to develop in the subsequent three to five years information on reactor materials, shielding, and power-plant and aircraft design so that the feasibility and the effort required to achieve nuclear-powered flight could be evaluated on a firm basis. In 1951 the objective was raised to include the demonstration of nuclear-powered flight.

Since 1951 ANP has undergone a series of "speed-ups" and "slow-downs." It has been studied by a variety of boards and committees appointed from Presidential, Congressional, Department of Defense, and Atomic Energy Commission levels. Throughout these years the Air Force has continuously supported the development of nuclear propulsion in the firm belief that such developments are actually on the threshold of a new age in aviation in which range is reduced to an essentially nonrestrictive dimension.

In keeping with Air Force policy of exploiting all advances in technology that may enhance its future mission capabilities, the study of nuclear propulsion for possible missile application also began during the early 1950's. By late 1955 we had reached a point where, in cooperation with the AEC, a joint program of feasibility studies on both nuclear rockets and ramjets could be started. After a short study period the program was reoriented to include demonstration of the technical feasibility of reactors for nuclear propulsion of rockets (Project Rover) and ramjets (Project Pluto). Work in these areas has been quite encouraging and indicates that the Air Force's confidence in these systems is justified. The nonnuclear component support work on the nuclear-rocket project was transferred from the Air Force to the National Aeronautics and Space Administration (NASA) by an Executive order on 1 October 1958. Nevertheless the Air Force monitors the program closely, since there are very many useful military applications of a nuclear rocket, including ICBMs, anti-ICBMs, military satellites and space probes, launching vehicles, and antisatellite missiles.

Yet another area of our interest has been development on systems for nuclear auxiliary power (Snap). The Air Force expressed the desire for small, lightweight, long-life generators, capable of providing power for continuous data transmission from space vehicles to earth. At the request of the Air Force in 1956, the Atomic Energy Commission assumed responsibility for a complete unit because of the close interrelationship between heat source (e.g., nuclear reactor or radioisotopes) and the conversion equipment. The initial result has been Snap-3, a small radioisotope thermoelectric generator, demonstrated to President Eisenhower by the AEC in January 1959. This is the first of a series of Snap devices that will employ either radioisotopes or reactors.

management of the programs

The management concept that has evolved from the ANP programs is unique within the Air Force. The Atomic Energy Commission is responsible by law for developing reactors suitable in nuclear-power applications. The nonnuclear portion has generally been agreed as being the responsibility of the interested agency. As applied to the Air Force's ANP programs, this statutory limitation vests the responsibility for developing the reactor and related shield in the AEC. Those areas exclusive of the reactor and shield—mainly turbomachinery, ramjet engines, airframes, and auxiliary components—have been agreed to be the responsibility of the Air Force. Thus there are two Government agencies involved in a complex research and development program in which many of the problems and solutions are interrelated. For example, many of the parameters determining optimum turbomachinery are a function of the reactor parameters, and vice versa. It became clear in the beginning of the ANP effort that a conventional Air Force organization could not be effective in this situation.

As the tempo increased in research and development, both the Air Force and the AEC became aware of the need for a more streamlined organization. Initially the AEC had established within its Division of Reactor Development (DRD) an organization designated as the Aircraft Reactors Branch (ARB). The Air Force, recognizing the need for one office to handle ANP matters, established an Assistant for Aircraft Nuclear Propulsion to the Director of Research and Development within Headquarters USAF. A basic step in streamlining the joint effort was taken when the AEC agreed to the Air Force designating one of its general officers as Chief of the AEC's Air-

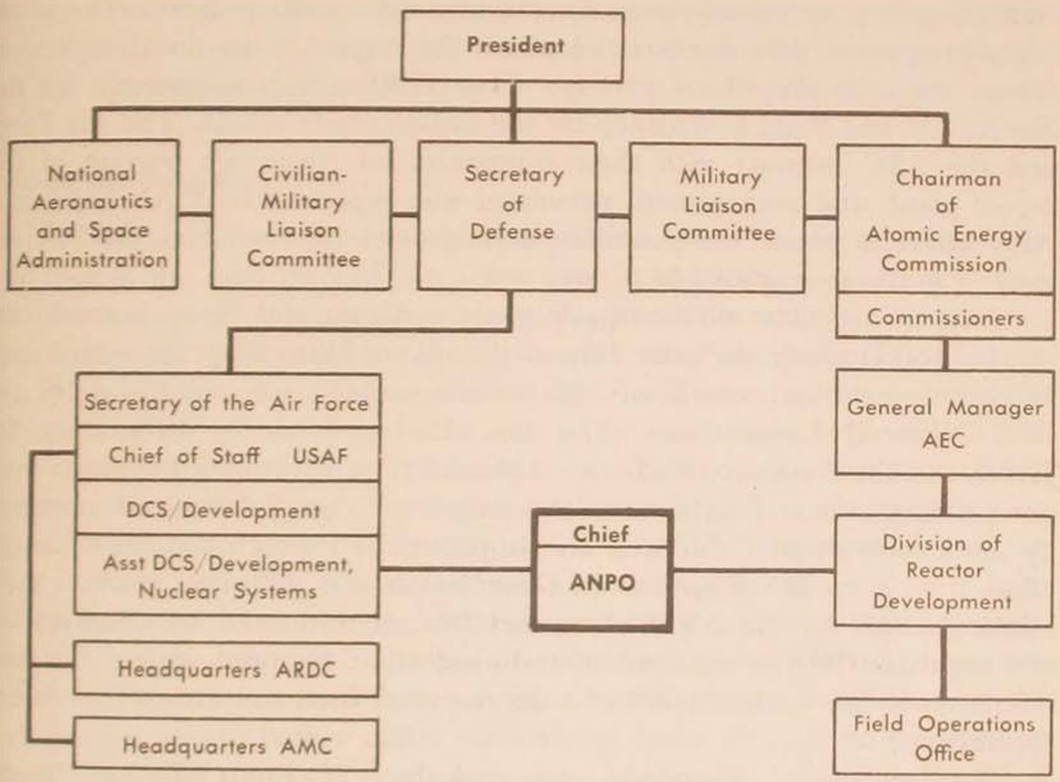


Figure 1. Management structure of the Aircraft Nuclear Propulsion program.

craft Reactors Branch (recently he has been redesignated as the Assistant Director, Division of Reactor Development, Aircraft Reactors). Thus one individual carries the responsibility and authority of both the Air Force and the AEC in the program. This officer's recognized title for Air Force matters is Chief of the Aircraft Nuclear Propulsion Office (ANPO). Finally, to connect the ANPO with the Air Staff, this same general officer occupies the Air Staff position as Assistant Deputy Chief of Staff, Development, for Nuclear

Systems (AFDDC-NS). This arrangement provides that, once policy and program direction have been decided at DOD and AEC levels, executive management can be conducted from one office under the control and supervision of one person.

The heart of the program management resides within the ANP office at AEC Headquarters in Germantown, Maryland. This office is staffed with a selected group of Air Force officers and Air Force and AEC civilian technicians, who exercise the dual directive authority of the Chief, ANPO. Also personnel have been assigned at important contractor plants and AEC field offices to coordinate and expedite the development work.

As a consequence of the dissimilar management procedures within the Air Force and AEC, the joint effort required some agreement by which differences could be worked out. Programs specifically involved were those requiring integrated efforts at the same location to produce a required propulsion system. The two projects in this stage of development are the direct- and indirect-cycle propulsion systems for the manned-aircraft program. The working arrangement that was enacted places the responsibility on a single contractor for each propulsion package. General Electric is responsible for the direct-cycle and Pratt & Whitney for the indirect-cycle system. The Air Force and the AEC contract with these companies for their own portion of the power plant, and management personnel who represent both Air Force and AEC interests under the executive management of the Chief, ANPO, are located at the contractor's facilities.

The management of the missile projects, Rover and Pluto, is conducted by the ANPO along the same line as the manned-aircraft projects with one exception—technical control of each missile project is vested in one of the AEC National Laboratories. The Los Alamos Scientific Laboratory for Rover and the Lawrence Radiation Laboratory at Livermore for Pluto exercise primary technical direction of the programs. These laboratories, operated by the University of California, are supported by research and developmen effort from a variety of specialized Government and industrial sources. Management effort by the ANPO has, therefore, concentrated on coordination and regulation of the segments of technical effort required, giving due consideration to the establishment of a development base and anticipated initial applications.

To date the Air Force has supported the AEC Pluto effort in the development of nonnuclear components and similarly may be expected to play a prominent role in the development of nuclear-ramjet propulsion systems that may follow. As stated previously, NASA is now responsible for research and development of the nonnuclear components for the nuclear-rocket project.

Personnel. No organization is stronger than the personnel assigned. Fortunately the need for highly qualified personnel was recognized early, and a small but intensive graduate education program was implemented at the Air Force Institute of Technology, Wright-Patterson Air Force Base, and, under it, at selected civilian universities. Carefully selected officers have been given the opportunity to participate in graduate work and then to enter the ANP program. At the present time seventy per cent of the officers assigned to ANPO have at least a Master's degree or equivalent in one of the pertinent engineering areas. Highly qualified civilian personnel have also been assigned by both Air Force and AEC to provide a balanced team of scientists, engineers, and administrators.

The U.S. Navy is interested in the nuclear-powered aircraft for naval applications. The Air Force and the AEC recognize this interest, and a Deputy for Naval Applications is assigned to ANPO. Additional Navy officers have been integrated into the organizational structure to take specific responsibilities within the program. This avoids costly duplication of parts of the effort elsewhere and ensures that certain tasks are investigated to the extent required for naval application.

The important qualities of ANP management, then, are in-being today. They include: good organizational structure, proved by experience through active program participation by the Air Force and AEC; selected contractors who are qualified in their specialized areas; personnel who are qualified, trained, and willing to accept the challenge of developing nuclear propulsion for manned aircraft, missiles, space vehicles, and auxiliary power units.

scope of the program

The scope of the aircraft-nuclear-propulsion effort has increased greatly from that of the early days of just a few people and a single contractor. The total investment in the manned-aircraft programs through fiscal year 1959 is approximately $880 million. Of this sum the Air Force has provided more than $490 million, the AEC more than $385 million, the Navy almost $2 million. The current funding is running at approximately $150 million per year. Through FY 1959 the AEC has expended slightly more than $60 million on the nuclear-rocket program and the Air Force $9 million. On the nuclear-ramjet program the amounts are $27 and $10 million, respectively, and for Snap, approximately $12 million and one million, respectively.

To staff and administer the ANP program and supervise the large-scale effort in progress, about 175 people are working in the ANP management structure. They direct the efforts of almost 8000 people in prime-contract work and an equal number under subcontract. Some idea of the task can be gained from the accompanying map, which shows the major facilities engaged in the ANP program. This complex, spread out across the United States, includes facilities of the U.S. Air Force and the Atomic Energy Commission and others owned by the contractors. Not shown are the myriad of subcontractors and their facilities engaged in basic support to the major-contractor efforts.

When the ANP programs expanded beyond the manned-aircraft projects, our technical efforts increased in proportion. It might seem logical to assume that propulsion reactors for aerospace vehicles would be quite similar, but the variance in technical parameters as one proceeds from the manned aircraft to the unmanned ramjet and the rocket has presented problems that had to be studied independent of much of the established experience. For example, since the nuclear aircraft will carry a crew, the maximum acceptable radiation dose is immediately limited to human tolerance, which is a thousand times lower than that of the most sensitive inanimate component. The divided-shield concept and the separation distance between reactor and crew thus became primary design considerations.

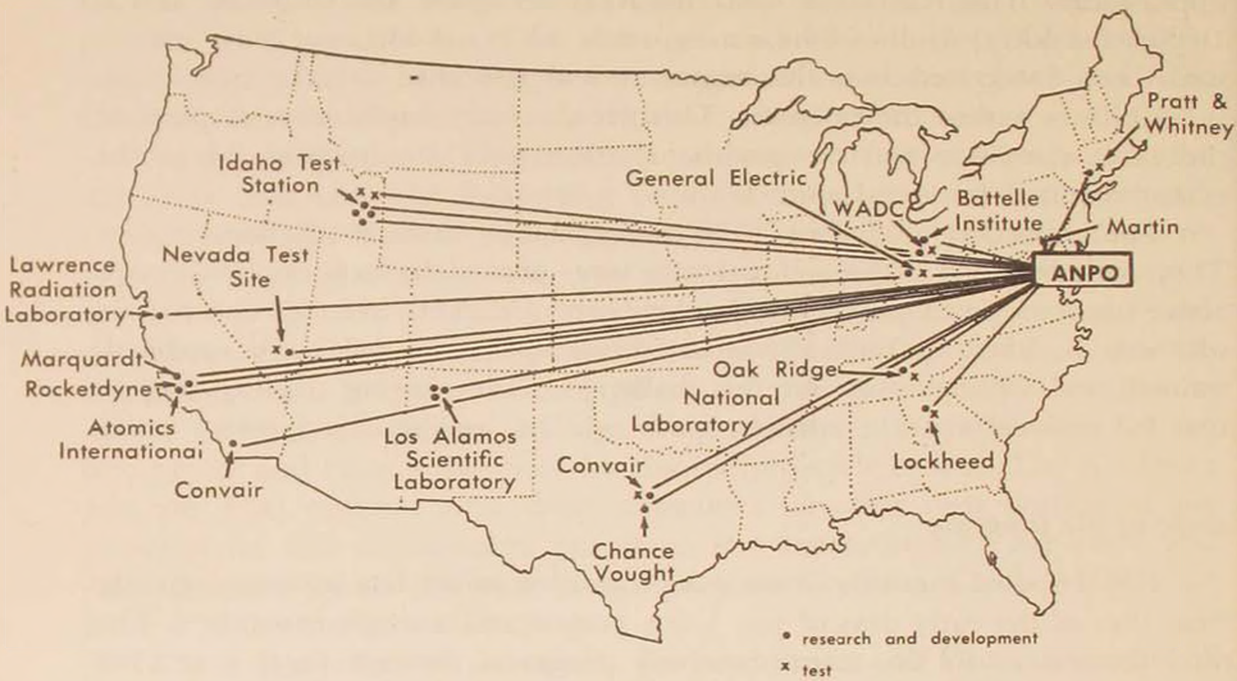


Figure 2. Facilities available to the Aircraft Nuclear Propulsion Office.

When consideration is given to lack of crews and shorter mission time, it is readily apparent that shielding problems are relieved for the unmanned rocket and ramjet vehicles. This advantage is partially offset, however, since correspondingly higher dose rates result from the higher-thrust, higher-power-density reactors required for these vehicles. Of perhaps greater significance than the effect of radiation on materials is the fact that nuclear ramjets and rockets must operate at higher temperatures if desirable performance is to be achieved. Thermal loads on the ramjet reactor are intensified by the severe aerodynamic heating inherent in supersonic flight. The most striking example of the problem of thermal stress is encountered in the nuclear-rocket reactor, which receives propellant at cryogenic temperatures and discharges it at temperatures approaching the melting point of the fuel elements. The material damage from radiation effects varies over this temperature range, as do the nuclear characteristics of the propellant as its density changes.

These are but a few examples of the superposition of nuclear and nonnuclear engineering problems involved in the major components and subsystems of a nuclear propulsion system. As they are added to the nuclear aspects of ANP research and development, one gains some appreciation of the magnitude of the advanced technical research and development that are incorporated in the nuclear propulsion programs. It is a monumental effort challenging the technological skills of the nation.

The engineers, scientists, and managers within the ANP programs have been working diligently and optimistically in the forefront of the unfolding work. The challenge has long since been accepted, and highly successful penetrations have been made into advanced fields. What is more important, useful answers have been obtained that enable the programs to move toward successful conclusions.

Aircraft Nuclear Propulsion Office

Manned Aircraft Nuclear Propulsion Program

COLONEL WILLIAM A. TESCH

Chief, Aircraft Projects Branch, ANPO

THIRTEEN years ago the first step was formally taken in aircraft nuclear propulsion with the award of a contract to implement the NEPA project—nuclear energy for the propulsion of aircraft. Through the years from this simple beginning with one contractor and a handful of Air Force officers has grown the present program, in which prime contractors and subcontractors are spread across the country and the Government management organization has evolved into a one-of-its-kind structure.

The Aircraft Projects Branch of the Aircraft Nuclear Propulsion Office (ANPO) manages the manned-aircraft program. This program is primarily concerned with two major development efforts in aircraft nuclear propulsion, the direct-cycle propulsion system and the indirect-cycle propulsion system. The General Electric Company is under contract to develop a direct-air-cycle nuclear turbojet engine. In such a system the air passes directly through the compressor, the nuclear reactor, and the turbine, all three being integral parts of the propulsion package. The Pratt & Whitney Aircraft Company is under contract to develop the indirect-cycle system. In the indirect cycle the reactor is remote from the turbojet engine, and a liquid-metal coolant carries nuclear heat from the reactor to a radiator in the turbojet, where the heat is exchanged to the air to produce thrust. Both development contracts are under the immediate technical management of two of the four sections comprising the Aircraft Projects Branch. Based upon Air Force and Atomic Energy Commission agreements, the branch constitutes an integrated project office for direct technical management of the propulsion programs.

This integrated technical channel flows through the Direct and Indirect Cycle Sections of the branch to the Atomic Energy Commission's Lockland Aircraft Reactors Operations Office (LAROO), which has been assigned both AEC and Air Force responsibilities. LAROO, located near the General Electric Company at Evendale, Ohio, has in turn established offices (Hartford Aircraft Reactors Area Office) at the Air Force-funded Connecticut Aircraft Nuclear Engine Laboratory (CANEL) of Pratt & Whitney and at the AEC National Reactor Test Station (NRTS), where reactor testing is carried out. In this manner Air Force and AEC technical project people are located at the site of the contractor's operations and have a single direct channel to the Aircraft Nuclear Propulsion Office in Washington. The integration of the AEC and

Air Force technical responsibilities into a common organizational structure, as well as the location of project technical personnel at the contractor's plants as contrasted to placing project people at centralized development centers, has greatly streamlined the conventional gaps between the day-to-day field operations and the policy- and decision-making staff at the headquarters level.

Separate Air Force and AEC contracts and funding are maintained, the contractual channels following the separate agency route. The AEC contractual channel leads to its Lockland Aircraft Reactors Operations Office, whereas the Air Force contractual channels lead to the Air Materiel Command.

The Airframe Section has executive management over the Air Force programs concerned with aircraft design and the allied problem of radiation effects. Direct technical management is vested in the Air Research and Development Command. The Airframe Section provides for Headquarters USAF guidance and policy over the major contracts at the Convair plant, Ft. Worth, Texas; over the Lockheed operations in their plant at Marietta, Georgia, and in the Georgia Nuclear Aircraft Laboratory at Dawsonville, Georgia; and over a host of contractors engaged in work on subsystems and radiation effects.

The Support Section is concerned with executive management of ARDC projects in ground support, nuclear safety, and radiobiology. It has technical management over AEC counterparts in these areas.

Since the inception of our hardware research and development program in 1951, ANPO has carried out design work and experimentation on reactor

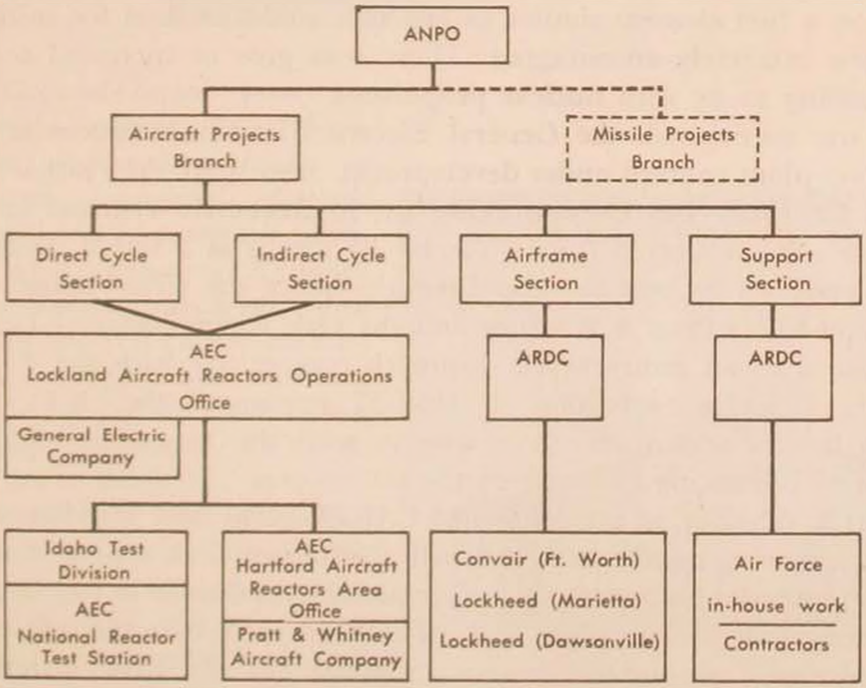


Figure 1. Organization of the Aircraft Projects Branch, ANPO.

components and turbomachinery and in the basic nuclear areas peculiar to nuclear propulsion. We have provided to the propulsion contractors and airframe contractors the facilities necessary to the definable development tasks. Notwithstanding several programmatic fluctuations, steady progress has been made on the technical front. In the direct-cycle program, high-performance propulsion machinery has been under development for several years and is now in the testing phase. In the more critical reactor development area, emphasis has been maintained on advancing the state of the art of high-temperature materials and on investigating reactor-core problems through a series of heat-transfer experiments.

As early as 1956 we operated what is known as Heat Transfer Reactor Experiment No. 1 (HTRE-1). For the first time a turbojet engine—a modified J-47—was operated on nuclear power. During this experiment approximately 150 hours of all-nuclear operation was accumulated, with a total energy output from nuclear sources of over 5000 megawatt-hours. HTRE-1 was a water-moderated system that had no flight-system characteristics. It was later modified for testing various fuel elements and moderators through insert packages in a section of the core. In this configuration, we call it HTRE-2. HTRE-3 followed in November 1958, employing a flight-type shield system and a solid moderator for higher-temperature operation in a configuration more in keeping with a propulsion system.

In addition to the HTRE tests we are conducting dynamic testing of various promising fuel-element materials suitable for flight application. In facilities such as the Engineering Test Reactor at the National Reactor Test Station various fuel-element and moderator candidates are subjected to operational temperatures, power levels, and reactor fluxes. Tests recently conducted on a fuel element similar to one that could be used for initial flight have been extremely encouraging. These tests give us increased confidence in our ability to fly with nuclear propulsion.

As was mentioned, the General Electric direct-cycle system is not the only power-plant concept under development. Since 1951 the Pratt & Whitney Aircraft Company has been working on indirect-cycle systems. In such a system heat is transferred from a reactor by means of a liquid metal, which in turn gives up its heat to propulsive air—hence the term "indirect" cycle. In the mid-1950's Pratt & Whitney and the Oak Ridge National Laboratory were teamed in an indirect-cycle approach competitive with the direct-cycle approach. Program evaluation in 1956–57 reoriented the effort and put P&W in basic research and development, with the long-range objective of significantly advancing the state of the art.

Pratt & Whitney, at the AF-owned CANEL plant near Middletown, Connecticut, is making significant strides with the indirect-cycle system. This system offers the potential for attractive performance in supersonic as well as subsonic applications. Our present plans at Pratt & Whitney include the fabrication of an experimental ground-test reactor to prove out the basic materials and components. Also at Pratt & Whitney we have built the necessary industrial and testing facilities, and through the development programs at P&W and at Oak Ridge we have developed a sound technological base.

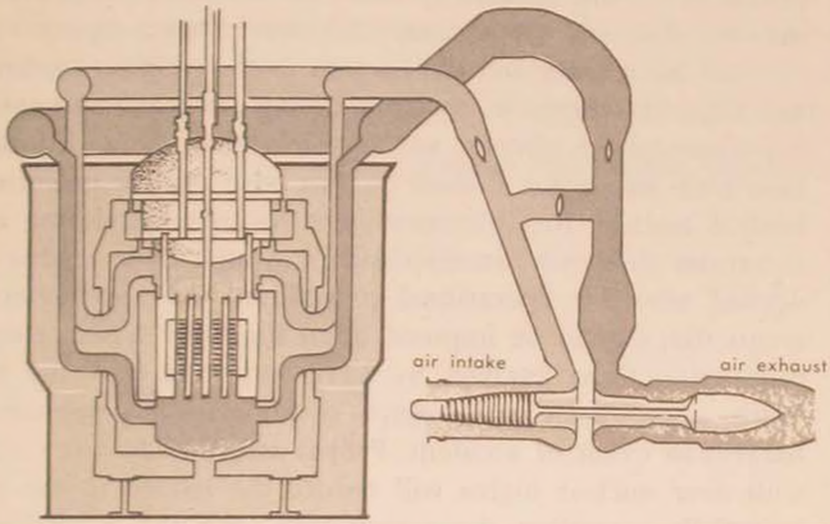


Figure 2. Ground-reactor tests for the direct-cycle system have been conducted in southeastern Idaho at General Electric Company's Aircraft Nuclear Propulsion Department facility within AEC's sprawling National Reactor Test Station (shown on map). In one part of the NRTS, an isolated test pad (above right) was provided to General Electric for the Heat Transfer Reactor Experiments (HTRE). Cutaway of HTRE-1 shows the modified J-47 turbojet deriving heat from the nuclear reactor. Air enters through the compressor in the front of the jet engine, passes through the inlet ducting, is heated in the reactor core, and expelled through the turbine to produce thrust. A look to the future is provided by the Flight Engine Test Facility, completed this summer. It would house the prototype nuclear propulsion system and provide for insertion and removal of the reactor.

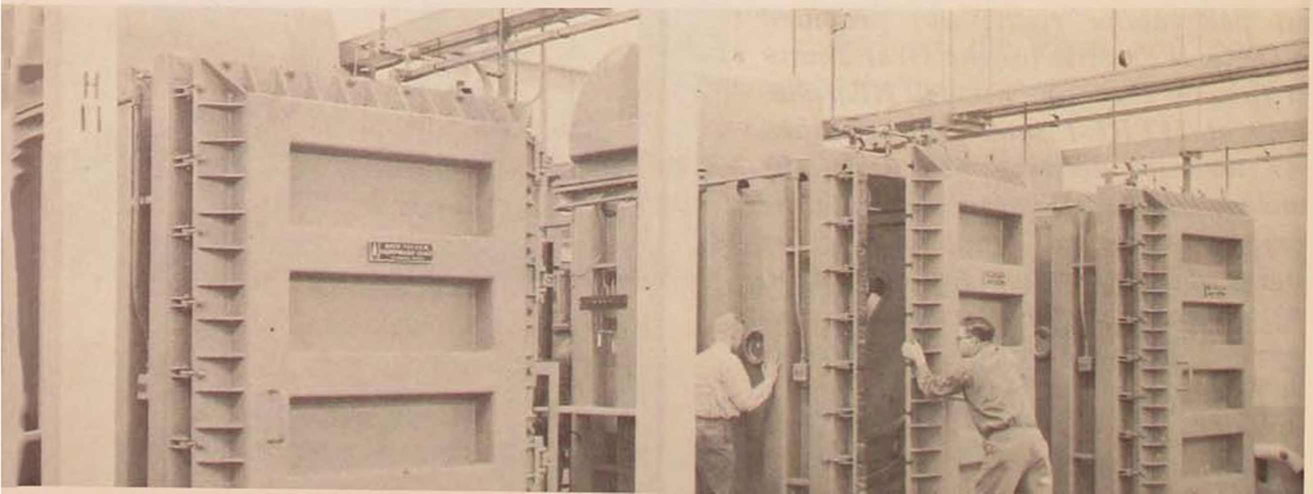
In the matter of shielding, we have conducted extensive testing with a one-megawatt shield-test reactor in a modified conventionally powered B-36. Forty-seven flights over a two-year period yielded 35 megawatt-hours of testing. As a result of these experiments and others, the correlation between theory and practice has been significantly improved.

With regard to radiation effects, a program of dynamic testing of typical aircraft components in a nuclear environment has indicated that flight with materials at hand is possible. Currently available off-the-shelf materials are adequate for a flight-development aircraft, and many are even adequate for weapon-system use. Specific programs are also in progress on the more sensitive materials to increase their life for eventual weapon-system use. For example, synthesized oils with excellent radiation resistance have been produced in the laboratory and can be made available for weapon-system use, but they are not necessary for development flying.

We have examined the hazards to the public originating from a ground and flight development program. Using our accident experience with all our experimental jet aircraft, we have analyzed the additional risks that would have been imposed had these aircraft been nuclear powered. We have actually burned nuclear fuel elements in a manner simulating a crash and fire to determine diffusion characteristics. Through these analyses and tests we have devised tentative operational procedures and have determined the requirements that should be imposed upon flight-test bases or operational bases. In conducting these analyses we have employed what we believe to be pessimistic assumptions with regard to all critical parameters affecting nuclear hazards in event of accident. Proper selection of bases and appropriate controls over nuclear flights will reduce the hazard to the public to levels not materially exceeding those associated with the operation of other military aircraft.

The Aircraft Nuclear Propulsion program has progressed to the point

Figure 3. The indirect-cycle power plant is being developed by Pratt & Whitney at the Air Force-funded Connecticut Aircraft Nuclear Engine Laboratory. One component of its extensive research and testing facilities is the inert atmosphere chambers. In them, forced-convection loops are operated in tests of new alloys.



where further development is a function of performance requirements deemed to be of military usefulness by the Department of Defense. The feasibility of operating aircraft propulsion machinery from a nuclear reactor has long since been demonstrated. The technology in both the power-plant and the airframe areas has advanced to the point where we feel confident that nuclear-powered, sustained flight could be demonstrated if it were desired. In the meantime development is continuing to advance the present technology to meet higher performance requirements.

THE MANNED-AIRCRAFT program of today is developing the nuclear propulsion systems that will provide greater flexibility and new operational concepts for our arsenal of weapon systems. Nuclear propulsion will add the dimensions of unlimited range and endurance to aerial operations, coupled with the advantages of the most unique control system yet evolved—man. This union—of nuclear propulsion and man—will very significantly widen the horizon of defensive, offensive, and deterrent planning by the United States Air Force.

Aircraft Nuclear Propulsion Office

Nuclear Missile, Rocket, and Auxiliary Power Programs

Colonel Jack L. Armstrong

Deputy Chief, Aircraft Nuclear Propulsion Office

As a result of advanced systems studies in the early 1950's the Air Force clearly recognized the enormous potential of applying nuclear energy to rocket and ramjet propulsion. The Secretary of the Air Force initiated discussions with the Atomic Energy Commission to establish program-feasibility studies. Having obtained AEC concurrence, the Secretary directed the Chief of Staff, USAF, to assign highly qualified Air Force officers to the existing Aircraft Nuclear Propulsion Office (ANPO) to direct and supervise these programs as a joint AF–AEC effort. About the same time, Air Force interest in space and satellite vehicles emphasized the need for long-life, light-weight auxiliary power units to make their missions most effective. Thus in 1955 a Nuclear Auxiliary Power Section was created along with the Nuclear Rocket and Ramjet Sections to form the Missile Projects Branch of the Aircraft Nuclear Propulsion Office.

The missile- and space-oriented programs developing special applications of nuclear energy are:

- Rover, pointed toward demonstrating the feasibility of applying nuclear energy to rocket propulsion
- Pluto, pointed toward demonstrating the feasibility of a nuclear reactor to power a ramjet
- Snap (Systems for Nuclear Auxiliary Power), directed toward developing nuclear energy and associated electrical conversion devices into lightweight, long-life power units for space applications.

In nuclear-rocket propulsion a nuclear reactor is substituted for the combustion chamber in the chemical rocket engine. In addition to the nuclear fuel for the reactor, a liquid fuel is still required. The liquid fuel is pumped through channels of the reactor core, acting as a reactor coolant at the same time that it is heated to high temperatures, and then expanded out through a conventional rocket nozzle to provide thrust. In the nuclear ramjet a reactor is substituted for the chemical burners and the air being rammed into the engine throat is heated in passing through the reactor-core channels and expanded out through the engine tailpipe. The Snap devices are designed to convert the heat energy of a radioactive isotope or of a small reactor into some usable form of electricity previously provided by conventional or solar batteries, to meet the internal electrical requirements of the space vehicle.

organization

The Atomic Energy Commission programs for military and space application are normally instituted at the request of other Government agencies. The Rover nuclear-rocket program, initiated by AEC in response to an Air Force request, is now under the guidance of the National Aeronautics and Space Administration (NASA) and oriented primarily toward filling advanced space propulsion requirements. The nuclear-ramjet program (Pluto), initiated to fill an Air Force requirement, is organized so that the AEC has responsibility for reactor design and development and the Air Force has development responsibility for the nonnuclear components of the ramjet engine. The Systems for Nuclear Auxiliary Power (Snap) program, established originally at the request of the Air Force, now serves both Air Force and NASA needs. In the Snap program, because of the complex relationship involved in integrating the nuclear heat source and the electric generating equipment, the AEC has been assigned responsibility for developing both the nuclear heat sources and the conversion equipment as an integrated electricity-producing power package. Thus with three separate Government agencies (Department of Defense, AEC, and NASA) involved, close integra-

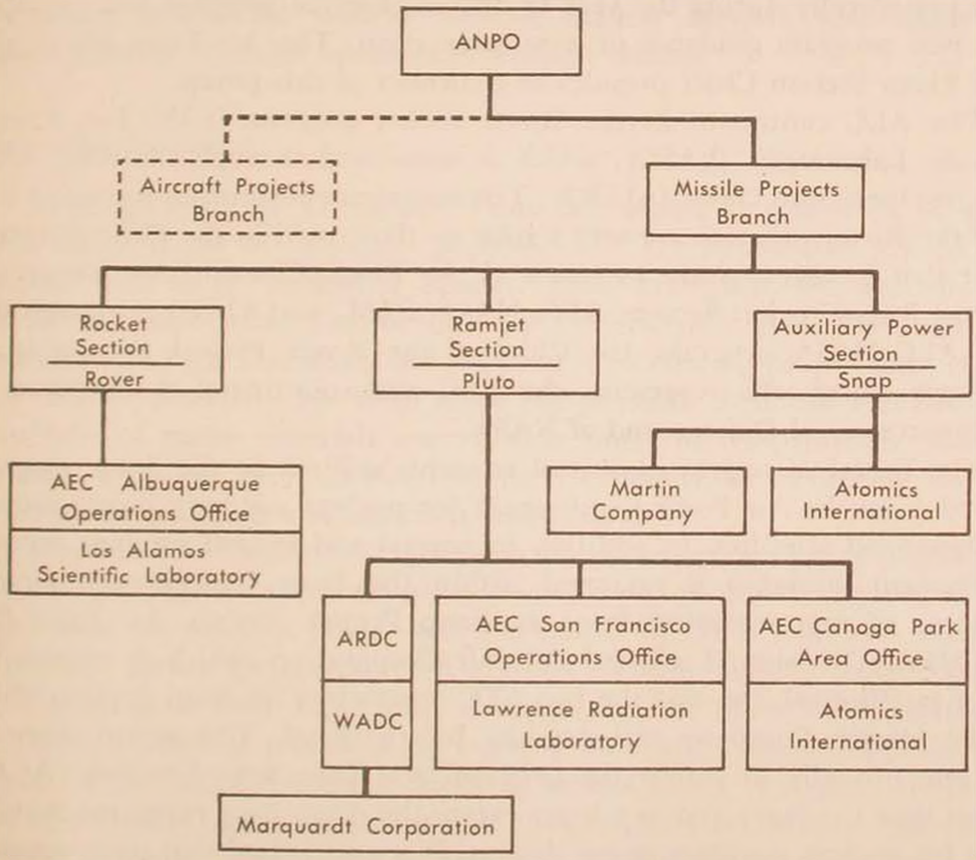


Figure 1. Organization of Missile Projects Branch, ANPO.

tion is accomplished through the management of these programs by the joint AEC–AF Aircraft Nuclear Propulsion Office. Atomic Energy Commission direction of the programs is from ANPO to the appropriate laboratory or contractor. Air Force direction of Pluto and Snap is from ANPO through Air Research and Development Command to the appropriate contractor. Research and development management of these programs (closely associated with the aerospace age) is in the hands of a small group of highly trained Air Force officers assigned to the AEC. They comprise the Missile Projects Branch of ANPO.

The Pluto ramjet program is implemented by three contracts: an Air Force contract with the Marquardt Corporation for nonnuclear research and development, channeled through ARDC; an AEC contract with the University of California, which operates the commission's Lawrence Radiation Laboratory, for reactor research and development; and an AEC contract with Atomics International for reactor materials research and development. A monthly series of progress reports and a detailed annual report are provided by each of the contractors to the Pluto Project Section at ANPO. In turn the Air Force project officers in the section visit the contractor locations and test sites at least every three months. The most valuable management control is the Pluto Coordination Group, consisting of the Pluto Project Section Chief and one representative from each of the contractors and from Air Research and Development Command, Wright Air Development Center, AEC San Francisco Operations Office, and AEC Canoga Park Area Office. This group meets periodically during the year to discuss program progress and to implement new program guidance or new orientation. The Air Force officer who is the Pluto Section Chief presides as chairman of this group.

The AEC contractor in the Rover rocket program is the Los Alamos Scientific Laboratory (LASL), which is monitored through the AEC Albuquerque Operations Office (ALOO). The management-control procedures that guide the Rover program are very similar to those used in the Pluto program, except that in this case the members of the Rover Coordination Group are from the Rover Project Section, AEC, NASA, LASL, and ALOO. Although this is an AEC–NASA program, the Chief of the Rover Project Section is an Air Force officer who represents the AEC and coordinates the interests of the Department of Defense and of NASA.

The initial management-control concepts utilized in the Snap program resulted from the Air Force requirement for nuclear auxiliary power sources for unmanned satellites. In addition to normal and annual progress reports, management guidance is reviewed within the Snap Coordination Group, consisting of representatives from the Snap Project Section, Air Force Ballistic Missile Division, Lockheed Aircraft Corporation—which is responsible for the satellite vehicle—and the two AEC contractors for Snap devices, which are the Martin Company and Atomics International. This group meets at least semiannually to review the program and issue new directives. At the present time the Navy and to a lesser extent the Army have expressed requirements for nuclear auxiliary power devices. It is anticipated that these agencies will also be represented on future program coordination groups.

The ramifications of the missile programs are so vast that it is axiomatic that timely, effective management control, as partially exemplified in the foregoing discussion, must be a consistent facet of the Missile Projects Branch.

technology

Although theory involved in these three advanced programs was fairly well founded from the outset, the materials technology that would lead to operational systems was largely unknown. For significant improvement of specific impulse in the rocket engine, for example, the reactor should operate at very high temperatures, with good heat transfer between the fuel elements and the working fluid. For the nuclear ramjet to be effective, the missile must have an on-the-deck capability at speeds normally associated with the stratosphere. Aerodynamic heating associated with such a performance profile, superimposed upon the problems of a nuclear environment, creates conditions requiring extensive research and development. In generating auxiliary power, the capabilities of nuclear sources make practical the use of unconventional heat-to-electricity conversion techniques. In this area much work has been done on thermoelectric and thermionic types of static converters. The operating requirements of long life and low weight necessitate the development of fantastically small and efficient rotating conversion equipment that must be dependable for at least a year of unattended life. These are representative of research and development problems involved in making practicable nuclear rockets, nuclear ramjets, and lightweight auxiliary power units for operational weapon systems.

nuclear propulsion

Although Projects Rover and Pluto are aimed at somewhat divergent goals, many of the development problems and the approaches toward their solution have been somewhat similar. Both are gas-cooled reactors that operate at temperatures limited only by the materials used. Very high temperatures and high heat fluxes are required if interesting propulsion performance is to be attained. One must know the physical, chemical, and neutronic properties of many materials over a wide range of temperatures. Much of the AEC technical effort to date has been expended in advancing the state of the art in materials and materials fabrication.

Despite their similarities, these two programs are aimed at considerably different propulsion applications. A nuclear rocket must carry its own reactive mass (or working fluid), which is heated by the reactor and expanded to produce thrust. Design power is applied for only 5 to 15 minutes, a very small fraction of total flight time. A ramjet, on the other hand, utilizes the air through which it travels as its working fluid and requires application of power for the entire mission, a period of several hours. A rocket-type propulsion system develops static thrust and thus requires no outside assistance to become airborne, whereas the ramjet must be boosted to near design speed before it can take over.

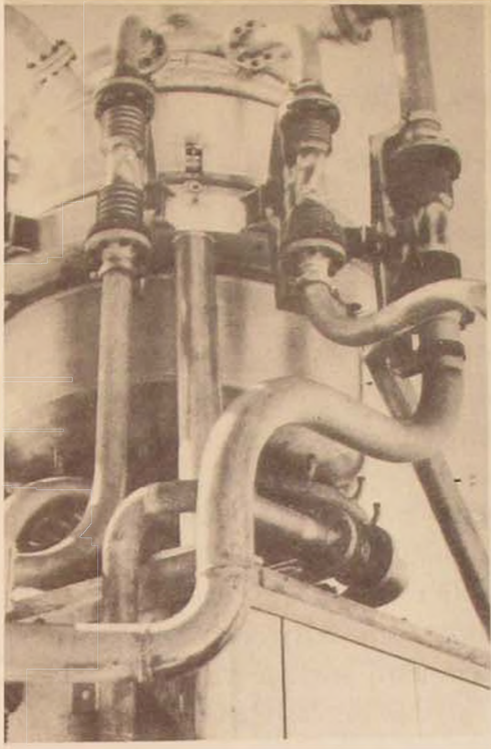


Figure 2. Kiwi-A nuclear-rocket test reactor.

Reactors will be tested at the AEC's Nevada Test Site in an area known as Jackass Flats, west of the weapons test area. This area is sufficiently isolated and facilities are so situated that hazard to personnel in operating and experimenting with test reactors is improbable. The organization and facilities developed for weapons testing are available to support these reactor projects.

Rover (nuclear rocket)

Recognizing the possible potential of nuclear rockets, the Air Force expressed to the AEC an interest in the development of a nuclear rocket more than three years before the word "sputnik" was added to our vocabulary. From this requirement the Rover project was initiated to demonstrate the feasibility of applying nuclear energy to rocket propulsion. The Air Force, realizing that feasibility demonstration involved more than reactor technology, initiated closely related programs under Air Research and Development Command in direct support of Rover to develop the nonnuclear engine components. Work was sponsored at Rocketdyne, a division of North American Aviation, Inc., and at Aerojet-General Corporation, to study means of integrating the nuclear rocket into advanced weapon systems and to extend the state of the art in turbomachinery, exhaust nozzles, and flow-control systems.

Nuclear-rocket reactors are to be field-tested at the AEC's Nevada Test Site in the propulsion test area, with remote handling of radioactive reactors after power runs. The first experimental reactor, affectionately dubbed the Kiwi-A after the flightless New Zealand bird, was tested in Nevada in the summer of 1959.

The heat-exchanger type of nuclear-rocket reactor of the Kiwi-A type, for all its promise, is able to utilize only a tiny fraction of the total nuclear energy available. To realize greater advantage and improve performance, vigorous research is under way to uncover better methods to exploit the latent energy of the atom.

In late 1958 responsibility for development of nonnuclear components and for general program guidance was transferred from the Air Force to the newly formed National Aeronautics and Space Administration. The Air Force, vitally interested in the application of nuclear rockets to military space requirements, still provides some direct support to the AEC through design studies, research, propellant supply, loan of important equipment and facilities, and assignment of qualified personnel. Air Force contractors participating in ARDC-sponsored, space-oriented system studies are encouraged to seek ways of exploiting the advantages of the nuclear rocket, for which the AEC provides the necessary reactor data.

Pluto (nuclear ramjet)

Air Force interest in applying nuclear energy to ramjet propulsion culminated in a Department of Defense request for the Atomic Energy Commission to investigate the feasibility of a reactor for this use, as significant advantages could be gained over chemically derived power. Range could be greatly extended by elimination of the heavy, complex fuel and consumption system imposed by chemical fuels. Fuel burnup for nuclear energy would be insignificant on a given mission.

Early in 1956 an AEC experimental program, to be known as Project Pluto, was established. The Pluto objective is to develop technology and to design, build, and test experimental reactors that will demonstrate scientific and technical feasibility of applying nuclear energy to a ramjet engine for missile propulsion. Pluto reactor work is under direction of the Atomic Energy Commission's Lawrence Radiation Laboratory (LRL) at Livermore, California, with support on materials research by the Atomics International Division of North American Aviation, Inc. The Marquardt Corporation under Air Force contract is providing assistance in engineering and developing nonnuclear components associated with tests of the Livermore experimental reactors.

The Pluto effort is generally divided into materials research, neutronics research, reactor experiments, and propulsion-system design. The major problem in demonstrating feasibility of nuclear-ramjet propulsion is the development of reactor materials that will withstand oxidation and other environmental conditions and still retain integrity at the high operating temperatures. Extensive effort has been expended, both at Atomics International and at Lawrence Radiation Laboratory, to broaden basic knowledge of high-temperature, gas-cooled reactor materials. The work also includes the development of techniques to fabricate these materials into shapes required by the reactor design. To verify the materials, neutronics, and other design information, an LRL reactor experiment designated Tory-2 is under way. Reactor design and fabrication are nearly complete. It is planned that the first Tory-2 experimental reactor will be tested in 1960 at Jackass Flats.

Considerable Air Force effort will be required to apply the nuclear reactor to an operational weapon system. ARDC has three aircraft contractors

(Chance Vought, North American Aviation, Inc., and Convair) working on conceptual designs to make preliminary determination of basic requirements of the nuclear-ramjet missile system designated Slam, for supersonic low-altitude missile. This effort provides information for over-all design and helps pinpoint problem areas to guide further experimental work.

As an example, current studies reveal that certain systems components may require longer development lead time than does the reactor. The Air Force has initiated development on these long-lead-time components. At the proper time an Air Force weapon system project office (WSPO) will implement the weapon system. Since a nuclear-ramjet-powered missile is an aerodynamic as opposed to a ballistic missile, it is controllable in flight, employing a guidance system that monitors and corrects the missile position. The extremely small probable bombing error obtainable by this technique will permit employment of smaller-yield weapons. Range capability inherent in nuclear propulsion makes practicable an omnidirectional approach and penetration of enemy territory at high speeds and low altitudes, the nuclear reactor providing energy to overcome the high drag under these conditions. This mode of attack will compound the enemy's air defense requirements. Consideration of all factors emphasizes clearly that such a delivery system offers many advantages and will be a valuable complement to other strategic systems at a very reasonable over-all cost.

We are confident that the Pluto program will culminate in supersonic bombardment vehicles with low-altitude, large-payload, and globe-girdling capability.

Snap (systems for nuclear auxiliary power)

Under an Air Force project during the period 1946 to 1954, the Rand Corporation made a study of strategic satellite reconnaissance. One recommendation was that the duration, reliability, and high power requirements for advanced reconnaissance systems could only be met by nuclear power sources. Air Force implementation of these recommendations resulted in the establishment of an R&D study task to examine further the feasibility of building a nuclear auxiliary power unit. In August 1955 the Department of Defense requested the Atomic Energy Commission to study and do experimental work in developing a reactor to be used as an auxiliary power source in a reconnaissance satellite. By July 1956 the Air Force Advanced Reconnaissance System was designated as WS-117L, and AEC development of the nuclear heat source proceeded concurrently.

In preliminary investigations of the feasibility of applying nuclear energy to lightweight power units, two sources of nuclear heat—radioisotope decay and nuclear fission—were selected as affording the greatest growth potential. Atomic batteries have been studied, but they offer generally insufficient power output to meet current and future operational requirements. Radioisotopic heat sources appear capable of producing up to several hundred electrical watts. Lightweight, compact-core reactor systems have the capability of supplying larger amounts of electric power. Radioisotope systems are under

AEC prime contract to the Nuclear Division of the Martin Company, Baltimore, Maryland. Reactor systems are under AEC prime contract to Atomics International at Canoga Park, California.

An integral part of the Snap program has been the development of advanced systems for conversion of heat to electricity. The space environment imposes unique limitations of compactness and reliability. Because waste heat can be dissipated to space only through radiation, optimum design of a heat cycle for space use dictates a high sink temperature so as to minimize radiator size and weight. The requirement for a high dump temperature, however, is contrary to conventional heat-cycle design, which requires as low a sink temperature as possible so that the maximum amount of energy can be extracted from the working fluid.

Design efficiency of a heat cycle intended for use in space represents an optimized choice between system weight limitations and system conversion efficiency. Snap rotating conversion equipment is being developed by Thompson Ramo Wooldridge, Inc. The thermodynamic cycle using rotating conversion equipment is currently the best means of supplying large space electric power demands (outputs above a few hundred watts). In such systems we are faced with rigorous reliability standards. Static conversion

Figure 3. Demonstration of Snap-3 on 16 January 1959 before President Eisenhower. At left the Snap-3 proof-of-principle device is at work driving a model airplane propeller. Another Snap-3 is displayed in a clear plastic cover. Major General Donald J. Keirn, Chief of the Aircraft Nuclear Propulsion Office, stands next to the President. Between General Keirn and Colonel Jack L. Armstrong, Deputy Chief of ANPO, is Mr. John A. McCone, the Chairman of the Atomic Energy Commission. Lt. Col. G. M. Anderson, Snap project officer, ANPO, is shown at the far right.

techniques are currently capable of providing only small amounts of electric power, but the units are highly reliable because they have no moving parts.

Space requirements and availability of nuclear heat have aroused a considerable interest in solid-state thermoelectric and thermionic conversion devices. Research and development efforts toward improving static conversion techniques so as to obtain higher power are quite active at the Minnesota Mining and Manufacturing Company, Thermo Electron Engine Corporation, Westinghouse Electric Corporation, and Los Alamos Scientific Laboratory.

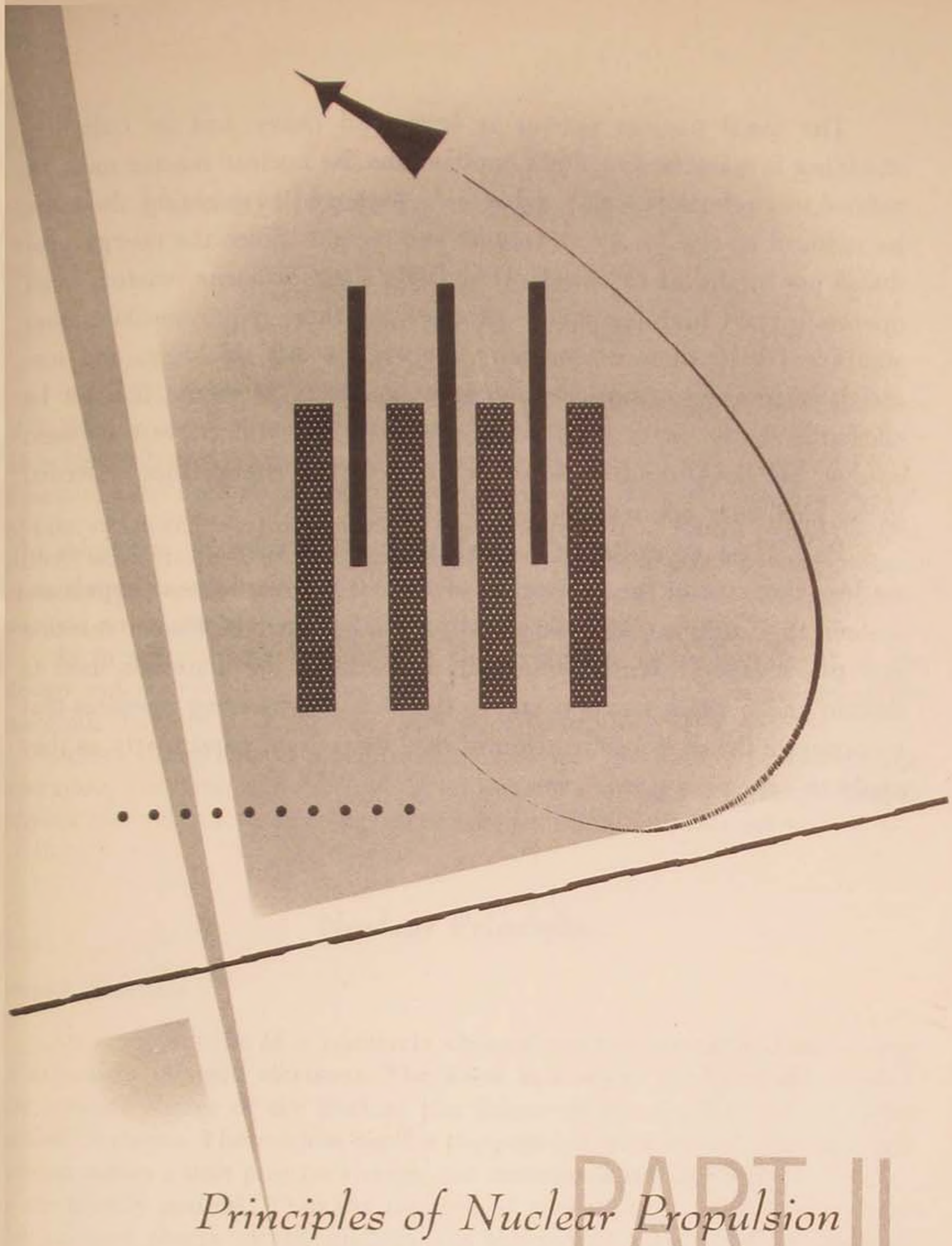
As a proof-of-principle device reflecting the state of the art, the four-pound Snap-3 radioisotope device demonstrated in January 1959 produced about three electrical watts with an over-all conversion efficiency of about six per cent. Further engineering could appreciably reduce the weight of the generator.

Units are under development that produce significantly higher levels of power from similar thermoelectric elements. Of special mention as an advanced static-conversion technique is the plasma diode demonstrated at the Los Alamos Scientific Laboratory in April 1959. Effort is being directed toward testing and refining hardware to improve unattended dependability and reduce weight and toward investigating new techniques for heat-to-electricity conversion methods and devices.

Once in space, interorbit transfer for travel between planets can be effected through use of low-thrust propulsion modes (ion and plasma jets). For successful operation these require long-lived, high-power electrical generating units. Nuclear energy can satisfactorily fill this demand, and for this application the reactor unit seems the proper energy source.

THE UNITED STATES is faced with the challenge of extending the superiority it now maintains in the air out into the vast realm of space. We are convinced that technological advancements evolving from the Rover, Pluto, and Snap programs will contribute much to space operations of the future and hence to U.S. military deterrent capability.

Aircraft Nuclear Propulsion Office



PART II
Principles of Nuclear Propulsion

IN THE one and one half decades since the attacks on Hiroshima and Nagasaki introduced the world to man's conquest of the atom, nuclear-power technology has passed from infancy into a dynamic growth of research and engineering. With each new year advances in theory and application add greatly to what is already known. Some have had far-reaching effect on pioneering concepts. In effect large strides in technological progress are becoming more commonplace in nuclear power than in conventional power.

The usual nuclear reactor is large and heavy and its radiation shielding is massive. For flight applications the nuclear reactor must be refined to a relatively small, lightweight package. Its shielding also must be reduced tremendously in volume and weight. Since the energy produced per pound of reactor must be high, these airborne reactors must operate in very high temperature ranges. All these requirements impose significant extensions of presently known reactor, shielding, and materials technology. And once the heat has been produced it must be efficiently conveyed to or through a system that will convert the heat energy into the propulsive force or the electrical energy that is needed in the particular application.

Part II is accordingly concerned with the relevant principles of nuclear theory and the projection of theory into aerospace propulsion-system applications. Beginning with a brief picture of fission reaction and power-reactor fundamentals, it proceeds to the materials used to sustain and contain reaction and to the basic engineering premises that incorporate the useful conversion of nuclear energy, particularly as they apply to aerospace power plants.

Power-Reactor Fundamentals

CAPTAIN THOMAS L. JACKSON
Nuclear Technologist, ANPO

A NUCLEAR REACTOR is a controlled device in which energy is liberated as a consequence of an interaction between neutrons and a fissionable fuel. The major portion of this energy is released in the form of heat. Essentially the nuclear reactor may be thought of as the most recent outgrowth of man's historic quest to develop a more effective heat source—a heat source which, when coupled to appropriate energy-conversion systems, has produced electrical power and submarine propulsive power and which will eventually provide power for aircraft, rockets, satellites, and spacecraft.

As in other energy systems, the factors that must be considered in the design and operation of a reactor are (1) the type and arrangement of the materials involved and (2) the method of controlling the device.

Before plunging too precipitously into considerations of reactor design, operation, and control, we should lay a foundation of the fundamental nuclear physics and reactor terminology necessary for later comprehension.

Nuclear Principles

atomic structure

An atom consists of a positively charged nucleus surrounded by a cloud of negatively charged electrons. The atom as a whole is electrically neutral, the positive charge of the nucleus just balancing the negative charge of the orbital electrons. The nucleus itself is composed of protons and neutrons. The proton carries a unit positive charge; the neutron carries no charge and hence is electrically neutral. Thus the number of protons in a nucleus determines the positive charge of the nucleus. On the atomic mass scale, the neutron has a mass of 1.00897 amu (1 atomic mass unit $= 1.660 \times 10^{-24}$ grams), and the proton 1.00758 amu.

The number of protons in the nucleus of an element is called the *atomic number* Z of the element. This is also the element number as it appears in the periodic table. The total number of protons and neutrons in the nucleus is called the *mass number* A of the element. The number of neutrons in a nucleus is then $A - Z$. The atomic weight of an element is of course very close to the mass number A, since both protons and neutrons are close to unity on the atomic mass scale and the electron mass is very much less than unity. An element is described for nuclear purposes by its atomic number and mass number; thus an unknown element X is represented by ${}_{Z}X^{A}$, and specific elements by ${}_{2}He^{4}$, ${}_{4}Be^{9}$, ${}_{6}C^{12}$, ${}_{82}P^{207}$, etc.

The chemical nature of an element is determined by the number and arrangement of its orbital electrons. Since the number of electrons is equal to the number of protons (the atomic number) in the neutral atom, the chemical properties of an element in effect depend on the atomic number. The chemical properties are independent of mass number.

This article is a qualitative, nonmathematical treatment of power-reactor fundamentals. It is not intended to be an all-inclusive treatment of the subject. It is hoped that the presentation will establish a clear, concise concept of the high lights of power-reactor design, operation, and control and that it will thus enable the reader to view the subject in the future with the assurance and equanimity stemming from a basic understanding.

isotopes

Elements having the same atomic number but different mass numbers, i.e., the same number of protons but a different number of neutrons, are called isotopes. Since they have the same atomic number, isotopes are identical chemically. They do have different nuclear properties, and this fact is of major importance in reactor physics.

Uranium, the element most prominent as a reactor fuel, occurs in nature in at least three isotopic forms: U^{238}, U^{235}, and U^{234}. The isotopic concentration (percentage) of natural uranium is:

mass number	*composition %*
U^{234}	.006
U^{235}	.712
U^{238}	99.282

radioactivity

Radioactive isotopes, or radioisotopes, are isotopes that because of their basic unstableness undergo spontaneous disintegration or decay. The three most important decay products of the nucleus are alpha particles (α), beta particles (β), and gamma rays (γ). The alpha particle is a helium nucleus, i.e., a helium atom stripped of its electrons. Its symbol is ${}_{2}He^{4}$. Alpha particles, though relatively heavy and energetic, have a very short range and a very limited penetrative ability. Alphas may be stopped by a sheet of paper. Their range in air is roughly 1 centimeter for each 2 mev (million electron volts) of energy. Beta particles are electrons that emanate from the nucleus. Since it was indicated previously that the nucleus contained no electrons but only protons and neutrons, a brief explanation is in order. The source of nuclear electrons may be described symbolically by the following neutron transformation within the nucleus:

$$_0n^1 \rightarrow {}_1H^1 + {}_{-1}e^0$$

In words, a neutron decays to a proton and a beta particle. This transformation converts the parent element into a daughter element with the same A but with a Z greater by one unit. An example of a beta emission is

$$_{58}Ce^{144} \rightarrow {}_{59}Pr^{144} + {}_{-1}e^0$$

The beta particles are generally much more penetrative than the alphas; still, a few millimeters of metal such as aluminum suffices to stop them.

Gamma rays are similar in character to X rays, the distinction being that they are of higher energy. Gammas are highly penetrating and have wave lengths on the order of from 10^{-8} to 10^{-11} cm. Elements of high atomic number or electron density are used to attenuate gamma rays. Thus lead is a common gamma shielding material. Often after a nuclear transformation the product nucleus is left in an excess or *excited energy* state. When this occurs, the excited nucleus may emit the excess energy in the form of gamma rays.

Radioactive elements decay at definite exponential rates. The two terms most frequently used to describe radioactive decay characteristics are *halflife* and *curie*. The halflife, T, is the time required for a radioactive element to decay to half its initial value. As an illustration, assume a 2-gram sample of an element with a halflife of 2 days, $T = 2$ days. At the end of 2 days, 1 gram of the sample will have disintegrated, leaving 1 gram or one half of the original sample. At the end of 4 days, one half of this remaining 1 gram will have further disintegrated, leaving ½ gram of the original sample. At the end of 6 days, ¼ gram will remain, and so on. The curie is a unit of radioactivity. It is used to express the rate at which a radioactive material decays or emits charged particles. Quantitatively the curie is defined as that amount of radioactive material which undergoes 3.70×10^{10} disintegrations per second.

neutrons

From our definition of a reactor it can be seen that neutron theory is of fundamental importance in description of reactors. The neutron is the heart of the reactor fission process. Consequently at this point certain concepts of elementary neutron physics may be usefully reviewed.

Source. Free neutrons—neutrons outside atomic nuclei—may be obtained in several ways. A neutron source frequently used in reactor start-up operation is an encased mixture of a natural alpha emitter, radium or polonium, with beryllium. The alpha particles emitted by the radioisotope interact with the beryllium to produce neutrons. Thus the nuclear reaction is

$$_2HE^4 + {}_4Be^9 \rightarrow {}_6C^{12} + {}_0n^1$$

Energy classification. In neutron-nucleus interactions, the energy of the interacting neutrons determines to a large extent the particular type of reaction that will occur and its probability of occurrence. Neutron energies are described most frequently in terms of electron volts (ev) or million electron volts (mev). The electron volt is the energy acquired by any particle carrying a unit electronic charge when it passes through a potential of one volt. In reactor terminology neutrons are classified into several general groups according to their energy. The energy range and title of the various groups are wholly arbitrary, no rigid or universal categorization having been established. The groupings in general usage are:

neutron class	*energy range*
thermal or slow	.025 to 1 ev
epithermal or resonance	.1 to 100 ev
intermediate	100 ev to .1 mev
fast	.1 to 20 mev
high energy	$>$ 20 mev

Reactors themselves are frequently classified by the dominating neutron energy spectrum that they operate on. Thus we speak of thermal reactors, of epithermal reactors, and of fast reactors.

Neutrons that are in equilibrium with the atoms or molecules of their surrounding medium are termed thermal neutrons. Their average kinetic energy is the same as that of the medium. Since this energy depends on the temperature of the medium, it is called thermal energy. In any case, even at a specific temperature, not all thermal neutrons will have the same energy or velocity. Just as with gas molecules, the kinetic energies of the thermal neutron will be distributed statistically according to the Maxwell-Boltzmann law.

Neutron reactions. Since the neutron has no electrical charge, it is not electrically repulsed when in the vicinity of a nucleus. Within a distance of about 10^{12} cm of a nucleus, the neutron may undergo either of two general reactions—scattering or absorption.

Scattering. There are two types of scattering reactions, elastic and inelastic. In elastic scattering both momentum and kinetic energy are conserved. In inelastic scattering momentum is conserved, but not kinetic energy.

In *elastic scattering* a bombarding neutron collides with an essentially stationary target nucleus and is deflected from its original path. It transfers part of its kinetic energy to the target nucleus and is slowed down. The fraction of energy transferred will depend on the angle through which the neutron is scattered and on the mass of the target nucleus. For any given scattering angle, the portion of energy transferred and thus the extent of the slowing process is greater, the smaller the mass of the target nucleus. This is essentially a billiard-ball type of collision and hence amenable to treatment by the laws of classical mechanics.

A neutron undergoing *inelastic scattering* is first captured by the target nucleus, and a compound nucleus is formed. The compound nucleus instantaneously emits a neutron of lower kinetic energy, and the target nucleus is left in an excited state. Thus part of the bombarding neutron's kinetic energy is converted into excitation energy of the target nucleus. The nucleus then returns to its ground state by the emission of gamma radiation. For inelastic scattering to occur, 1.0-mev or higher-energy neutrons are required.

Absorption. Neutrons also take part in absorption reactions. Two of the absorption reactions important in nuclear reactors will be considered: radiative capture and fission.

• Neutron absorption may convert a nucleus into a different isotope. In the *radiative capture* reaction, a neutron is captured by the target nucleus, and a high-energy or excited compound nucleus is formed. The excess energy of the excited compound nucleus is emitted almost instantaneously in the form of capture gamma rays, leaving the isotopic nucleus in its ground state. The compound nucleus is an isotope of the target nucleus, since it has the same atomic number Z but a different mass number A. If the product isotope is unstable, it will further emit beta particles and gamma rays. The radiative capture reaction is most frequently referred to as the (n, γ), i.e., neutron-gamma reaction. An important illustration of the (n, γ) process occurs in the production of the artificial element plutonium, a fissionable fuel:

$$_{92}U^{238} + {}_0n^1 \rightarrow {}_{92}U^{239} + \gamma$$

The resulting uranium isotope, U^{239}, is radioactive and decays by beta emission to neptunium:

$$_{92}U^{239} \rightarrow {}_{-1}e^0 + {}_{93}Np^{239}$$

Neptunium is also unstable and decays by beta emission to form plutonium:

$$_{93}Np^{239} \rightarrow {}_{-1}e^0 + {}_{94}Pu^{239}$$

This is the process which takes place in the plutonium-production reactors at Hanford, Washington.

• The *fission* process will be mentioned briefly at this point and covered in more detail later. Basically, in the fission process a bombarding neutron is again absorbed by a target nucleus. The resulting compound nucleus is so unstable that it immediately breaks up into two fragments termed *ff* (*fission fragments*). Several neutrons are emitted and energy released. The general fission process may be described as

$$n + \text{fuel} \longrightarrow 2\,ff + 2 \text{ to } 3\; n + \text{energy}$$

Cross sections. The probability of occurrence of an interaction between a neutron and a nucleus is a quantity termed the *nuclear cross section* σ. This quantity may be considered as the effective target area of a nucleus. Thus σ is measured in area units expressed as barns (1 barn $= 10^{-24}$ cm^2). The cross section σ is further identified as the *microscopic cross section;* it applies to a single nucleus. The term *macroscopic cross section* Σ denotes a bulk or volume cross section: $\Sigma = N\sigma$ cm^{-1}, where N is the number of nuclei/cm^3. Thus Σ is the total cross section of the nuclei in 1 cm^3 of material, and it has units of reciprocal cm. Cross-section values are dependent on the energy of the bombarding neutron and on the particular target nucleus bombarded. A comprehensive listing of this most important property of nuclei is contained in the book, *Neutron Cross Sections,* Brookhaven National Laboratory-325, commonly referred to as the "Barn Book." In light of the scattering and absorption processes previously mentioned, we may now indicate some of the cross-section symbolism. The symbol σ is usually reserved for the total cross section, which includes all the neutron interactions. Thus,

$$\sigma = \sigma_s + \sigma_a$$

where s refers to scattering and a to absorption. Further,

$$\sigma_s = \sigma_{se} + \sigma_{si}$$

$$\sigma_a = \sigma_c = \sigma_f$$

where e refers to elastic, i to inelastic, c to radiative capture, and f to fission.

It may be noted from Barn Book listings that even for U^{235}, an isotope that has been under intensive investigation for some time, completely accurate cross-section measurements have defied determination. The accurate determination of cross sections for the total spectrum of neutron energies for the many isotopes is one of the major difficulties confronting the nuclear and reactor physicists.

A few generalizations concerning cross sections may be useful. For most elements, scattering cross sections decrease slowly with increasing neutron energy. In the thermal region the absorption cross section of most nuclei decreases with increasing neutron speed, i.e., $\sigma_a \sim 1/v$, the so-called "$1/v$ law." In classical terms this might be explained by the fact that a slow-moving neutron may be considered as spending more time in the vicinity of the nucleus than a faster neutron. The probability of interaction would consequently be expected to be larger in the former case. For neutrons of about 0.1 ev to 100 ev interacting with high-mass-number elements, there are often discrete energies for which the reaction probability, i.e., the cross section, is exceptionally high. This phenomenon is called *resonance absorption*. For example, U^{238} has an absorption cross section of roughly 3 barns on either side of a resonance absorption peak of 7000 barns at 6.7 ev.

fission

It is now appropriate to return to a more detailed consideration of the fission process—the last essential part of an introduction to the reactor itself. Of course this separation of fission from the reactor proper is purely an editorial convenience, since the fission process is the essence of reactor operation.

As was seen, the fission process may be represented as

$$n + \text{fuel} \longrightarrow 2\,ff + 2 \text{ to } 3\,n + \text{energy}$$

Consider the left side of this equation. Fission occurs only in the heaviest elements—uranium, plutonium, thorium. Either thermal or fast neutrons can cause fission in the isotopes U^{235}, U^{233}, and Pu^{239}. These isotopes have a much higher cross section for thermal fission than for fast fission. Thus it is much more efficient from the standpoint of fuel economy and neutron economy to utilize slow or thermal neutrons to cause their fission. The isotopes of U^{238} and Th^{232} will not fission under the bombardment of slow neutrons; neutrons of the order of 1 mev or higher are required. Most of the ensuing discussion will concern itself with the thermal fission of U^{235}, the most prevalent fission process used in present-day reactors.

The three factors on the right side of the above generalized fission equation are fission fragments, fission neutrons, and fission energy:

• A wide spectrum of *fission fragments* results from the thermal fission of U^{235}. Investigation shows that U^{235} splits up in more than 30 different ways, producing more than 60 primary fragments. The fission-fragment mass numbers range from 72 to 158. The thermal fission of U^{235} is quite asymmetric. The masses of nearly all the products fall into two broad groups—a light group with mass numbers from 80 to 110, and a heavy group with mass numbers from 125 to 155.

One of the most significant properties of the fission products is their radioactivity. The fission fragments have too much mass for their charge, i.e., the neutron–proton ratio is too high for stability. They tend to reach stability by emitting neutron and beta particles. The immediate daughter products of the fission fragments are themselves frequently radioactive, so that radioactive decay continues until a stable isotope is eventually reached. Since some 60 different radioactive fission fragments are produced and each is on the average the precursor of two others, some 180 radioisotopes are present shortly after fission. The many neutrons, betas, and gammas given off by the millions of fission-produced radioisotopes can cause serious biological damage to man and also have adverse effects on associated reactor and system components. Herein lies the necessity for shielding a reactor.

• As previously indicated, most of the fission fragments formed are neutron-unstable, and consequently they almost instantaneously eject one or more neutrons plus highly penetrating gamma rays. The average number ν of neutrons emitted for each thermally fissioned nucleus of U^{235} is 2.5 ± 0.1, and for Pu^{239} it is 3.0 ± 0.1. This number is not an integer, since the nucleus splits in many different ways. Although the number of neutrons emitted in any particular fission must obviously be an integer, the average clearly does not have to be.

Fission neutrons are classified as *prompt* neutrons or *delayed* neutrons. The prompt neutrons constitute over 99% of the fission neutrons and are released within about 10^{-14} seconds of fission. These neutrons have a broad spectrum of energy ranging from 10 mev to thermal, the most probable energy being 0.72 mev and the average energy 2 mev. It should be emphasized that, though thermal neutrons have the higher fission cross sections and hence are economically desirable for reactor fission, the actual fission neutrons are for the most part born fast and therefore must be slowed down for maximum efficiency.

About 0.73% of the 2.5 neutrons emitted in the thermal fission of U^{235}

are delayed neutrons, i.e., they are emitted with gradually decreasing intensity over a period of minutes rather than instantaneously. Delayed neutrons have

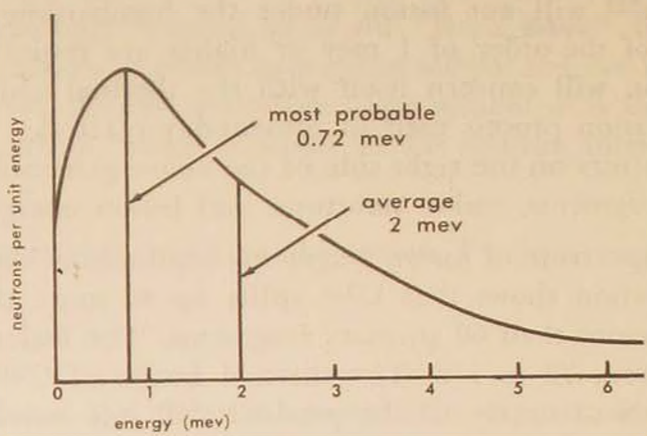


Figure 1. Neutron fission energy spectrum.

an important function in the time-dependent behavior and control of reactors. This topic will be considered later in more detail.

• The great promise of nuclear reactors lies in the tremendous amount of *fission energy* released. Very simply, the large energy release associated with fission stems from the fact that the sum of the particle masses on the right side of our generalized fission equation does not equal, and in fact is appreciably smaller than, the sum of the particle masses on the left side. The energy equivalent of this mass defect may be determined by use of the well-known Einstein mass energy equation. $E = mc^2$, where c is the velocity of light. It is convenient in the equation to use energy E, units of mev, and mass m, units of amu. With the proper manipulation of conversion units, the equation then becomes $E\,(\text{mev}) = m\,(\text{amu}) \times 931$.

The most direct method of calculating the fission energy is to calculate the mass defect between the reacting particles and the final stable products, and then to convert this mass to energy. The fragments most often appearing in the thermal fission of U^{235} have mass numbers of 95 and 139. To balance the mass numbers in the equation, it is assumed that two neutrons are emitted. Thus,

$$n^1 + U^{235} \longrightarrow Mo^{95} + La^{139} + 2n^1$$

Comparing masses before and after fission:

mass before fission		*mass after fission*	
U^{235}	235.124	Mo^{95}	94.945
1 neutron	1.009	La^{139}	138.955
		2 neutrons	2.018
	236.133 amu		235.918 amu

Thus the mass defect is 236.133 − 235.918 = .215 amu. Converting this mass to energy, $E = 931 \times .215 = 198$ mev per fission. (This energy may be compared to the few ev that are released in the chemical combustion of an atom.) Translating roughly the 200 mev/fission to conventional power-system units shows that 3.1×10^{10} fissions release 1 watt-sec of power, or 1 watt = 3.1×10^{10} fissions/sec. The fissioning of 1 gram of fuel per day corresponds to approximately 10^6 watts, or 1 megawatt. Reactor output is customarily listed as so many watts, thermal; this may be thought of as the heat energy per unit of time available for transfer to the reactor coolant.

More than 80% of the fission energy is released in the form of fission-fragment kinetic energy. The fission fragments are slowed down by collision with atoms of the surrounding medium. Thus they transfer part of their energy to the medium and raise its temperature. This nuclear-generated heat is then carried off by a circulating coolant to perform whatever design function has been established for the system.

The approximate distribution of the fission energy is:

Kinetic energy of fission fragments	167 mev
Kinetic energy of fast fission neutrons	5 mev
Energy of instantaneous gamma rays	7 mev
Energy of fission-product beta particles	5 mev
Energy of fission-product gamma rays	6 mev
Energy of neutrinos	10 mev
	200 mev

The beta particles with their accompanying neutrinos and the delayed gamma rays are set free gradually as the fission products decay, whereas the fission fragments, fast neutrons, and prompt gamma rays are emitted at the time of fission. The highly penetrating neutrinos (subatomic particles with no charge or mass) do not contribute to the heat energy, since they do not interact appreciably with matter. The total reactor energy available is still roughly 200 mev, since excess fission neutrons may take part in the (n, γ) reaction—radiative capture—with U^{238}, moderator, coolant, structure, etc. The energy of the resultant capture gamma rays is on the order of 3 to 7 mev. The products of the (n, γ) reaction may also be radioactive, so another 1 or 2 mev may result from the beta and gamma decay of these products. Thus the delayed energy release resulting from the radioactive capture process approximately balances the unproductive neutrino energy. An important consequence of this delayed energy release is that coolant circulation must be continued for some time after reactor shutdown in order to remove the residual heat.

The Reactor

Having laid the groundwork by describing the fundamental processes that are necessary to the understanding of nuclear reactors, we may now proceed to the general description of a heterogeneous thermal reactor using fuel elements enriched in U^{235}. This is the type of reactor most commonly referenced as a present-day, high-density power reactor. The generalized description will then lend itself to a somewhat more detailed and expansive treatment of basic reactor operation.

As we have seen, the fission of U^{235} yields approximately 200 mev of useful energy and an average of 2.5 fast neutrons. The fission-fragment kinetic

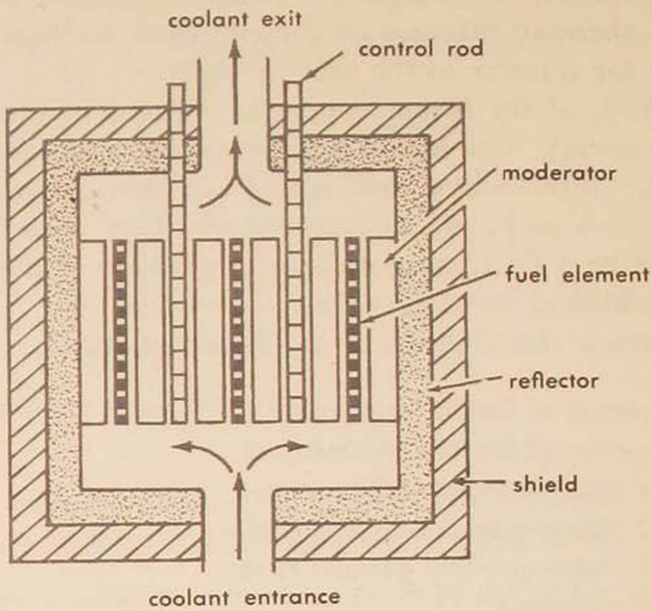


Figure 2. Schematic of heterogeneous thermal reactor.

energy is the primary source of heat. The heat is removed by a heat-transfer agent, a circulating coolant. In our model reactor, a moderating material containing a light element, such as hydrogen, lithium, beryllium, or carbon, is interspersed with the fuel elements. The fast-fission neutrons collide with the moderator nuclei, losing their high kinetic energy and slowing down to thermal values. The thermalized neutrons have a high fission cross section in comparison to that of fast neutrons. But neutrons may escape from the active fuel zone, reactor core, and be lost to the system. A reflector enveloping the core reduces the neutron leakage by scattering neutrons back into the core. In thermal reactors the reflector is frequently of the same material as the moderator, so that in addition to its reflecting function it provides further neutron moderation. In the heterogeneous reactor the fuel is lumped into rods, plates, rings, etc., which are separated by moderator and so spaced as to reduce the resonance neutron capture of U^{238} to a minimum. The principle is to arrange the materials so that the fast neutrons slow through the resonance range of energy to thermal values quickly and with a low probability of finding a U^{238} atom to react with. It is not enough that moderator, reflector, and structural material be selected solely on the basis of how well the particular material performs its primary function at the reactor temperatures involved. These materials must have low capture cross sections if excess loss of reactor neutrons is to be avoided.

To make practical use of the fission energy released, a reactor must incorporate the materials and controls in a geometry that will support a self-sustaining chain reaction. The minimum requirement for such a self-sustaining reaction is that at least one of the neutrons resulting from a fission causes another fission, or, macroscopically, that each generation of fission neutrons leads to a numerically equal succeeding generation after losses are allowed for. The fate of reactor neutrons is governed by three main processes: leakage, nonfission capture (structure, moderator, coolant, fission product, and U^{238} resonance capture), and fission. The neutron losses from leakage and nonfission capture must be such that enough neutrons remain in the system to support a self-sustaining fission chain. Reactor control is usually achieved by means of control rods, which are composed of materials such as boron and cadmium that have high thermal neutron absorption cross sections. The shield, though not directly involved in the controlled fission process, is necessary for the protection of personnel and material from the damaging radiations emitted from the reactor.

the multiplication factor

The condition for a self-sustaining chain reaction is conventionally expressed in terms of an *effective multiplication factor, k_e*. The effective multiplication factor may be defined as the ratio of the number of neutrons present

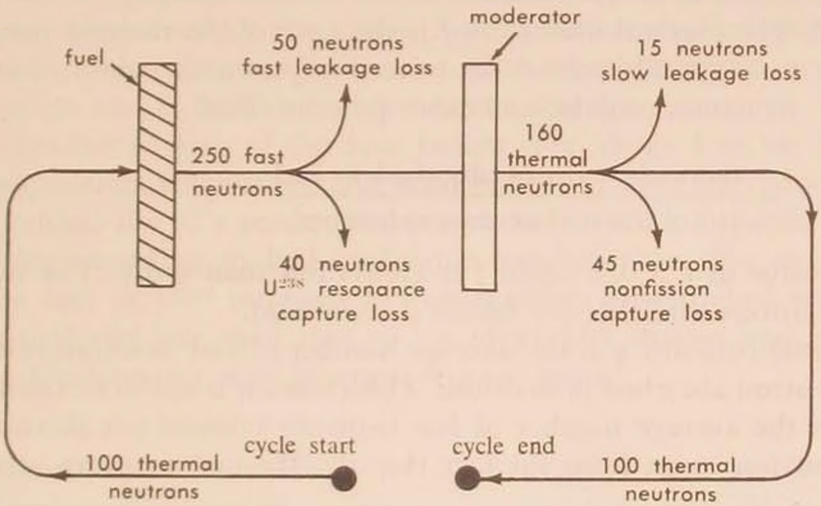


Figure 3. The self-sustaining chain criticality.

at the end of any particular neutron generation to the number of neutrons present at the start of that generation. A reactor is said to be critical when the effective multiplication factor is unity, $k_e = 1$, i.e., the number of neutrons in the system is constant. With the number of neutrons or the fission rate constant, the power level is also constant; this condition is referred to as the *steady state*. For $k_e > 1$, the reactor is said to be *supercritical;* the neutron density, or flux, and the power level increase at an exponential rate. For $k_e < 1$, the reactor is said to be *subcritical,* and the flux and power level decrease exponentially. In referring to an infinite reactor system (a convenient model having no neutron leakage loss through the reactor boundary), the *multiplication factor* is expressed as k_∞ or, more simply, without the subscript as k. In calculational transformations from an infinite reactor to a finite reactor, neutron leakage effects must be considered. For a finite critical reactor then, k will be somewhat greater than unity, and k_e will equal unity.

The multiplication factor was historically broken down into four measurable or calculable quantities; thus $k = \epsilon p f \eta$.

Consider the fate of n fast neutrons present at the start of a particular neutron generation. Before the fast neutrons slow down appreciably, they may cause some fast fission in the U^{235}—U^{238} fuel. A slight increase in the number of fast neutrons in the system will result, since more than one fast neutron is produced in the fission process. The fast *fission factor* ϵ is a measure of this effect. For a natural uranium reactor, the value of ϵ is about 1.03.

As a consequence of elastic collision with the moderator, the $n\epsilon$ fast neutrons begin slowing toward thermal energies. During the slowing process some of the neutrons will be captured in nonfission interactions, so that not all of the $n\epsilon$ neutrons will be thermalized. The fraction of the fast neutrons that escape capture while being slowed down is called the *resonance escape probability* p. The value of p is always somewhat less than unity. A typical p value for a natural uranium, heterogeneous reactor is 0.9.

Thus the number of neutrons that eventually reach thermal energies is $n\epsilon p$. Again all the neutrons absorbed at the thermal energies are not absorbed in the fuel. The *thermal utilization* f is the ratio of the thermal neutron fuel absorption to the total thermal neutron absorption, i.e., absorption in fuel, moderator, structure, coolant, and other poisons. Thus

$$f = \frac{\text{thermal neutrons absorbed in fuel}}{\text{total thermal neutrons absorbed}}$$

A typical value of f is 0.9; again f is always less than unity. The number of thermal neutrons available for fission is then $n\epsilon p f$.

The final constant η is the average number of fast neutrons released per thermal neutron absorbed in uranium. This constant is not to be confused with ν, which is the average number of fast neutrons released per thermal fission. This distinction stems from the fact that the thermal neutrons absorbed in the fuel do not all cause fissions. Thus $\eta = \nu \frac{\sigma_{fu}}{\sigma_{au}}$ where σ_{fu} is the thermal fission cross section of the uranium fuel and σ_{au} is the total absorption cross section of the uranium fuel. A typical value of η might be 1.32.

The n fast neutrons of our original generation have produced $n\epsilon p f \eta$ fast neutrons of the succeeding generation. Thus the multiplication factor k by definition is given by $k = \frac{n\epsilon p f \eta}{n} = \epsilon p f \eta$.

Using the values we have assigned to $\epsilon p f \eta$, we have $k = (1.03)\ (.9)\ (.9)\ (1.32) = 1.10$, and our infinite reactor is supercritical. If in converting our infinite system to a finite system we assign a value of .91 as a *nonleakage probability*, then $k_e \doteq .91k = (.91)\ (1.10) = 1.00$, and our reactor is critical.

The foregoing discussion of the multiplication factor leads quite naturally to the important considerations of reactor critical size and mass and of reactor control and reactivity. Reactor critical size and mass will be considered first.

critical size and mass

The size of a reactor that is necessary to produce an effective multiplication factor of unity, $k_e = 1$, is called the *critical size* of the reactor. The mass corresponding to the critical size is termed the *critical mass*.

Since k_e was shown to be a function of the nonleakage probability and of k, it is necessary to examine the effect of these two factors in determining the critical size.

Neutron escape occurs at the reactor exterior or boundary, while neutron absorption takes place throughout the reactor interior. Thus the number of leakage neutrons is a function of surface area, and the number of capture neutrons is a function of reactor volume. Decreasing the area-to-volume ratio of the reactor minimizes the neutron leakage, or, stated another way, increases the nonleakage probability. This ratio can be maximized by increasing the reactor size and by selecting an optimum geometrical shape. For a given volume, a sphere furnishes the smallest area-to-volume ratio, and neutron leakage is minimal for this shape. As was indicated previously, a reflector may be used to scatter many neutrons (that otherwise might escape) back into the system and to further reduce neutron leakage.

A qualitative analysis of the four factors $\epsilon p f \eta$ shows k to be dependent on the composition, proportion, and arrangement of the fuel and moderator. Thus the critical size of a reactor is not constant even for a specific geometry but will vary according to fuel–moderator considerations. For example, enriching the fuel in U^{235} increases k. Consequently an enriched reactor will have a critical size less than that of an identically shaped and structured natural uranium reactor with identical leakage losses.

reactor control

Thermal-reactor control may be achieved by controlling neutron multiplication. It has been shown that for steady-state reactor operation it is sufficient to achieve an effective multiplication factor of unity, $k_e = 1$. If the reactor is to achieve an appreciable power output, the multiplication factor must exceed unity, $k_e > 1$.

One method of accomplishing this control is to insert into the thermal reactor neutron-absorbing elements such as boron, cadmium, and hafnium in the form of rods. These elements have high capture cross sections for thermal neutrons. In shutdown, control rods are inserted to the extent of a large removal of neutrons from the system, and the effective multiplication factor is much less than unity. On start-up, the control rods are drawn out until $k_e > 1$. The neutron multiplication and hence power rise exponentially to the level desired. At this time the control rods are positioned to maintain the power at the desired level with $k_e = 1$. If it is desired to increase the power level, the control rods are further withdrawn, and the neutron multiplication increases, with a consequent rise in fission rate and power. When the desired power level is reached, the control rods are driven in to their original position at which $k_e = 1$. The reactor now operates at the higher power level as a result of the increased neutron density or inventory. The reverse process produces a reduction in power level.

The rate at which the neutron density of a reactor varies depends on the excess multiplication. The difference between the effective multiplication factor and unity is a measure of the excess multiplication, and is labeled delta-*k*-effective, i.e., $\delta k_e = k_e - 1$. Recalling the definition of k_e (the ratio of the number of neutrons present at the end of a generation to the number of neutrons at the start of that generation), let n represent the number of neutrons at the start of a generation; then $n(k_e - 1)$ will be the rate of neutron change per generation. If l is the neutron lifetime, cycle time, or average time between succeeding generations, then the time rate of neutron change is

$$\frac{dn}{dt} = \frac{n(k_e - 1)}{l} = \frac{n\delta k_e}{l} \qquad (1)$$

Integration of Equation (1) yields

$$n = n_o e^{t(\delta k_e/l)} \qquad (2)$$

where n_o is the number of neutrons at the instant of change, $t = 0$, and n is the number at an time, t. The ratio $l/\delta k_e$ is called the reactor period, T. Substituting the reactor-period T in Equation (2) yields

$$n = n_o e^{t/T} \qquad (3)$$

The reactor period is thus the time required for the neutron density to change by the factor $e = 2.718$.

For example, if we assume a reasonable value of $l = 0.0002$ sec, and we select $\delta k_e = 0.002$, or 0.2%, then $T = l/\delta k_e = 0.1$ sec. Substituting this value of T into Equation (3) indicates that at the end of 0.1 sec the neutron density will have increased by a factor of 2.718; at the end of 0.5 sec, by a factor of e^5 or 148; at the end of 1 sec, by a factor of e^{10} or 20,000. Such a rapid rise in the neutron density poses a difficult control problem. Safe reactor operation requires that the reactor period T should be reasonably long. For a more or less fixed value of l, a long period means that the excess multiplication δk_e must be kept small. Reactors are ordinarily equipped with *period scrams*. Thus if a reactor by miscalculation or accident begins a power excursion on a dangerously short period, the reactor is automatically scrammed, i.e., safety rods (rods of the same material as control rods) are positively inserted into the reactor.

delayed neutron effect

The fact that the reactor fission products emit a small fraction of the total fission neutrons in accordance with the usual laws of radioactive decay has an important consequence in reactor control. In the previous example, the neutron lifetime l was taken as 0.0002 sec. Actually this was the average time between neutron release, or birth, and fission capture. If all the fission neutrons were released promptly, this would be the correct input of l used to determine the period. However there is an additional time lapse between fission capture and release because of the delayed neutrons that must be considered. This has the effect of extending the neutron cycle time considerably Of the fission neutrons released, a fraction, β, is *delayed,* and hence $1 - \beta$ neutrons are *prompt.* In U^{235}, 0.73% of the neutrons are delayed, i.e., $\beta = 0.0073$. For U^{235}, the halflife of the five groups of delayed emitters ranges from about 0.43 to 55.6 sec. By properly weighting these groups, the average delay time is computed to be about 0.1 sec. The *effective neutron cycle time* is thus 0.002 + 0.1 sec, or approximately 0.1 sec. Inserting this new value of $l = 0.1$ sec in our previous example, $T = l/\delta k_e = 0.1/0.002 = 50$ sec. Now, at the end of 50 sec the neutron density will have increased by a factor of 2.718; at the end of 100 sec, by a factor of e^2 or 7.4; at the end of 300 sec, by a factor of e^6 or 400. Clearly the rate of increase of neutron density is now much slower than if all the neutrons were prompt.

This is still not the complete picture. The excess multiplication may be of such a large value that the delayed neutrons have no opportunity to slow the rate of increase in neutron density. If $k_e(1 - \beta) \leq 1$, then the rate of neutron increase will be controlled essentially by the delayed neutrons. This condition is achieved if k_e lies between 1 and 1.0073. If the value of $k_e(1 - \beta) > 1$, that is, $k_e > 1.0073$, the multiplication will be critical on prompt neutrons alone. This reactor condition is described as *prompt critical* and is an accident condition, since the reactor period will be dangerously short. Thus with $\delta k_e < \beta$, l is determined by the effective neutron cycle time, and the reactor will be on a safe period. With $\delta k_e > \beta$, l is determined solely by the prompt neutron lifetime, and an unsafe period will result.

reactivity

The expression "excess multiplication" is not often used in reactor terminology. Instead a quantity termed *reactivity* and symbolized as ρ is customarily used. Reactivity is defined as the ratio of the change in the effective multiplication factor to the effective multiplication factor, i.e., $\rho = \delta k_e/k_e$. For small values of δk_e, the reactivity is almost the same as δk_e itself. Two units of reactivity are commonly referred to: the *dollar* is equal to a reactivity of $\beta = 0.0073$, and the *cent* is equal to 1/100 of the dollar.

Reactivity may be positive or negative, depending on whether the perturbation causing the change produces an increase or decrease in k_e. Introduction of a positive reactivity requires the reactor control rods to drive in if the reactor is to remain critical. Conversely, introduction of a negative reactivity requires the control rods to drive out if the reactor is to remain critical.

A reactor must be designed with an excess reactivity to compensate for the changes in negative reactivity that result from fuel consumption and fission-product poisoning. Obviously fuel is consumed during the course of reactor operation. Eventually there will be such a reactivity loss that the reactor will no longer be able to maintain criticality. ***Burnup*** is defined as the percentage of the total fuel that may be consumed before the reactor must be shut down for refueling.

The most important fission-product poison is xenon-135. It has an extremely high thermal absorption cross section, $\sigma_a = 3.5 \times 10^6$ barns. The Xe^{135} forms as a result of the beta decay of the Te^{135} fission fragment.

$$_{52}Te^{135} \xrightarrow[(2\text{ min})]{} {}_{53}I^{135} \xrightarrow[(6.7\text{ hr})]{} {}_{54}Xe^{135} \xrightarrow[(9.2\text{ hr})]{} {}_{55}Cs^{135} \xrightarrow[(2.1 \times 10^6\text{ yr})]{} {}_{56}Ba^{135}$$

Assuming a clean condition at start-up, there will be no Xe^{135} present. After start-up, the concentration of Xe^{135} gradually builds up. Thus the control rods are gradually pulled out to compensate for this negative reactivity effect and to maintain criticality. Since Xe^{135} is a strong absorber, it will be continually burned out by the neutron flux. Eventually an equilibrium condition will be established wherein the rate of Xe^{135} formation, decay, and burnout are balanced.

After shutdown, the Xe^{135} equilibrium is destroyed, and the concentration begins to increase. This buildup occurs for two reasons: first, I^{135} has already been formed, and since the decay rate of I^{135} to Xe^{135} is faster than the decay rate of Xe^{135} to Cs^{135}, the Xe^{135} concentration increases; second, the neutron flux is now so low as to reduce the Xe^{135} burnout to insignificance. Within a short period of time the Xe^{135} concentration may be so high that even complete removal of the control rods will not suffice to start the reactor. After 30 to 40 hours of shutdown, the reactor may be restarted.

Another important reactivity effect stems from temperature change. Reactor designers strive to obtain what is termed a *negative temperature coefficient* of reactivity, i.e., reactor reactivity or k_e decreases as temperature increases. If a dangerous power surge causes the reactor to overheat, the density of all reactor materials decreases. This increases the intranuclei distances and consequently reduces the number of fissions and increases neutron leakage. Thus the negative temperature coefficient is an important consideration in reactor control and reactor safety.

flux, temperature, and power distribution

Possibly the most important parameter in reactor design physics is that of neutron flux. Here our interest in neutron flux is limited to a brief consideration of only one aspect—flux distribution.

Assume that a neutron density is n neutrons per cubic centimeter and that the neutrons are moving with a velocity of v cm/sec. Then the product nv is called the *neutron flux* ϕ. Or, neutron flux is simply the product nv, which is the sum of all the speeds of the neutrons in a cubic centimeter. Thus

$$\phi\left(\frac{\text{neutrons}}{\text{cm}^2\text{ sec}}\right) = n\left(\frac{\text{neutrons}}{\text{cm}^3}\right) v\left(\frac{\text{cm}}{\text{sec}}\right)$$

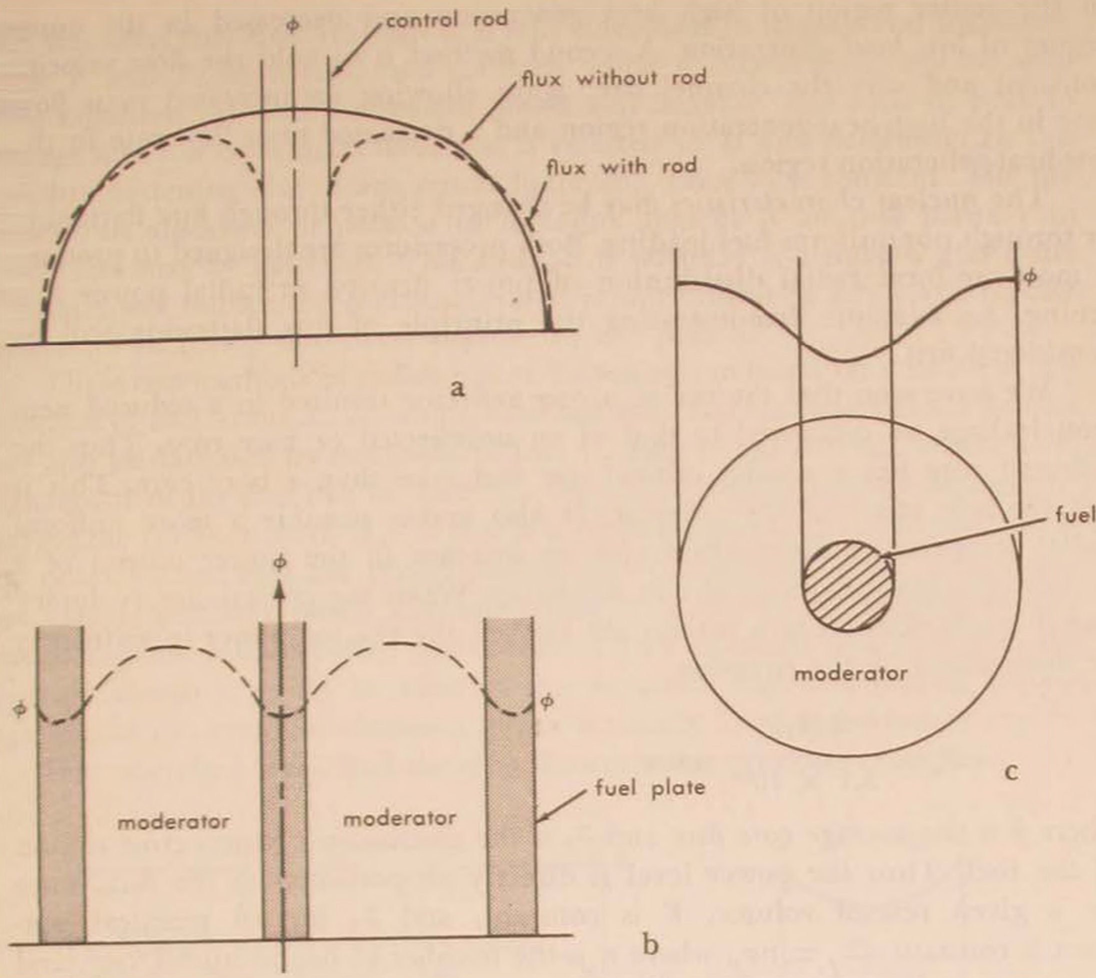


Figure 4. Diagrams of three flux distributions affecting reactor design: (a) flux distribution for a thermal, homogeneous, cylindrical reactor. Insertion of a neutron-absorbing control rod will depress the flux; (b) flux distribution for a plate-type reactor; (c) flux distribution for a heterogeneous, cylindrical reactor.

Flux distributions have been derived for the more elemental reactor geometries: spheres, cylinders, slabs, etc. In general the distributions are cosine functions or very close approximations to cosine functions.

In a reactor with many coolant channels, it is desirable to have uniform coolant-outlet temperatures to improve the system's thermal efficiency and to reduce the maximum fuel-element temperature, often the limiting factor in achieving higher power output. As a consequence of achieving relatively uniform radial distribution of temperature, the reactor power output normally increases. There are two general methods of achieving uniform radial temperature distribution: varying the reactor's heat-removal rate or changing the reactor's nuclear characteristics.

The *heat-removal rate* may be varied in two ways. One method is to hold the channel size constant and vary the coolant flow velocity by the use of orifices. Thus the flow velocity, and hence mass flow rate, may be increased in the center region of high heat generation and decreased in the outer region of low heat generation. A second method is to hold the flow velocity constant and vary the channel size, again allowing an increased mass flow rate in the high-heat-generation region and a decreased mass flow rate in the low-heat-generation region.

The *nuclear characteristics* may be changed either through flux flattening or through nonuniform fuel loading. Both procedures are designed to produce a more uniform radial distribution of power density, or radial power flattening. An example demonstrating the principle of flux flattening will be considered first.

We have seen that the use of a core reflector resulted in a reduced neutron leakage, as compared to that of an unreflected or bare core. Thus the reflected core has a smaller critical size and mass than a bare core. This is not the sole effect of the reflector. It also makes possible a more uniform radial temperature distribution and an increase in the power output of a reactor through the device of flux flattening. When the critical size (volume) and flux distribution in a reactor are known, the reactor power in watts may be determined by the equation

$$P = \frac{\bar{\phi}\, \Sigma_f V}{3.1 \times 10^{10}} \text{ watts} \qquad (4)$$

where $\bar{\phi}$ is the *average core flux* and Σ_f is the macroscopic fission cross section of the fuel. Thus the power level is directly proportional to the flux, since for a given reactor volume, V is constant, and Σ_f for all practical purposes is constant ($\Sigma_f = n\sigma_f$, where n is the number of fission nuclei/cm^3, and hence n actually decreases very slowly). Consequently neutron flux is widely used as a measure of reactor power.

In a reflected reactor the neutron flux at the core center is essentially the same as that in a bare reactor. However, at the reflected core boundary the flux is appreciably higher than at the bare core boundary. This flux increase at the core-reflector interface is caused by the reflection and return of neutrons to the core. The flux peak occurring in the reflector adjacent to the core boundary appears because the reflector region does not absorb neutrons as strongly as the core. The outermost fuel region is consequently used more effectively in a reflected core reactor. Thus the average thermal flux over the

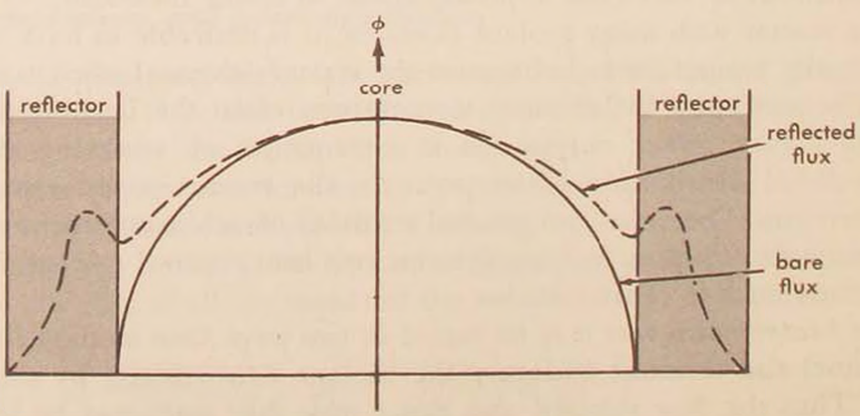


Figure 5. Thermal flux distribution in a bare and a reflected core.

core has been flattened (though it is still sinusoidal in shape) and increased. Since V and Σ_f have remained constant while $\bar{\phi}$ increased, it can be seen from Equation (4) that the reactor power will increase. The ratio of peak to average flux has been decreased; this is referred to as *flux flattening*. In this case flux flattening also means power flattening, since Σ_f is constant. The use of neutron absorbers or poisons in high-flux regions is another manner in which flux may be flattened. This method is wasteful of neutrons and quite obviously will reduce the maximum rated power output of any given reactor because of increased nonfission capture by the poison.

These two methods of radial power flattening are based on a uniform distribution of fuel, constant Σ_f, and a flattened flux. But the radial power density may also be flattened by nonuniform fuel loading in the reactor. Where U^{235} enrichment of the fuel can be varied, a flat power density may be realized by varying the U^{235} concentration so that it is inversely proportional to the flux at any point, i.e., so that the power density $\bar{\phi}\Sigma_f/c$ is constant even though the flux varies. Similarly power flattening may be achieved by loading various reactor regions with depleted and enriched fuel elements. For example, the depleted elements would be used in the normally high-flux central reactor region, and the enriched elements in the normally low-flux boundary region.

The attending simplified sketches illustrate the previous examples.

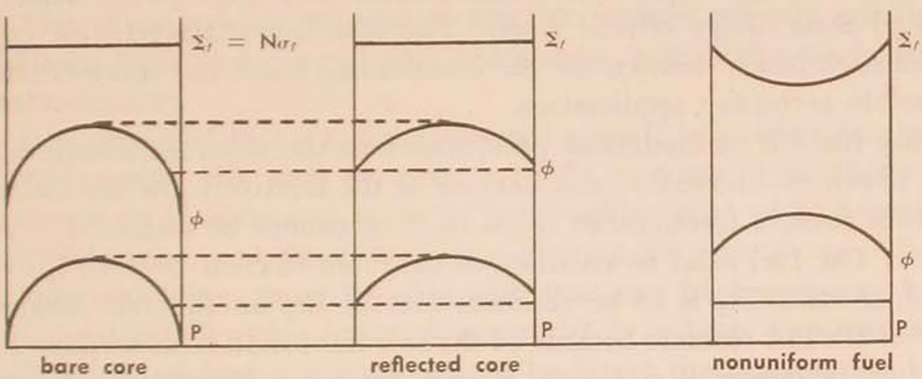


Figure 6. Fuel, flux, and power radial distribution.

In our consideration of flattening flux and power distributions, we have restricted our analysis to the radial effects required to produce a uniform coolant-outlet temperature. The axial or longitudinal distribution of fuel-element temperature, coolant temperature, and power is also an extremely important concern in reactor systems. As was previously mentioned, the maximum temperature that a fuel element can tolerate is often the limiting factor in reactor power output. The coolant-outlet temperature is an obviously important parameter of the following conversion system. The accompanying illustration indicates fuel-element temperature T_0, coolant temperature T_c, and power as a function of the axial length of a reflected cylindrical reactor. Coolant flow is from left (coolant inlet) to right (coolant outlet). It is seen that the core power is a chopped-sine (cosine) function and that the fuel-element temperature is a maximum somewhere past the axial or longitudinal mid-plane of the reactor. Thus the hottest area in a heterogene-

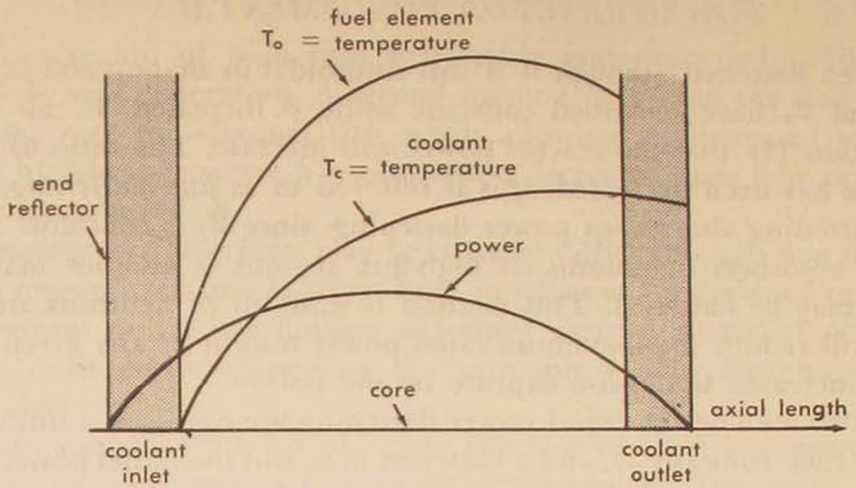


Figure 7. Axial distributions in a heterogeneous cylinder.

ous cylindrical reactor occurs in the axial region somewhere past the midplane of the cylinder.

fast reactors

A reactor having no moderator is termed a *fast reactor*. Such a reactor is characterized by compactness (small critical size), high power density, and large fuel mass (large critical mass). The first two characteristics, compactness and high power density, are the features that make fast reactors attractive for possible aerospace applications.

Since there is no moderator present to slow the neutrons, fission is caused by fast neutrons—above 0.3 mev. Because of the relatively low fast-fission cross sections of fuels, a fast-neutron chain reaction cannot be sustained in natural uranium. The fuel must be enriched in the more efficient U^{235}, or Pu^{239} must be used, if criticality is to be reached. Herein lies an inherent unattractive feature of the fast reactor: because of the low fast-fission cross sections, a much larger fuel inventory is necessary (larger critical mass) than in the thermal reactor, and a large portion of this inventory must be the more expensive U^{235} or Pu^{239}.

The core size of a fast reactor is appreciably smaller than that of a thermal reactor. The reduction in core size stems from the fact that there is no need for moderator or other materials of low mass number to slow the neutrons as in the thermal reactor. The compactness of fast reactors may be considered as an advantage or a disadvantage. It is an advantage in that a high power density, power per unit volume, kw/cm^3, is achieved, and this is most desirable for aerospace applications. A disadvantage of compact size is that the heat-transfer area is limited. Thus the removal of the large heat release becomes a problem, and the power output of the fast reactor is in practice limited by the efficiency of the heat-transfer process. To cope with this problem, liquid metals with their high specific heats are used to cool fast reactors.

Several other aspects of fast fission in a reactor are worthy of mention. The low capture cross section of materials at fast-neutron energies allows a wider selection of reactor auxiliary and structural materials. Materials that cannot be used in thermal reactors because of their adverse effect on the neutron economy may be used in fast reactors. For this same reason, i.e., low fast-capture cross sections, fission-product poisoning is no longer a problem in the fast reactor. Again, low fast-capture cross sections make it impossible to control a fast reactor by increasing or decreasing the multiplication factor k through the manipulation of neutron-absorbing control rods. However, as was indicated, the effective multiplication factor k_e is the product of k and a nonleakage probability. This fact suggests that fast-reactor control may be obtained by regulating the neutron leakage through movement of fuel elements or reflector segments.

Special Considerations of Aircraft Nuclear Reactors

THUS FAR, with the exception of the previous section on fast reactors, we have made no allusion to the special characteristics and problems peculiar to the design of aircraft nuclear reactors. We have limited the discussion to a very general treatment of power reactors, as opposed to research and production reactors.

The characteristics peculiar to aircraft nuclear reactors might be listed as follows: high power, small size, low weight, high temperature, and operational reliability.

It is estimated that a nuclear-powered aircraft will weigh on the order of 500,000 pounds. For such an aircraft to fly at mach .9 at 35,000 feet, the reactor power is calculated to be in the neighborhood of 300 megawatts.

Reactor size is an important consideration for aircraft use. The reactor, including shielding, must be of a size that can be incorporated within a streamlined aerodynamic frame. Reactor size is in large measure the governing factor in nuclear aircraft weight. The larger the reactor, the larger and thus heavier the shield must be that protects the crew from radiation. The tremendous weight of reactor shielding is one of the main considerations in the successful development of the nuclear aircraft.

An aircraft reactor must be a high-temperature reactor. For a reactor of given size and weight, the higher the temperature the greater will be the power output. Or, the higher the temperature, the smaller will be the size and weight required to yield a given power. In the conventional turbojet propulsion system, we have continually striven for the highest possible combustion-chamber exhaust temperatures for the highest efficiency. So too in aircraft reactor propulsion systems, we strive for the highest reactor coolant-outlet temperature. The high-temperature requirement of aircraft reactors introduces a myriad of specialized and difficult materials problems—materials for fuel elements and cladding, moderator, shield, coolant, and structure.

It is clear that requirements for operational reliability in an aircraft reactor system are quite different than those of stationary land plants. The aircraft reactor, of course, will hardly approach the operational lifetime of a stationary reactor. On the other hand it must be much more reliable during its shorter life span. The unfortunate consequences that may follow from power-plant or engine failure in flight are obvious. Nor are stationary reactors subjected to the acceleration and attitude changes that will impact upon aircraft reactors.

Thus it may be seen that the design and development of aircraft reactors are problems of an entirely different order of magnitude than those of stationary power reactors. The lengthy developmental program that has been under way in this country since 1946 is adequate testimony to the difficulty of the task.

Aircraft Nuclear Propulsion Office

Thrust and Power Production from Nuclear Energy

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THE ENERGY released by nuclear fission appears for the most part as kinetic energy of the fission products. It is conceptually possible to use this kinetic energy in a fairly direct manner; but in nearly every scheme that has been shown to be feasible from an engineering viewpoint, the kinetic energy released by the fission is transformed into heat energy by absorption of the fission products. In this discussion the fission reactor will be considered as a heat source from which power or thrust may be obtained by the use of some form of thermodynamic cycle.

In the sense that the reactor is a heat source in a thermodynamic system, the reactor takes the place of the combustion component in the chemical thrust or power system, but there is a basic and important difference. In the chemical system, heat is generated directly in the working gas (usually air) by the combustion process. This hot gas is then used in a thermodynamic cycle to transform the combustion-generated heat energy into either shaft power or directed kinetic energy for thrust production.

In the nuclear system, on the other hand, heat is generated by the nuclear reaction in the reactor core materials, and this heat must be *transferred* to a working fluid (liquid or gas), which may then be used in a thermodynamic cycle to produce power or thrust, much as in the chemical system. Because the fluid in question derives its heat from the reactor core, it is commonly known as a coolant. The coolant (heated fluid) may be used either directly as a working fluid in a thermodynamic cycle (direct cycle) or indirectly by a secondary transfer of heat to another fluid which is then used as the working fluid in a thermodynamic cycle (indirect cycle). Before considering in more detail some of the technical problems peculiar to nuclear systems, let us briefly consider the elements of a thermodynamic cycle in general and as applied to nuclear systems in particular.

Figure 1 shows in schematic form the elements of a direct thermodynamic cycle involving a heat engine. The box labeled "heat addition" represents the combustion process in the chemical system or the reactor in the nuclear system. The "heat engine," a turbine for example, converts heat energy to work. Since any heat engine can convert only a portion of the input heat energy into work, i.e., has a low thermal efficiency, the unused heat must be rejected or "thrown away." Finally, the pump provides the motive force for the working fluid which carries the heat energy through the cycle. Normally the pump receives its work input from the engine, which produces this in addition to the net work output of the cycle. This schematic both represents the fundamental elements of all thermodynamic cycles and illustrates what is

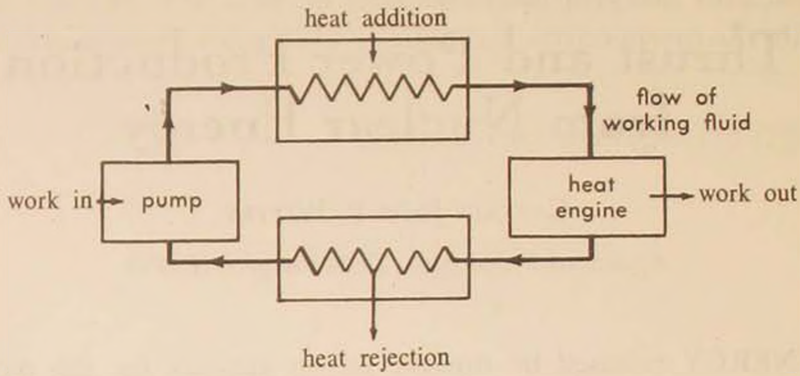

Figure 1. Basic thermodynamic cycle (the direct-cycle, closed-cycle system).

known as a closed cycle—one in which the working fluid continuously recirculates through the system.

It should be borne in mind that Figure 1 is only a schematic. Although every real cycle will embody these fundamental elements, many vari-

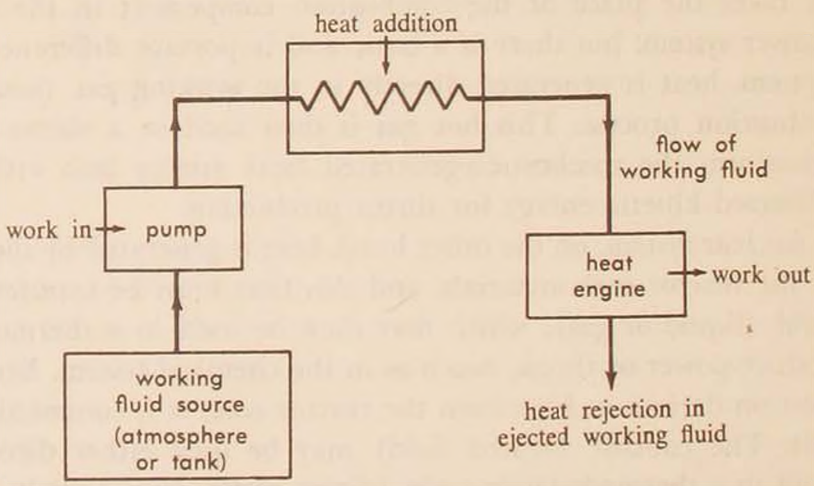

Figure 2. Open-cycle system.

ations will be found. A common variation of this basic system is the open cycle as diagramed in Figure 2. In the open cycle the working fluid, instead of continuously recirculating, is exhausted from the system, carrying the rejected heat with it. Only enough shaft work need be extracted in the engine to drive the pump; hence a smaller portion of the available heat energy is used by the engine than in the closed-cycle system. On the other hand, most of the input heat energy is used to accelerate the working fluid as it is being ejected from the system to produce thrust. In both the open and closed systems about the same proportion of the heat input to the system is "thrown away"—i.e., both have about the same thermal efficiency. The open-cycle system is typical of the turboprop and turbojet engines, the basic difference between the two being in the amount of the input energy extracted by the turbine for shaft work and the amount used to accelerate the exhaust fluid.

Another variation of the basic thermodynamic cycle is the indirect cycle. This is simply a combination of the closed and open cycles or of two closed cycles. It finds particular application in nuclear propulsion and power systems. In the indirect cycle shown in Figure 3 the reactor-generated heat is transferred by the primary coolant in a closed loop to a secondary fluid, or working fluid, in an open loop via a heat exchanger. The pump in the closed loop may be driven by the engine in the open loop, or the closed loop might contain an engine to extract sufficient energy to drive the closed-loop

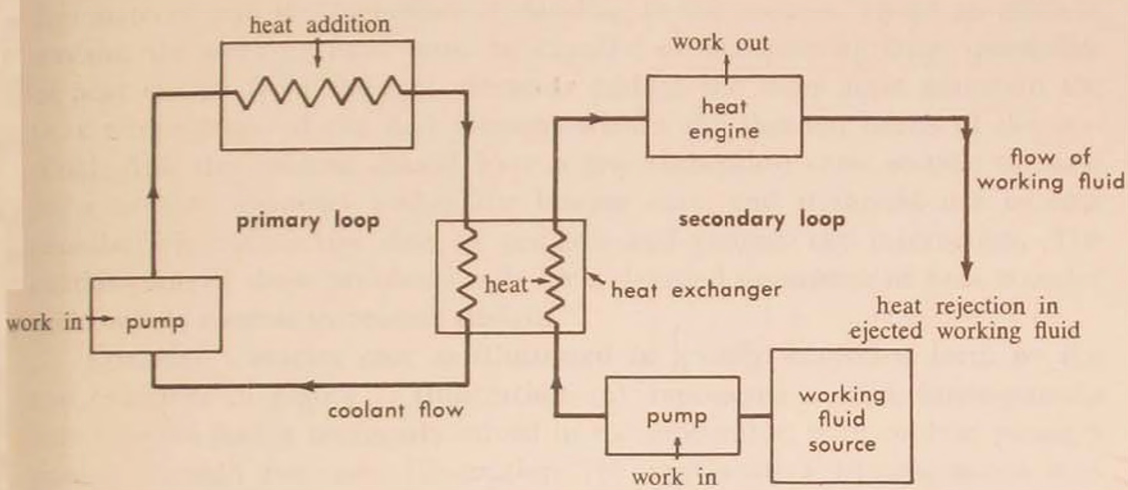

Figure 3. Indirect-cycle system.

pump. This cycle is typical of the indirect-cycle nuclear turbojet and turboprop.

In the indirect cycle embodying two closed loops, the primary loop is identical to the primary loop shown in Figure 3. The secondary loop is simply another closed loop wherein the working fluid is continuously recirculated instead of being ejected. A waste-heat rejection device such as a radiator is included, and all the work output is obtained in the form of shaft power from the engine.

Other variations and refinements of these cycles are possible. Some other forms, such as the rocket and ramjet type cycles, will be seen in subsequent sections where more specific application of these general schemes will be presented.

It is readily apparent that the utilization of reactor-generated heat in a thermodynamic cycle to produce power or thrust relies on the transfer of the heat to other system components. In a nuclear reactor the upper limit of the rate of energy release is governed not by fission considerations but by the rate at which heat can be removed from the reactor core. Hence the design of a reactor depends largely on the heat-removal aspects. For airborne reactors, where the highest possible power density (power/volume) and specific power (power/weight) are of the utmost importance, the attainment of high heat-removal rates is all the more critical.

Aircraft Nuclear Propulsion Office

Heat Transfer and Coolant Systems

Captain John P. Wittry

Advanced Propulsion Technologist, ANPO

The task of removing useful heat energy from a nuclear reactor poses several interrelated problems to the design engineer. The heat energy generated within a fuel element is transferred to the coolant by conductive and convective heat transfer. In this process the heat must pass through the fuel material and the fuel-element cladding to the coolant. To be an efficient coolant, the working fluid must be capable of transporting large quantities of heat energy from the fuel elements and at the same time maintain the peak temperature of the fuel element within the thermal limits of the material. Also the coolant should have a low absorption cross section to maximize neutron economy within the reactor core, and it should not become prohibitively radioactive due to neutron and gamma ray interaction. The combination of these problems calls for a detailed discussion of heat transfer and coolant systems in reactor design.

Consider a reactor core as illustrated in greatly simplified form by the two examples in Figure 1. Illustration (a) represents a solid, homogeneous core wherein fuel is uniformly mixed in the moderator, with coolant passages passing through the core. Illustration (b) represents a heterogeneous core

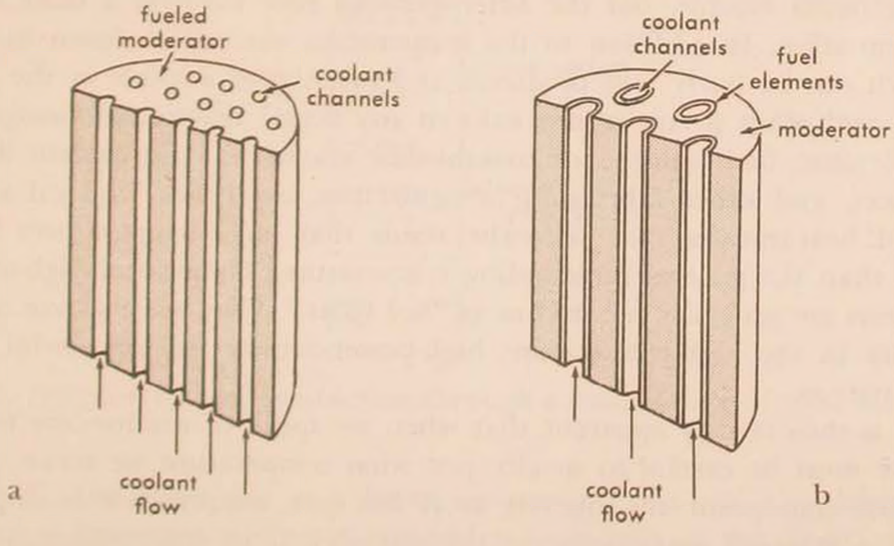

Figure 1. Two types of reactor cores: (a) half section of a solid, homogeneous core showing the coolant channels through the core; (b) half section of a heterogeneous core having hollow-rod fuel elements through which the coolant flows.

wherein the fuel is contained in discrete elements placed in a regular pattern within the moderator volume. In the latter illustration the fuel elements are shown as hollow rods, with the coolant flowing through the center of the fuel elements. Various configurations are possible. A previous chapter has shown how the temperature profile varies both longitudinally and radially within the reactor because of the geometrically nonuniform manner in which the nuclear energy generation takes place within the reactor core. The presence in the core of the coolant passages causes further perturbations in the pattern of heat generation, since these passages represent voids in the nuclear reaction process.

Figure 2, showing a smaller section of the reactor core in the immediate neighborhood of two coolant channels, illustrates the temperature depression within the core itself near the channels, as well as the temperature drop across

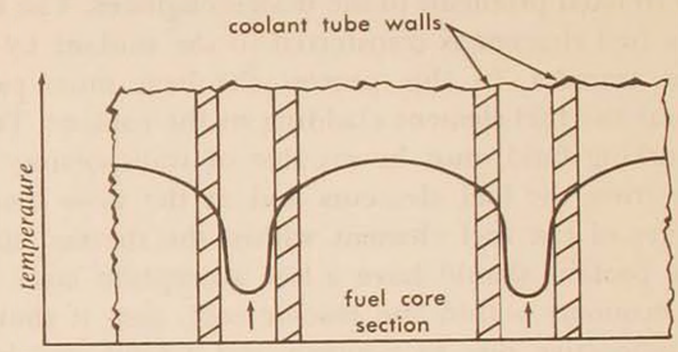

Figure 2. Temperature profile across coolant channels.

the coolant-tube walls, the wall-coolant interface, and within the coolant itself. This illustration represents the solid, homogeneous core. The heat-transfer processes discussed here are applicable as well to the more common heterogeneous reactor, but the heterogeneous core involves a more complicated situation. In addition to the temperature variations shown in Figure 2, which can be fairly well predicted and taken into account in the reactor design, still other perturbations exist in any actual reactor. Inhomogeneities in moderator, fuel element, or coolant-tube materials, local coolant flow disturbances, and other fabrication irregularities can result in local areas of reduced heat-transfer rate, with the result that local temperatures become higher than the general surrounding temperature. These local high-temperature areas are generally referred to as "hot spots." They are a source of much difficulty in the high-temperature, high-power-density reactors useful in airborne systems.

It is thus readily apparent that when we speak of reactor-core temperature we must be careful to specify just what temperature we mean. From a materials standpoint the highest local hot-spot temperature is important, since the material must maintain the integrity of its composition, strength, and geometry at all points in the reactor. From the system performance standpoint the average bulk temperature of the coolant leaving the reactor is of paramount interest, since it is this temperature that represents the energy input into the power conversion system or thrust-producing device.

It is of utmost importance that the difference between the maximum hot-spot temperature in the reactor and the maximum average fuel-element temperature be minimized so as to take advantage of the full potential of the reactor as a heat source. Otherwise the total heat energy actually removed from the reactor must be cut down to allow for hot spots without locally exceeding materials limitations. This temperature differential between the maximum hot-spot temperature and the maximum average fuel-element temperature sometimes exceeds 100°F. Unfortunately the location and severity of hot spots are not entirely predictable in the design stage, and a certain amount of experimentation with different conditions of coolant flow rate, pressure, etc., may be necessary to evaluate the problem.

Since heat extraction from a reactor core involves the processes of conduction and convection, let us examine these processes to identify the factors that are important in the design of a reactor from the point of view of heat transfer.

heat transfer by conduction

Heat conduction refers to the transfer of heat from one place to another by molecular contact without any accompanying displacement of matter. Flow of heat within solid bodies takes place exclusively by this process. The flow of heat by conduction is governed by the Fourier equation:

$$q = A\,(T_1 - T_2)\,k/L$$

where q is the heat flux or amount of heat conducted per unit time through a plane of area A between two points at temperatures T_1 and T_2 at a distance L apart. Figure 3 illustrates these parameters with a cross section of a slab of solid material whose thickness is L. One side of the slab is at tem-

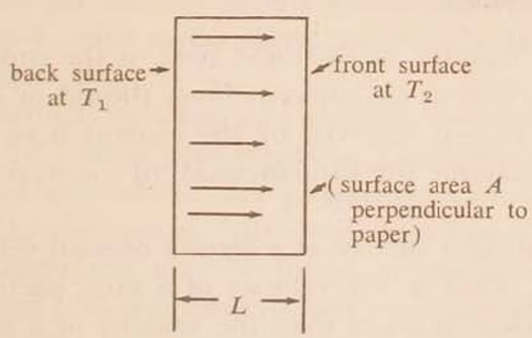

Figure 3. Diagram of heat conduction through a cross section of solid material.

perature T_1, the other side at a lower temperature T_2, and the slab's area is A. Since a temperature drop is assumed to exist only in the direction normal to the surface of the slab in this illustration, heat will flow only in this direction. The Fourier equation clearly indicates that heat will flow only from a higher to a lower temperature. The same equation holds true between any two planes within the slab, and also between any two points at different temperatures. The important thing here is that the rate of heat transfer q within the material for any given configuration is dependent on the temperature difference between the points in question and the thermal conductivity k of the material. The thermal conductivity is a function of the material, metals having the highest values, followed by metal alloys, nonmetallic solids, liquids, and gases in that order. Iron, for example, has a thermal conductivity of about 30 Btu/hr-ft-°F, and that of copper is about six times higher. Stainless steel, an iron alloy, has a conductivity value of about 9. Nonmetallic solids (including ceramics) have thermal conductivities in the range 0.03 to 2. Liquids range from about 0.06 to 0.3. Gases have values about one tenth those of liquids.

Conduction heat transfer is applicable primarily within the solid portions of the reactor core, since it is by conduction that the heat flows from the many source points within the fueled solid to the surface where it can be removed by the coolant. If the thermal conductivity of the solid material is low, the interior of the material will tend to be much hotter than the surface, since the heat generated within the fueled material cannot flow rapidly to the surface for removal. High thermal gradients within the fueled material cause high thermal stresses across the material; and unfortunately those solid materials with lowest thermal conductivity, and therefore high thermal stresses, are the materials that can least tolerate high thermal stresses. Metals, which conduct heat so readily that there is relatively little temperature difference between the interior and exterior, are limited in upper temperature tolerance, and, generally speaking, those metals which can tolerate high temperature are deficient in nuclear characteristics. Compromises must be made in reactor design, as in any engineering design.

heat transfer by convection

Convection heat transfer, as discussed here, is the process by which heat flows from a solid surface to an adjacent fluid (liquid or gas). Since it is by this process that the heat is removed by the coolant from the surface of the fuel element, let us examine the fundamentals of convection much as we did those of conduction.

A fluid flowing along a surface at a certain over-all velocity has a varying velocity cross section. That is, the velocity of a fluid particle at a very short distance from the surface is lower than the velocity of a particle well within the fluid. In fact, the fluid particles immediately adjacent to the surface have zero velocity. The portion of the fluid with a changing velocity profile forms the so-called boundary layer. The exact shape and thickness of this boundary layer depend on many factors, including the over-all velocity of the fluid, the configuration of the passage through which the fluid flows, the nature of the wall, and even the distance along the surface in the flow direction. We will not discuss these factors in any detail. Suffice to say that a new equation using the boundary-layer thickness can be written to describe convection heat transfer:

$$q = (k/d)\, A\, (T_w - T_f) = hA\, (T_w - T_f)$$

The term k/d is generally replaced by h and called the film heat-transfer coefficient.

Figure 4 illustrates the temperature variation across the boundary layer between the solid surface and the body of the fluid outside the boundary layer. It should be pointed out that the temperature variation shown here is

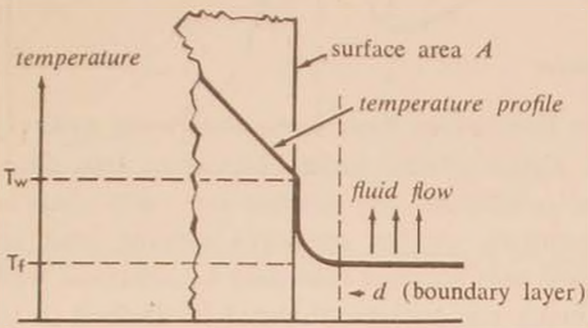

Figure 4. Profile of temperature variation across the boundary layer.

purely illustrative and that the actual variation in any given case may be considerably different from that shown, particularly in flow through a tube, where the boundary layer may have no definable limit.

Obviously the value of the film coefficient is a function both of the thermal conductivity of the fluid and of all the intricate factors that determine the nature of the boundary layer. For this reason no value of h can be listed for any fluid except under exact, particular circumstances. Those materials having high thermal conductivity will also exhibit the higher values of film coefficient. Recall that the metals (including liquid metals) have the highest conductivity k, with metal alloys, nonmetals, liquids, and gases following in that order.

The coolant channels in a reactor, whether homogeneous or heterogeneous, may have any of several configurations. Considering a tubular channel as a typical case, let us examine the parameters contributing to the value of h for tube flow. In the case of fully developed flow through a tube, equations for the film coefficient may be found on the basis of boundary-layer theory by using certain idealistic assumptions, and experimentation has tended to confirm these equations reasonably well. For fully developed laminar flow, h turns out to be a function simply of k and the tube diameter.

For turbulent flow, which almost always exists in a power reactor and results in substantially higher heat-transfer rates than for laminar flow, the situation is far more complicated. The film coefficient is dependent on the fluid mean velocity, density, viscosity, specific heat, and other factors, in addition to the thermal conductivity and tube diameter. There would be little point in setting down any equation here for the film coefficient in turbulent flow, since in practice no single equation is applicable for all types of coolants or for all values of the parameters.

In any design problem, the available equations may be applied for an approximate solution, but the true heat-transfer values may best be found by experimentation. The equations do indicate that a high value of the film coefficient requires high fluid thermal conductivity, specific heat, density, viscosity, and velocity and small tube diameter. It is particularly important that the fluid specific heat, density, and thermal conductivity be high so that the fluid velocity may be kept lower to reduce the pumping power required by the system.

boiling heat transfer

The previous discussions have been concerned entirely with heat transfer to coolants in a single phase, either liquid or gas, throughout the reactor core. Under these conditions the coolant can carry away a certain amount of heat energy, depending on the coolant's specific heat and other factors. A substantially higher heat-transfer rate may be achieved within the reactor core if the liquid entering the coolant channel is allowed to boil, thereby making use of its latent heat of vaporization to absorb even more heat energy. A considerable amount of knowledge and experience has been attained with boiling water in a reactor, but for the high-power-density airborne reactors of interest here, boiling liquid metals are far more attractive. Boiling is also important in a two-loop system, which uses a single-phase (most likely liquid) coolant in the reactor core and transfers the heat energy of this primary coolant to a secondary fluid that changes phase in a boiler. This latter approach is somewhat easier than boiling directly in the reactor, since the boiling is separated from the already intricate core design problem.

In ordinary boiling of a pool of liquid, evaporation occurs at the free surface without the formation of bubbles when the heating-surface temperature (T_w) is only a few degrees above the saturation temperature or boiling temperature (T_{sat}) of the liquid. Then as $T_w - T_{sat}$ is increased, vapor bubbles form in the vicinity of the heating surface, agitate the liquid, and rise to break through the surface. This type of boiling is called nucleate boiling. Eventually, as $T_w - T_{sat}$ is further increased, the amount of heating surface covered with bubbles increases until the entire surface becomes "vapor blanketed," resulting in a process called film boiling. The heat-transfer rate associated with nucleate boiling is very high because the bubbles agitate the fluid near the heating surface. The heat-transfer rate associated with film boiling is much lower because of the insulating effect of the vapor film.

These processes can be described qualitatively and compared to single-phase convection heat transfer with the aid of Figure 5. While the model is not strictly accurate for boiling in a tube, the processes involved are similar. Since T_{sat} is a fixed value for a given fluid at a given pressure, the quantity $T_w - T_{sat}$ expresses the amount by which the heating-surface temperature exceeds the coolant temperature. The quantity q/A is the heat-transfer rate per unit area. In region I, single-phase convection heat transfer takes place, and the heat-transfer rate is seen to be almost directly proportional to the temperature difference, as would be expected. In region II, nucleate boiling takes place, and the heat-transfer rate increases very rapidly with increase in heating-surface temperature until a peak value is reached

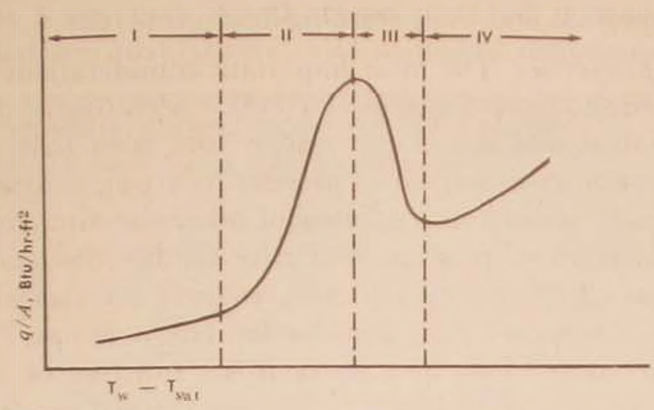

Figure 5. Characteristic curve for pool boiling within a reactor.

where partial film boiling commences. Region III, where partial film boiling takes place, shows a rapid decline in the heat-transfer rate. Region IV shows another increase because the heating-surface temperature has reached a high enough point that direct heat radiation from the surface to the fluid comes into play. It may be seen that the peak heat-transfer rate achieved at the boundary of regions II and III would again be achieved somewhere in region IV, but only at a much higher heating-surface temperature. Most existing boilers operate at a very low point on the curve in region II, whereas it would be desirable to operate near the peak of the curve, allowing only enough margin to account for instabilities and local perturbations. Region III must be avoided, since it is unstable—i.e., an increase of surface temperature decreases the heat-transfer rate, which causes a further increase in the surface temperature. This situation would quickly lead to heating-surface meltdown.

The successful accomplishment of boiling within a reactor makes possible a reduction in core size, at least insofar as heat-transfer considerations dictate the design. The higher q/A can be made, the less heat-transfer surface A need be provided, leading to a compact core and high power density. On the other hand, boiling within the core calls for substantially higher fuel-element temperatures than single-phase convection, as can be clearly seen from Figure 5.

reactor coolants

The foregoing discussion presented a basic picture of the processes involved in removing the heat energy generated in a reactor and of the desirable thermal properties and characteristics of coolants involved in its transfer. But the thermal properties are only one criterion out of many involved in the selection of a coolant. Now let us consider coolant materials in general, pointing out some of the many characteristics they must possess and the advantages and disadvantages of certain possible coolants in use.

An evaluation of coolants for reactor systems must consider their nuclear properties, their heat-transfer properties, their availability and cost, their corrosion properties, and their working-fluid properties.

Nuclear properties. The most important considerations in nuclear properties are neutron-absorption cross section, moderating ability, and induced activity. A coolant material in the reactor core must have a sufficiently low neutron-absorption cross section to prevent its acting as a poison in the core. This factor tends to exclude a number of otherwise attractive materials from use in thermal reactors. It is less restrictive for fast reactors, since many materials that have high absorption cross sections for thermal neutrons have relatively low absorption cross sections for fast neutrons.

The moderating ability of a material is a function of its scattering cross section and is not too restrictive a factor. For thermal reactors a coolant with good moderating ability is desirable, but this factor is secondary in importance to absorption characteristics.

The radioactivity induced in a fluid is important primarily in an operational sense. If coolant becomes highly activated by the neutron bombardment that it undergoes in passing through the core, then the entire loop through which the coolant flows must be shielded. Otherwise a high level of nuclear radiation will emanate from all parts of the loop. In a two-loop system, the primary-loop coolant may become activated, but the secondary-loop fluid will not be activated by the fluid in the primary loop. The significance of the type of induced radiation is in the amount and type of shielding required for the primary coolant. Alpha and beta radiation can be absorbed by light shielding, but very dense material such as lead is required against gamma radiation.

Heat-transfer properties. The previous sections on heat transfer have pointed out the required heat-transfer properties of a coolant, the most important of which are the thermal conductivity and specific heat, c_p, or heat capacity of the fluid. Another parameter useful for comparing coolants from a heat-transfer point of view is ρc_p, the product of the density and specific heat. The relation of the total heat-release rate of the reactor, q, to the total mass flow rate of the coolant w, the fluid specific heat c_p, and the coolant mean temperature rise through the reactor, ΔT_c, is $q = wc_p\Delta T_c$. The term w may be replaced by $v\rho A_f$, where v is the coolant flow rate and A_f is the total flow area, so that $q = \rho c_p v A_f \Delta T_c$. Hence for a given coolant flow rate, total flow area (reactor void fraction), and coolant temperature rise through the reactor, the parameter ρc_p (called volumetric heat capacity) is indicative of the heat-transfer rate attainable with a given coolant. A high volumetric heat capacity will allow lower temperature rise ΔT_c (for thermal stress reasons), lower flow area A_f (to reduce the reactor void fraction), and lower coolant flow rate (to reduce pressure loss and pumping power requirements) for a given heat-transfer rate q.

The accompanying table shows the major heat-transfer characteristics of several possible reactor coolants. These properties are temperature-dependent and in the case of gases are pressure-dependent as well, so that direct comparisons are somewhat difficult. The properties are presented with reference to dry air as an arbitrary standard and must be considered only approximate values. Even though the temperature of 1000°F chosen for presentation of the data is somewhat lower than actual temperatures of interest, the relative standings indicated are qualitatively valid at higher temperatures as well.

Heat-Transfer Properties of Coolants
1000°F and 1 Atmosphere Pressure

Material	Thermal Conductivity k/k_{air}	Specific Heat $c_p/c_{p\,air}$	Density ρ/ρ_{air}	Volumetric Heat Capacity $\rho c_p/\rho c_{p\,air}$
Dry air	1.0	1.0	1.0	1.0
Helium	5.7	4.7	0.15	0.67
Sodium	1280	1.15	1890	2170
Sodium-potassium	560	0.94	1800	1690
Lithium		3.7	1110	4100

Availability and cost. There are a number of materials, particularly certain isotopes, that would be very attractive as coolants were it not for their scarcity or difficulty of manufacture in usable quantities. Isotopes must be separated from the natural material. While cost is generally subordinated to good performance in military systems, it is a factor that must be considered.

Corrosion properties. One of the most important and troublesome characteristics of coolant fluids is their tendency to be incompatible with other materials. Corrosion involves chemical interaction, including oxidation, between two or more materials in the reactor system. It is a particularly troublesome problem in airborne reactor systems because of the high operating temperatures which stimulate chemical interaction between materials that would be relatively compatible at low temperatures. In direct-air-cycle systems, such as the ramjet and direct-cycle turbojet systems, where air is in direct contact with the hot elements of the reactor core, oxidation is the biggest problem and further limits the choice of materials usable as fuel elements, moderators, and construction parts. Oxidation of these materials leads to loss of their structural integrity.

With closed-loop systems, in which liquid metals are commonly used as coolants, mass transfer is one of the biggest difficulties. Any coolant flows through both very hot and relatively cool portions of the system. In the process it is likely to corrode the hotter elements of the system and carry off bits of material loosened by the corrosion. The coolant will then carry these stray particles to the cooler portions of the system, where they tend to be redeposited. Since the cooler portions of the system where the deposit occurs are likely to be the small passages in the heat exchanger, any extensive mass transfer tends to plug the system and cause severe performance loss. Pumps and fluid-lubricated bearings are likely to suffer as well. It is extremely important, then, that fuel-element cladding, coolant piping, etc., be of a material that can withstand the chemical attack of the coolant at high temperature.

In the indirect-cycle turbojet system another variation of the corrosion problem exists. The primary system, cooled by liquid metal, is beset by the corrosion and mass transfer associated with liquid metals, and in addition the heat exchanger that transfers the heat energy to the airstream is subject to oxidation on its exterior surfaces. The heat exchanger must be constructed of a material that will withstand both the liquid-metal attack on its interior surfaces and the oxidation attack by the airstream on its outer surfaces. Few materials are capable of satisfying this requirement at very high temperatures. Various techniques have been proposed as solutions, such as cladding a metal suitable for liquid-metal containment with a material that is oxidation-resistant. The intricate construction of heat exchangers makes such approaches extremely difficult and costly on a practical scale. One of the major advantages of a helium-cooled system is the inertness of helium gas, which practically eliminates the corrosion problem in the primary loop. But helium has shortcomings in other respects as a heat-transfer medium and also requires extremely high pumping power.

The problems encountered with corrosion have made necessary extensive research on materials to raise the temperature limitations for reactor application. Significant progress has been made, particularly with liquid-metal systems using materials about which little was previously known.

Working-fluid properties. The fluid properties previously discussed are concerned primarily with the fluid as a reactor coolant. Because very few fluids are suitable both as reactor coolants and as engine working fluids, the two-loop system with its intermediate heat exchanger is utilized. Ideally a single-loop system would be preferable, if a single fluid could fully qualify as both reactor coolant and working fluid. The direct-air-cycle turbojet and ramjet systems under development are notable examples of the single-fluid approach. There it is employed for the sake of "simplicity," even though air is not a particularly good reactor coolant and requires large reactor-core volumes that are difficult to shield. Certain liquid metals can be used in the vapor phase in turbines to extract power, and these metals can be vaporized in a boiler in a two-loop system. A single-loop, liquid-metal system, however, requires boiling in the reactor core. The dual sets of property requirements impose even further limitations on available coolant materials and in general require extensive acquisition of new knowledge of the physical and thermal properties in the high-temperature regime as well as development of techniques for manufacturing these very specialized materials.

THIS explanation of cycles, heat transfer, and coolants has attempted to point out some of the basic considerations in design of a reactor system. It should be apparent that the choice of a particular design approach for any application is never clearly confined to a single avenue. Each different application weighs the various requirements and properties differently. Each particular application allows various approaches in type of reactor, thermodynamic cycle, and coolant and heat-transfer method.

Aircraft Nuclear Propulsion Office

Reactor Materials

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ALL TYPES of aerial nuclear propulsion systems, whether rocket, ramjet, or turbojet, have the basic requirement of heating the discharge gases to the highest possible temperatures. This requirement stems from the necessity to have energy sources of small volume and low weight. In this respect nuclear propulsion imposes materials problems considerably more severe than those imposed by chemical systems.

A fundamental difference in the release of energy can impose quite different requirements on materials. In a chemically fueled engine energy is released by a chemical reaction between the various gas molecules that raises the temperature by increasing the kinetic energy of the combustion products. While the temperature of the combustion products may be from 2500 to 3000°C, the temperature of the combustion-chamber wall is maintained below 1000°C by passing cooling air through it and preventing the combustion products from coming in contact with it. Conversely, in a nuclear engine the energy is released within a solid body, whence it must be transferred to the gas. Since heat (energy) flows only from a hot body to a cooler one, it is necessary to provide a "combustion chamber" with walls at operating temperatures several hundred degrees higher than the discharge gas. It is readily apparent, then, that one of the most vital requisites to developing nuclear-powered aircraft and missiles is the attainment of high-temperature materials with properties that do not deteriorate over long periods in extreme thermal environments.

From the very beginning of the aircraft nuclear propulsion program, technologists have been faced with many new and trying materials problems. The design engineer has found that presently available metal alloys fall short of meeting many of the high-temperature requirements. Considerations such as corrosion resistance, erosion resistance, and high-temperature strength have imposed limitations on the types of materials that can be utilized. Materials are available today that will satisfy these limitations. But it would be little gain to use them, either separately or in combination (as in cladding a low-strength, highly oxidation-resistant material over a high-strength, good-nuclear-heat-transfer type of material), if they cannot be formed into the desired shapes and with very close tolerances. The materials must offer some quality of workability and ease of fabrication.

To the usual physical and chemical properties desired in high-temperature materials the nuclear reaction adds a new criterion—nuclear properties. Since the combination of physical, chemical, and nuclear properties required for reactor use has been found only in unusual materials or in certain exceedingly pure common materials, continuous research has been necessary in purification, separation, and evaluation of these "rare" items, and methods have been constantly sought for producing commercial quantities of exceptionally pure elements and compounds. The reactor materials problem has resolved itself into an involved struggle to overcome the deficiencies of common materials and to uncover new and more suitable materials.

Although all materials used in a reactor system must meet the basic requirements of adequate strength, corrosion resistance, and dimensional stability, each component of the reactor poses its own special materials problems. The materials required for reactor construction may be classified according to their particular function: fuel, moderator and reflector, structure and cladding, coolant, and shield.

fuel materials

The basic premise of a nuclear-fuel material is that it contains at least one of the fissionable species: uranium-233, uranium-235, or plutonium-239. From the nuclear viewpoint it matters not in which form the fissionable material is present—as a metal, an alloy, an intermetallic compound, or a chemical compound. The form is determined by particular reactor conditions, such as operating temperature, environment, required strength, and operating lifetime. Metallic fuels can be used for low-temperature applications, with suitable claddings for oxidation protection. As the desired operating temperature is increased, one must start looking at combinations of fuel and other materials, keeping always in mind that when gains are made in obtaining some of the desired high-temperature properties other properties usually decline.

The properties of metallic fuels can be enhanced to a degree by the formation of alloys, in particular those of zirconium, titanium, niobium, and

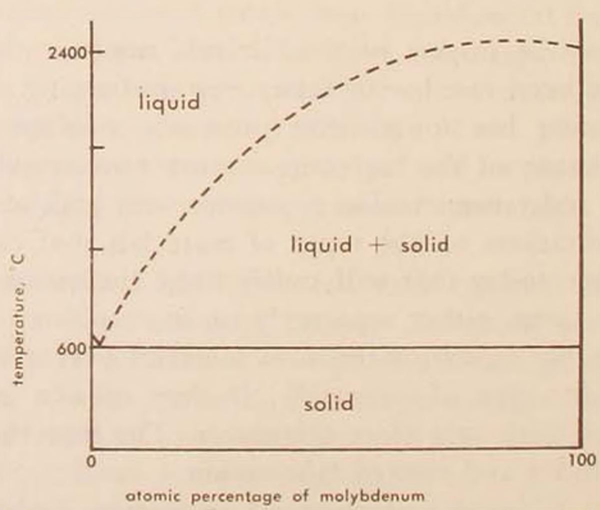

Figure 1. Formation of plutonium-molybdenum phase (a metallic fuel and metal alloy). A bimetal system in which each of the metals is completely soluble in the other admits selection of an alloy in any desired proportion of the two metals.

molybdenum. These elements show an appreciable solid solubility with fuel material, improving both the mechanical properties and corrosion resistance of the combination at elevated temperatures. Unfortunately alloying also requires additional fissionable material to compensate for the loss of neutrons through capture by the alloying material. Phase diagrams resulting from fundamental studies on various fuel-material alloy systems have pointed out that other metallic elements, such as aluminum and beryllium, form chemical compounds called intermetallic compounds. These are characterized on phase diagrams by having a higher melting temperature than either of the constituents or their adjacent alloys. (See chart illustrating the formation of $PuBe_{13}$.) Intermetallic compounds generally exhibit good physical and me-

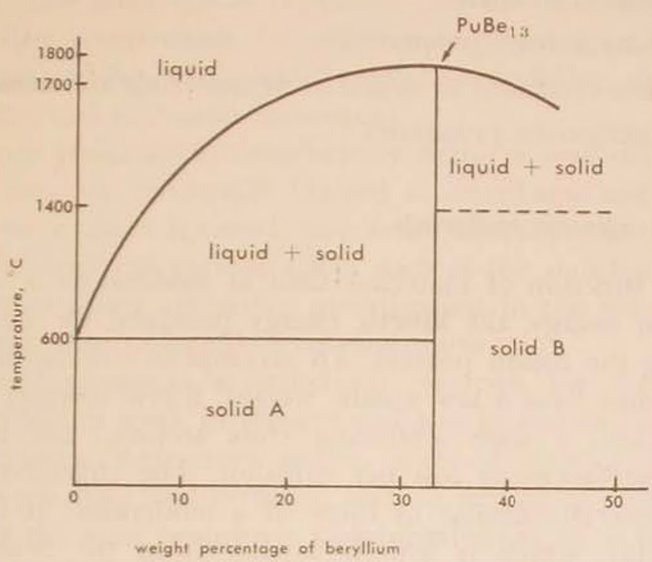

Figure 2. Formation of plutonium-beryllium phase (intermetallic compound $PuBe_{13}$). Intermetallic compounds are two metals that combine in stoichiometric ratios to form chemical compounds. These compounds exhibit characteristics (as, higher melting temperature) that are considerably different from those exhibited by alloys of the same metals. $PuBe_{13}$, for example, has a melting temperature of 1700°C, but alloys composed of lesser amounts of Be (solid A) commence melting at 600°C and alloys composed of greater amounts of Be (solid B) commence melting at 1400°C.

chanical properties and oxidation resistance at high temperature but are very hard and brittle at room temperature. This presents a formidable problem for fabrication.

Ceramics start to appear attractive for the highest-temperature applications. This family of materials includes the carbides, the nitrides, the oxides, and graphite. Although at first the ceramics would seem quite promising because of their high melting temperatures and good corrosion resistance, they have several serious disadvantages. They have low thermal conductivities compared to metals, are brittle and hard, cannot be machined or welded, are very weak in tension, and in general exhibit poor radiation-damage resistance and fission-fragment retention. To preserve the good ductility and mechanical properties of metals while obtaining the refractoriness of ceramics, investigations have been carried out on mixtures of ceramics and metals. The resultant new materials are known as cermets. Cermets are being investigated for use both as a coating material and as a homogeneous material.

Regardless of what type material is used for the fuel element of the reactor or in what desired operating-temperature regime the element will be used, fuel materials must meet certain demands:

- good nuclear characteristics
- adequate mechanical properties under the most adverse conditions of temperature, external loading, irradiation, and burnup
- dimensional stability
- good heat-transfer properties
- corrosion resistance to neighboring materials and atmospheres
- good fabrication properties

moderator and reflector materials

The basic function of materials used as moderators is the rapid reduction of neutron energy, the kinetic energy possessed by the neutrons when released during the fission process. To accomplish this function, the moderator material must have a low atomic weight, a low thermal neutron-absorption cross section, a high scattering cross section, and a large average logarithmic neutron-energy loss per collision. The characteristics of a good reflector are generally similar to those of a moderator. It should be noted that the reflector, which is usually farther from the heat-producing fuel material than the moderators, may operate in a lower-temperature region. In some instances the moderator is mixed with the fuel in the fuel elements to form a somewhat homogeneous solid-fuel reactor, and the moderator therefore attains the same temperature as the operating temperature of the fuel.

Under the foregoing list of conditions, the elements that are of most interest are hydrogen, beryllium, carbon, and oxygen. In the temperature region of interest for nuclear propulsion, beryllium and carbon are the only good elemental solid moderators. The metal hydrides lend themselves as moderators in the low end of the temperature spectrum, but they exhibit considerable room-temperature brittleness and undergo solid-state phase changes accompanied by hydrogen rejection when the temperature is raised. In general, hydrides must be contained by some material impervious to hydrogen, must be able to withstand various internal pressures, and must produce a good metal-to-metal bond with the container material for easy heat removal. Intermetallic compounds of beryllium look promising for the intermediate-temperature region, but they exhibit the undesirable properties of intermetallic compounds previously mentioned. Refractory ceramics such as beryllium oxide, beryllium carbide, and graphite are favored for the higher-temperature regions.

In addition to the nuclear requirements for moderator and reflector materials, they must also possess adequate strength, thermal stability, amenability to fabrication, corrosion and radiation resistance, and good heat-transfer properties.

structural and cladding materials

The absolute requirement for any reactor structural material is that its capture cross section must be low enough to avoid a reduction of the criticality factor of the reactor below unity. Reactor structural materials serve a dual purpose. They must provide a mechanical framework for holding the reactor components in their proper positions under both dynamic and static conditions, and they must act as containers for the fuel, fission fragments, coolants, and other components. In addition to the desired nuclear characteristics they must exhibit adequate strength, fabricability, thermal stability, radiation stability, and corrosion resistance.

The elements available for moderately high-temperature structural use in thermal reactors are essentially limited to beryllium and zirconium. As the operating temperature is raised, one must take a penalty in the desired nuclear properties and use various alloys such as the stainless steels and the nickel alloys. Other alloys are under investigation in the search for strength and corrosion resistance to liquid-metal environments.
are the only good prospects as structural elements for the very-high-tem-
Ceramics, although weak in tension and low in thermal shock resistance, perature applications. Refractory oxides, such as beryllia, silica, and zirconia, as well as graphite and carbides, such as zirconium carbide and beryllium carbide, are the most promising. Combinations of these various ceramics are also being investigated for improved properties.

The same material may be used for many purposes in a reactor. Beryllium oxide, for instance, can function as a moderator mixed with a fuel ceramic and also provide structural support. Since the number of materials available for use in a reactor at a particular operating temperature is limited, the complexity of design is increased by the compromises that must be made in selection. It becomes very difficult to categorize materials for only structural or cladding use.

coolants

Most of the energy liberated in fission appears as heat and must be extracted from the reactor in order to be useful and to prevent the melting of various reactor components. It is especially imperative that an adequate cooling system be employed in the high-heat, high-power-density reactors being considered for aircraft propulsion. A good coolant should possess certain characteristics: good thermal properties, a high boiling point and low melting point, thermal and radiation stability, low neutron-capture cross section, suitable corrosion characteristics in a given system, and low pumping-power requirements. Liquid metals, such as sodium, mercury, sodium-potassium alloys, and lithium, have many of the desired properties but are corrosive. The compatibility of liquid metals with their containers also presents a difficult problem associating solubility, formulation of intermetallic compounds, and erosion. Sodium or sodium-potassium alloys can be used up to about 800°C with some of the stainless steels and nickel alloys. Leaks must be avoided because of the fire hazard and the rapid attack on the liquid metal by oxygen at these temperatures. Higher-temperature applications yet require research for suitable container materials that can present an inner surface inert to the catastrophic effects of the liquid metals and an oxidation-resistant outer surface to the air.

Because of their low density, the high pumping power they require, and their generally inferior heat-transfer properties, gases are being considered for the coolant only in applications that transfer the heat generated in the fuel elements directly to the working fluid. When an oxidizing atmosphere or air is involved, care must be exercised in the selection of the other reactor materials. In air at high operating temperatures the use of graphite is prohibitive and other coolants such as hydrogen or hydrocarbons must be used.

The coolant materials are directly concerned with the container materials, and their investigation must be accomplished jointly.

shielding material

The basic requirements for a good shielding material are good moderating properties to slow down the neutrons, a high neutron-capture cross section, and high density to attenuate gamma radiation. To meet these diverse requirements, several materials, each providing one of the necessary properties, are used together in the construction of a shield. Heavy metal hydrides combine most of the essential properties and would be ideal but for their thermal instability. Lead, tungsten, depleted uranium, and tantalum are of interest for gamma attenuation, but they oxidize readily in air and must be protected at elevated temperatures. The prohibitive cost of the required quantities precludes the use of several of the rare earths with their very desirable neutron-capture ability. It appears that the greatest gain in shielding technology lies in improved configuration design that takes fullest advantage of present material properties. Considerable emphasis is being placed upon this aspect of the problem.

Aircraft Nuclear Propulsion Office

The Shield

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Nuclear propulsion for flight has introduced aircraft and aircraft-engine designers to many new and varied problems. One of the most formidable is shielding. This discussion considers why a shield is necessary, why it is a problem, and what is being done to resolve the problem.

Why a Shield Is Necessary

Each fission in a reactor liberates approximately 200 mev of energy. Most of this is manifest as heat in the immediate vicinity of the event. However, 10 per cent or so of this energy is carried away by neutrons and gamma rays, which are very difficult to stop. This radiation will kill a human being or damage a piece of equipment to the point that it will not perform its function. If people and equipment are to work in the vicinity of a reactor, then, a shield is needed to attenuate this penetrating radiation to a harmless level.

As Figure 1 illustrates, every fission of a U^{235} nucleus liberates from 1 to 3 neutrons. For simplicity let us assume that 5 fast neutrons are generated for every pair of fission events and that 5 gammas are emitted for each fission with energy of 2 mev. These assumptions are for sake of illustration and do

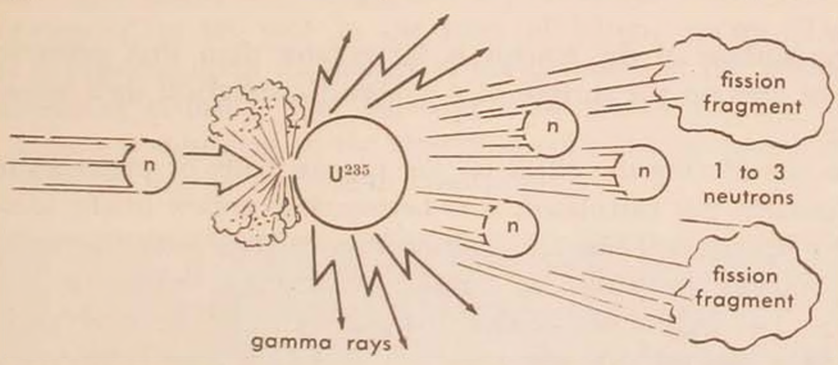


Figure 1. The fission reaction of uranium-235.

not truly represent the situation. Actually the prompt neutrons released by fission cover a spectrum of energy. The gammas also cover a range of energies, and the radiation scheme from fission is very complex. For each watt of reactor power, there are 3×10^{10} fissions per second. Thus a 100-megawatt aircraft reactor will generate 7×10^{18} neutrons per second. Unfortunately it is impossible to keep all these neutrons in the core lattice where they would be most useful for continuing the fission reaction. If 10% of them leak from the core, the flux at a distance of 20 meters (66 feet), treating the reactor as a point source, becomes $\frac{7 \times 10^{18}}{4\pi (2 \times 10^3)^2}$ or 1.4×10^{10} neutrons per cm² per second. The gamma flux at 20 meters, assuming a leakage of 40%, is $(2/5)\ (5)\ (3 \times 10^{18})\ (1/4\pi\ 4 \times 10^6)$ or 1.2×10^{11} gammas per cm² per second. The neutrons and gammas emitted are as likely to leave in one direction as another. In a medium such as air the motion of these radiations may be assumed to be straight-line, and this accounts for the geometry factor $(1/4\pi r^2)$ in the above expressions. Figure 2 illustrates this inverse-square spreading effect of radiation. The quantity of rays penetrating a unit of

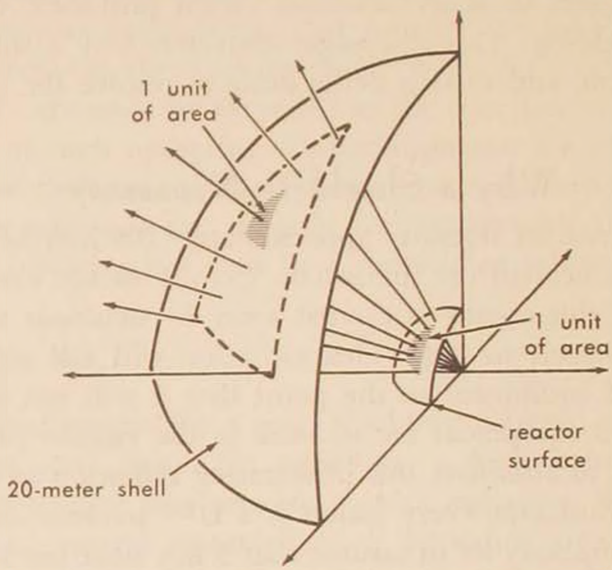


Figure 2. The inverse-square spreading of radiation from a point source.

area on the surface of the reactor is far greater than that penetrating the same unit of area on the surface of a concentric spherical shell whose radius is 20 meters.

Before considering the effect on the human body or materials of a flux of the magnitude just calculated, it is necessary to review briefly some of the processes by which neutrons and gamma rays interact with matter.

Fast neutrons slow down as a result of elastic or billiard-ball collisions with nuclei. The lighter the nuclei, the more energy the neutron loses per collision. As a general rule neutrons are absorbed more readily when they are at low energy; consequently the moderating process is instrumental to neutron removal. Other neutron interactions have been covered in detail in the section on the reactor core.

Gamma rays lose their energy through collisions with electrons. The principal processes are photoelectric and Compton effects and pair production. These interactions are illustrated schematically in Figure 3.

- In the photoelectric phenomenon, a gamma photon hits an orbital electron and transfers all its energy to the particle. A specific amount of the photon's energy is required to remove the electron from the field of the atom.

Whatever energy the photon carries in excess of this amount is manifest in the form of electron kinetic energy.

• The photon, a quantum of energy, behaves like a solid particle for the Compton effect, experiencing a billiard-ball collision with an electron. It is possible to predict the direction of the recoil electron and the change in wave length (loss of energy) of the scattered photon through application of the laws of conservation of energy and momentum.

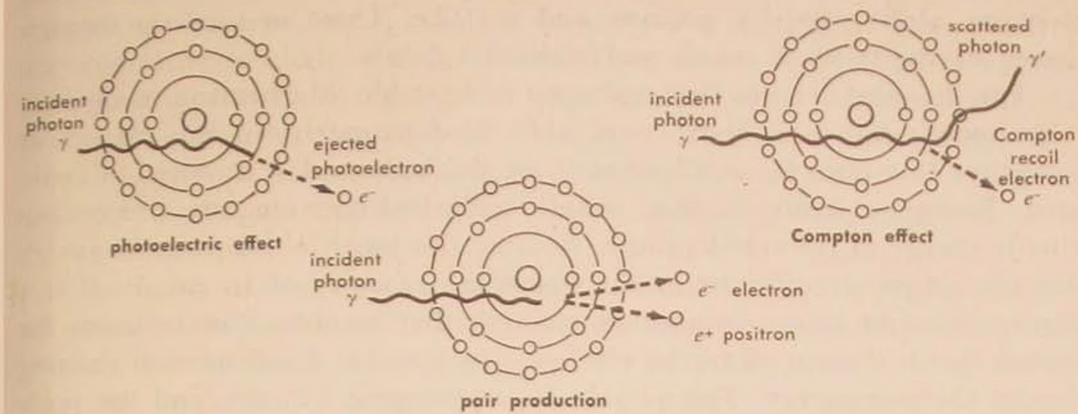


Figure 3. The three principal gamma interactions (collisions) with matter.

• The final process, pair production, involves the conversion of photon energy to mass. In the vicinity of a nuclear force field, the energy of a hard gamma may form an electron-positron pair. The entire gamma-ray energy is used in creating these particles. Since the electron mass is equivalent to 0.51 mev, a gamma of at least 1.02 mev is needed before the phenomenon can take place. Once again, the energy that a photon has above this threshold value is imparted to the pair in the form of kinetic energy. These three effects are dependent upon the energy of the photon and the atomic number of the absorbing element. The importance of atomic number and hence electron density is exhibited in the attending table listing comparative thicknesses of material to give equivalent absorption.

Comparative Thicknesses
To Effect Equivalent Gamma-Ray Absorption

gamma-ray energy (mev)	materials			
	lead	iron	aluminum	water
0.5	1	2.7	7.4	19
1.0	1	1.75	4.8	11.5
1.5	1	1.4	4.1	10
2.0	1	1.5	4.3	10
2.5	1	1.5	4.8	11
3.0	1	1.6	5.0	12
5.0	1	2.0	6.5	16

Neutrons and gamma rays interact with atoms in the same way regardless of where the atoms exist. When the atoms with which they interact are part of a living cell in a human being, the fundamental changes in atomic and molecular structure may upset the delicate balance that exists, causing the cell to function improperly or not at all.

Like everything else, the body is comprised of millions upon millions of atoms. The neutrons and gammas that penetrate the body and interact with constituent atoms transfer their energy to secondary ionizing radiation such as electrons, alpha particles, protons, and the like. These in turn rip through tissue, leaving trails of atomic and molecular debris.

For the same reasons that hydrogen is desirable as a neutron moderator, it is undesirable as a body constituent. Unfortunately, in this respect, it comprises 10 weight % or 63 atom % of the body and is uniformly distributed. Energetic neutrons that collide with hydrogen impart tremendous kinetic energy to the recoil proton. Because this particle dissipates its energy through frequent collisions in the immediate vicinity of its origin, it is a deadly bullet in tissue. In another reaction that involves slow neutrons the proton that is thrown off carries 600 kev, which makes it a dangerous ionizing tion of the gamma ray. This photon is an energetic 2.2 mev, and the prob-particle capable of great local cellular damage. Finally there is the producability of the photon escaping the body altogether is high. However, because hydrogen is plentiful throughout the body, because the cross section for the event is relatively large, and because the spewing radiation is of such high energy, this particular reaction is very dangerous to the whole body.

The body damage effected by radiation may not be grossly recognizable for some time and may accumulate as time goes on. Tissues vary in radiosensitivity as well as in ability to recover from radiation damage. All of us are continually exposed to some radiation. For example, at sea level one absorbs about 0.03 roentgen each year from cosmic radiation. A chest X ray amounts to from 0.05 to 0.20 roentgen. A radium dial of a wrist-watch will provide a local dose rate at the wrist of about 0.10 roentgen per day. The dose expected to kill 50% of the persons exposed to it, if absorbed in a very short time, is from 400 to 500 roentgen.

In the example introduced at the beginning of the discussion, the flux at a distance of 20 meters from a 100-megawatt aircraft reactor was calculated to be about 1.4×10^{10} neutrons per cm^2 per second and 1.2×10^{11} gammas per cm^2 per second. Assuming 5-mev neutrons and 2-mev gammas, the dose rates delivered are 2.2×10^6 rem per hour and 4×10^5 roentgen per hour, respectively. These dose rates are far greater than may be tolerated by the human body for exposure times even less than a fraction of a second. So if this reactor were to be used as a heat source in an aircraft, some provision would have to be made to protect the crew from devastating radiation.

As already pointed out, equipment and materials in the flight vehicle also are susceptible to radiation damage. Fortunately their thresholds for observed gross effects are far greater than for human beings. Still, materials are affected by low enough doses to cause aircraft and aircraft-engine designers to reassess the suitability of materials and components used heretofore for airplane and missile application. The radiation environment is capable of producing changes in the chemical constitution and physical properties of unshielded materials. Let us investigate briefly some of the basic mechanisms that explain the gross effects.

The chemical bonds that hold atoms together may be grouped in three categories: covalent, ionic, and metallic. Covalent bonding occurs when atoms are grouped together as molecules by sharing electrons, and the molecules "stick" because of the weak van der Waals forces. Water and plastic are examples of this type. Ionic bonding consists of a transfer of electrons from electropositive to electronegative atoms. Thus a lattice is formed of negative and positive ions held together by electrostatic forces. Common table salt, NaCl, illustrates this type of bond. A lattice of positive ions surrounded by a sea of electrons constitutes metallic bonding. Actually the outer electrons are very loosely held and hence are capable of moving from one positive ion field to another quite readily.

Radiation damage can be attributed to either ionization or displacement of atoms in the lattice structure. Ionization affects the covalent bonds most severely, for the bond energies, of the order of a few electron volts, are less than the ionization potential of orbital electrons. Consequently radiation easily breaks these bonds, producing free atoms or radicals that cause decomposition of the material and the possible formation of new compounds. For ionic and metallic compounds, principal damage results from heavy-particle radiations that knock atoms from their normal lattice positions. As a result, holes are created at the positions from which the atoms are driven, and interstitial atoms are left where they stop. The vacancy-and-interstitial combination is called a Frenkel defect (Figure 4). The region where perma-

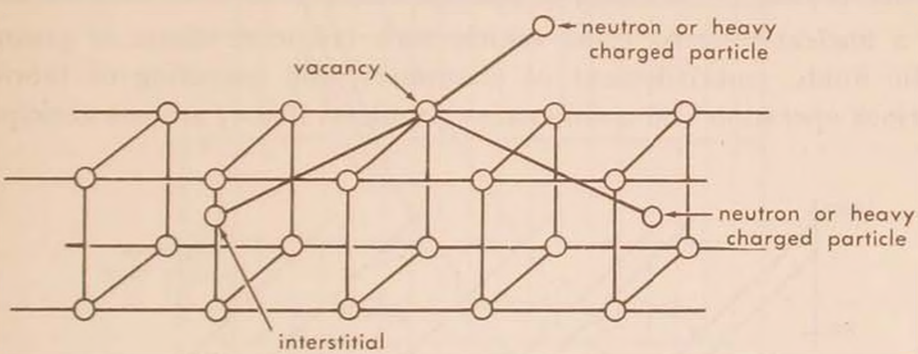


Figure 4. The Frenkel defect—displacement of atoms in the lattice structure.

nent disruption of the lattice arrangement of atoms has occurred is referred to as a thermal spike.

As a result of the microscopic havoc caused by radiation, macroscopic properties of the material change. The most important problems of radiation damage occur in solids. Effective indicators of the amount of effect are electrical resistivity, thermal conductivity, hardness, and color change, because these properties are relatively sensitive.

To measure radiation damage, the integrated flux *(nvt)* is commonly used.

Damage is proportional to the product of the total time of exposure and the intensity of the radiation. For example, exposure to a reactor flux of 10^{12} neutrons per cm^2 per second for a period of 10,000 seconds represents a total integrated flux of 10^{16} neutrons per cm^2. For reactor exposure, in general, the *nvt* value refers to thermal neutrons per cm^2 which struck the sample. Usually the sample receives an equal number of incident photons in the low-mev energy range as well as perhaps one tenth as many fast neutrons. The table lists materials and the integrated flux level that damages them.

Radiation Damage

nvt neutrons and gammas/cm^2 ←	(damage may occur above)	→ equivalent to 1 year at flux* of
3×10^{22}	ductile and fluid metals	1×10^{15}
3×10^{19}	asbestos and mineral insulators	1×10^{12}
3×10^{18}	electronic circuitry	1×10^{11}
1×10^{18}	special radiation-resistant lubricants natural rubber	3×10^{10}
1×10^{1}	small electric motors with standard lubricants	3×10^{9}
3×10^{16}	dry-cell batteries normal glass darkened	1×10^{9}
1×10^{16}	rectifiers (Ge, CuO)	3×10^{8}
1×10^{15} (gammas)	food (flavor may be affected)	3×10^{7}
1×10^{12} (thermal neuts)	food and drinking water (activation)	3×10^{4}

*nvt divided by 3×10^7 sec/yr.

In a nuclear-powered flight vehicle such radiation effects as gassing of hydraulic fluids, embrittlement of elastomers, and gumming of lubricants pose serious operation and maintenance problems if they are not anticipated.

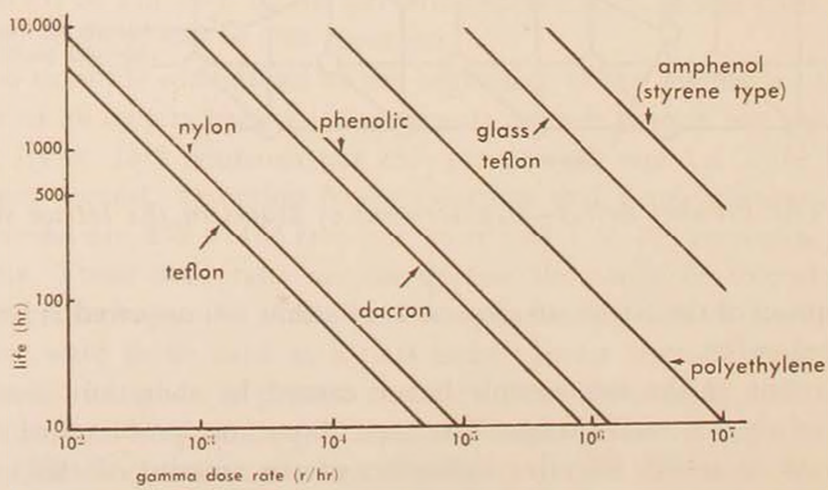


Figure 5. Effect of gamma radiation on the life of various materials present in a nuclear-powered aircraft, material life as a function of the gamma dose rate.

Figure 5 shows the life of various materials frequently used in an aircraft as a function of dose rate. If nylon were used for leads in a fuel booster pump within the radiation field of the hypothetical 100-megawatt aircraft reactor, the pump would fail after less than ten hours' operation. This points out that not only the crew but radiosensitive materials too must be protected from the radiation environment associated with a nuclear heat source.

Why the Shield Is a Problem . . . And Its Resolution

HAVING established that a shield is necessary, let us next consider the problems generated by the integration of a shield into an aircraft or missile. The discussion treats the effect of the shield on aircraft design and the problems associated with efforts to minimize undesirable shield characteristics.

Concrete is a shield material commonly used on stationary reactors because it is both cheap and effective. The curves in Figure 6 are examples of

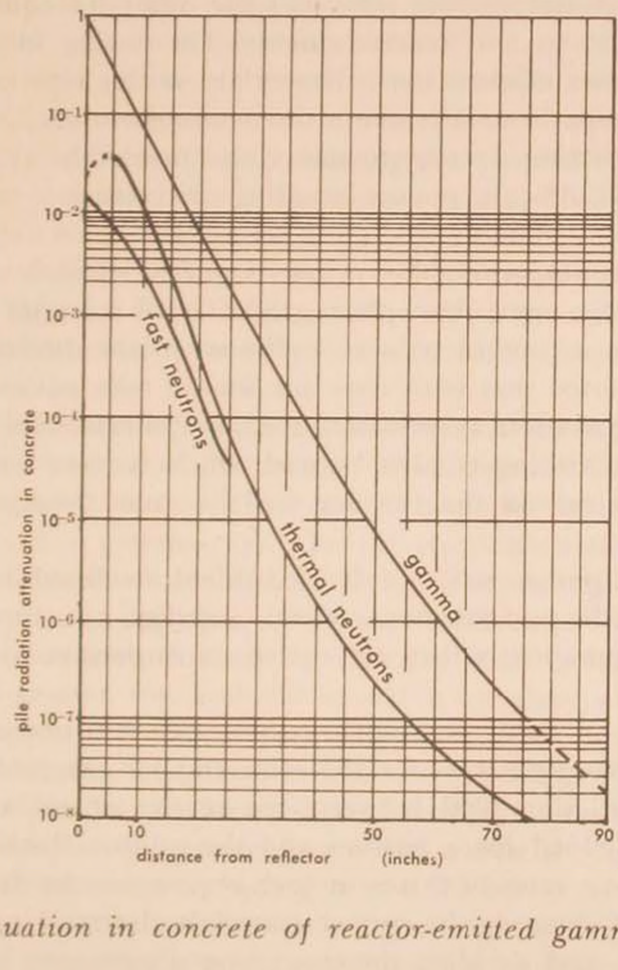


Figure 6. Attenuation in concrete of reactor-emitted gammas and neutrons.

the attenuation effect of concrete on reactor radiation. But if concrete is used to shield the hypothetical 100-megawatt aircraft reactor, too ungainly a mass results. To reduce the radiation field to a harmless level necessitates attenuations of the order of 10^8. This requires approximately 100 inches of concrete. Assuming a reflector diameter of 4 feet, the reactor shield assembly would then be about 21 feet in diameter and the shield alone would weigh about 1,000,000 pounds. This example, while extreme, serves to illustrate the challenge confronting the aircraft and shield designers. The huge size and weight of necessary shielding must be cut to a minimum if nuclear-powered flight is to succeed.

There are essentially two types of shields that may be used in nuclear aircraft—the unit shield and the divided shield. The unit shield concentrates all the attenuating material at the reactor. At the shield's outer surface the radiation has been reduced to established permissible levels. This type of shield provides the crew freedom of movement, reduces radiation damage to materials to a minimum, and considerably eases aircraft maintenance. The price for it is an extremely large, concentrated weight and a huge, ungainly size.

The divided concept places a portion of the shield at the reactor and the remainder at the crew compartment. This involves the definition of two permissible dose rates—one for the crew and the other for equipment between the crew compartment and reactor shields. The saving in weight and size effected by the more efficient use of materials in this type of shield is most attractive. In comparison, attendant disadvantages—such as cramped crew quarters, high radiation damage to materials outside the reactor shield and crew shield, and difficult remote-handling maintenance—assume less importance.

Both these concepts employ what is called shadow shielding. This amounts to nothing more than placing additional material in front of the reactor to provide a cone of reduced radiation in the direction of the crew. And it is to be noted that both concepts should take advantage of as great reactor-to-crew separation as possible. Studies indicate, however, that there is a point of diminishing returns beyond which it costs less weight to add shielding than to extend the fuselage for the same reduction in radiation dose to the crew.

The essential parameters of a divided shield are listed in Figure 7. They vitally affect vehicle performance, control, stability, structural strength, and maintenance. Consequently they are extremely important to the aircraft designer.

Before work on these parameters may begin, it is necessary to establish the permissible exposure level for the crew and for the susceptible material in the higher radiation field between the reactor shield and crew shield. Once these are defined for a mission and the mission duration is specified, the permissible dose rates or fluxes in each region may be determined. Then begins the task of choosing the proper materials, determining their thickness and arrangement, and deciding the separation distance.

To predict radiation levels, the shield designer must be able to trace neutron and gamma spectra from the core to the point of concern. Thus he must

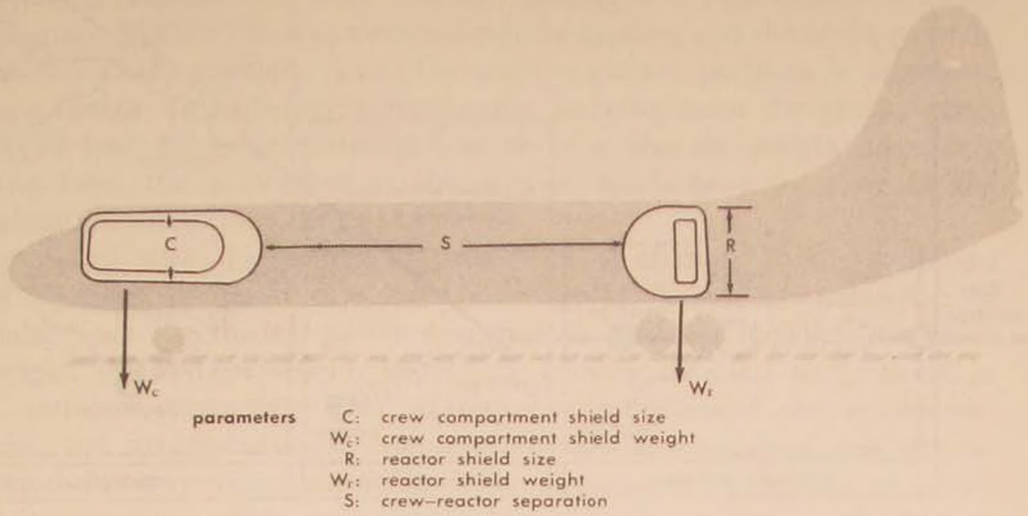


Figure 7. Divided-shield parameters affecting aircraft design.

account for all spectral changes as the radiation passes through the reactor shield, then travels along the paths possible in the extended media, air and ground, and finally penetrates the crew shield.

The reactor shield separates naturally into neutron- and gamma-attenuating components. Basic mechanisms of the interaction of neutrons and gamma rays with matter have been defined, allowing the qualitative conclusions that light elements are best suited for neutron attenuation, while elements of high electron density are most effective for attenuating gammas. These components need not take the form of separate layers or slabs but may be mixed together homogeneously. Figure 8 serves to illustrate each of the two type shields, homogeneous and slab, as well as to point out several important basic phenomena.

Illustration (a) shows a possible fast-neutron history in an iron-aggregate concrete. Concrete, because of the amount of hydrogen it contains, is a better shield material against neutrons than against gammas. Adding iron increases its effectiveness to stop gamma rays. The 10^8 attenuation effected by approximately 9 feet of standard concrete in the initial example can be accomplished by 4 feet of iron-aggregate concrete. In (a) the neutron is shown in two possible processes with iron nuclei. The first is an inelastic collision that generates a hard gamma ray, and the second is an absorption that involves the emission of approximately 2 energetic gammas. The cross section for the latter event is 2.43 barns. The neutron is shown bouncing off hydrogen in an elastic collision. Note that the neutron could suffer an elastic collision with an iron nucleus also, but the energy loss would not be as great. The thermal-neutron-capture cross section in hydrogen in 0.330 barns. This process results in the release of a 2.2-mev gamma. Unless great thickness can be employed, this type of shield presents a severe gamma problem because the capture gammas generated in the outer regions augment the core gamma rays. Since there is little material left to stop these hard photons, they are very dangerous.

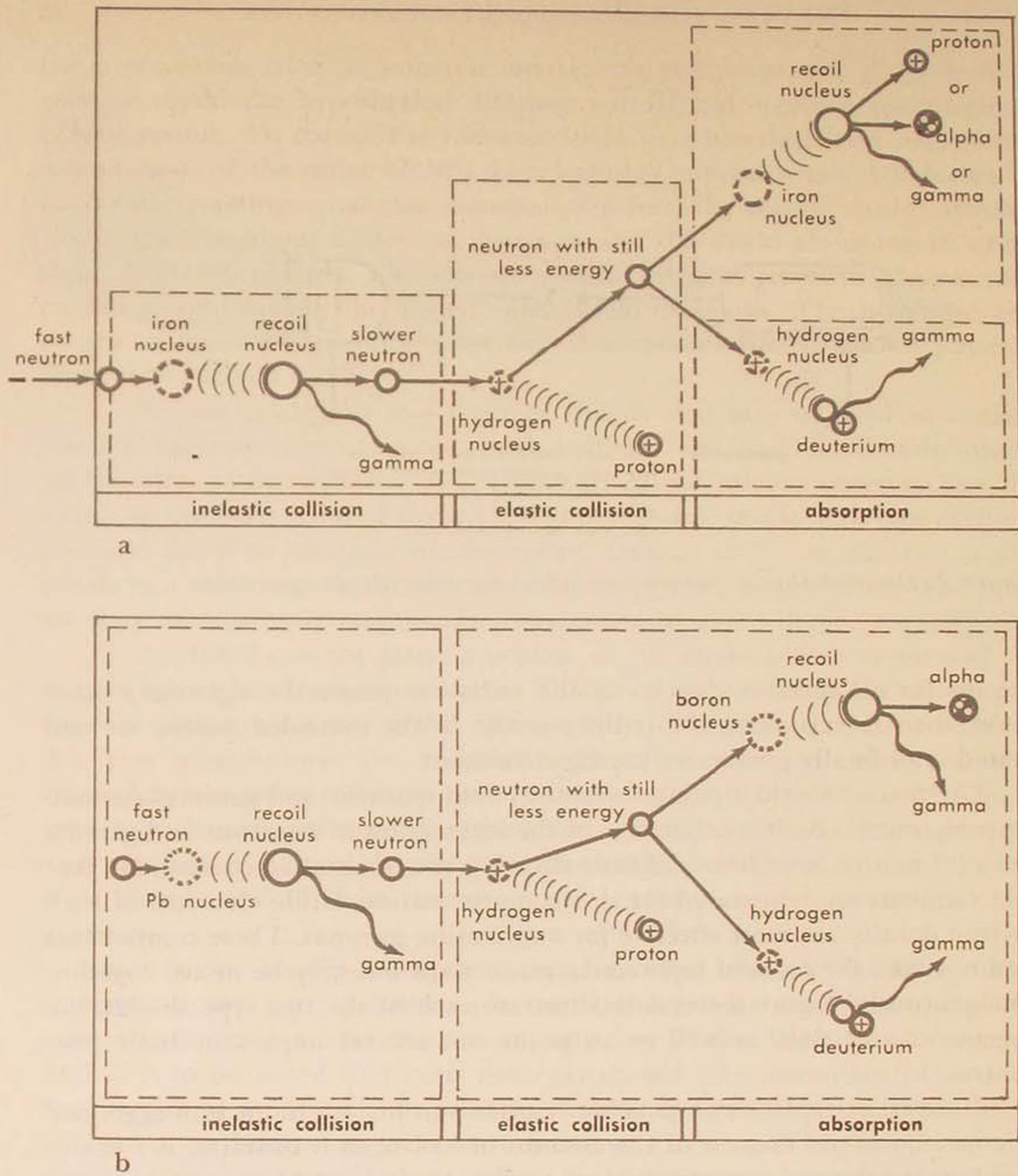


Figure 8. Nuclear interactions within the two types of reactor shields: (a) shows possible fast-neutron history in an iron-aggregate concrete homogeneous shield; (b) shows the possible neutron history in a lead-and-borated-water slab shield.

Illustration (b) presents a slab shield designed to reduce the capture-gamma problem. Lead, being more effective for this purpose, is used as the gamma component in place of iron. The neutron is shown colliding inelastically with a lead nucleus, giving rise once again to hard gammas. It then enters the borated-water slab used for neutron attenuation and is quickly slowed down by hydrogen collisions. The boron is distributed uniformly throughout the water, and the isotope boron-10 competes favorably with hydrogen for the thermal neutrons, since its capture cross section is of the order of 3400 barns. Once it makes a capture, it decays by alpha emission, returning to the ground state with the release of a weak 0.40-mev gamma ray. This gamma is much easier to stop than the 2.2-mev hydrogen-capture gamma, and the alpha particle presents no shield problem. Thus the capture-gamma problem is alleviated with this design. In addition to the benefit accruing from the greater effectiveness of lead for gamma attenuation, there is also the weight advantage resulting from the placement of the gamma component in close to the core where it will assume the least volume.

Associated with the matter of prediction of changes to the radiation spectra in shield penetration is the knowledge of nuclear characteristics of materials. Since the nuclear-powered aircraft is the first requirement for a lightweight, reduced-size shield, there is a scarcity of data, particularly in exotic and rare materials. This scarcity has complicated the evaluation, selection, and arrangement of attenuating materials. Neutron and gamma absorption and scattering cross sections for elements are examples of microscopic data that are costly, time consuming, yet necessary to obtain. Macroscopic data result from bulk experiments. A facility often used for this purpose is a bulk shield facility that provides a fission source and an adjacent water volume where slabs of material may be inserted. Here the gross effects of various materials, their thicknesses, and arrangements are measured.

Once the radiation is free of the reactor shield, it may take one of several paths on its journey to the crew shield, as depicted in Figure 9. First, the radiation may be absorbed by matter in the air, ground, or aircraft structure.

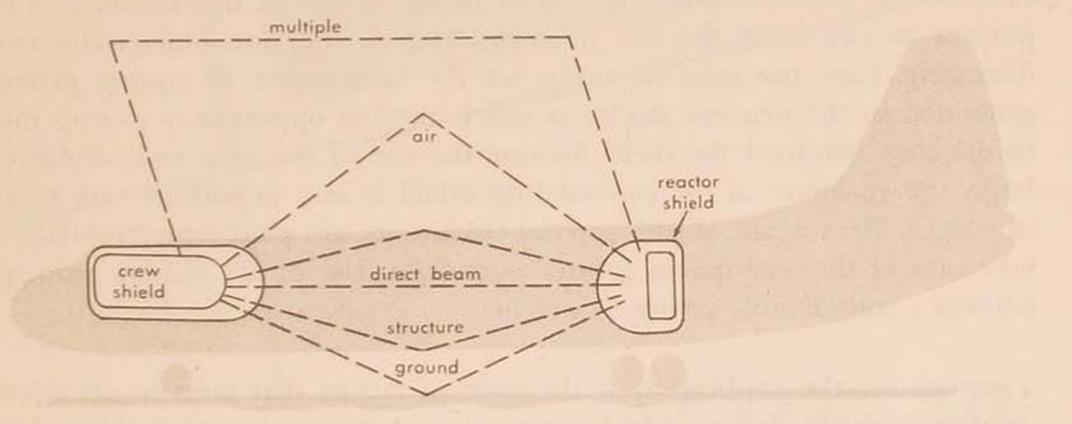


Figure 9. The effect of air, ground, and aircraft structure in redirecting scattered radiation from the nuclear reactor toward the crew compartment shield.

Next, some rays may travel straight to the crew compartment shield without incident. The once-scattered radiation may suffer collisions with the aircraft structure, the ground, or the air and thence be redirected to the crew shield. Then there are those particles that arrive after multiple scattering events.

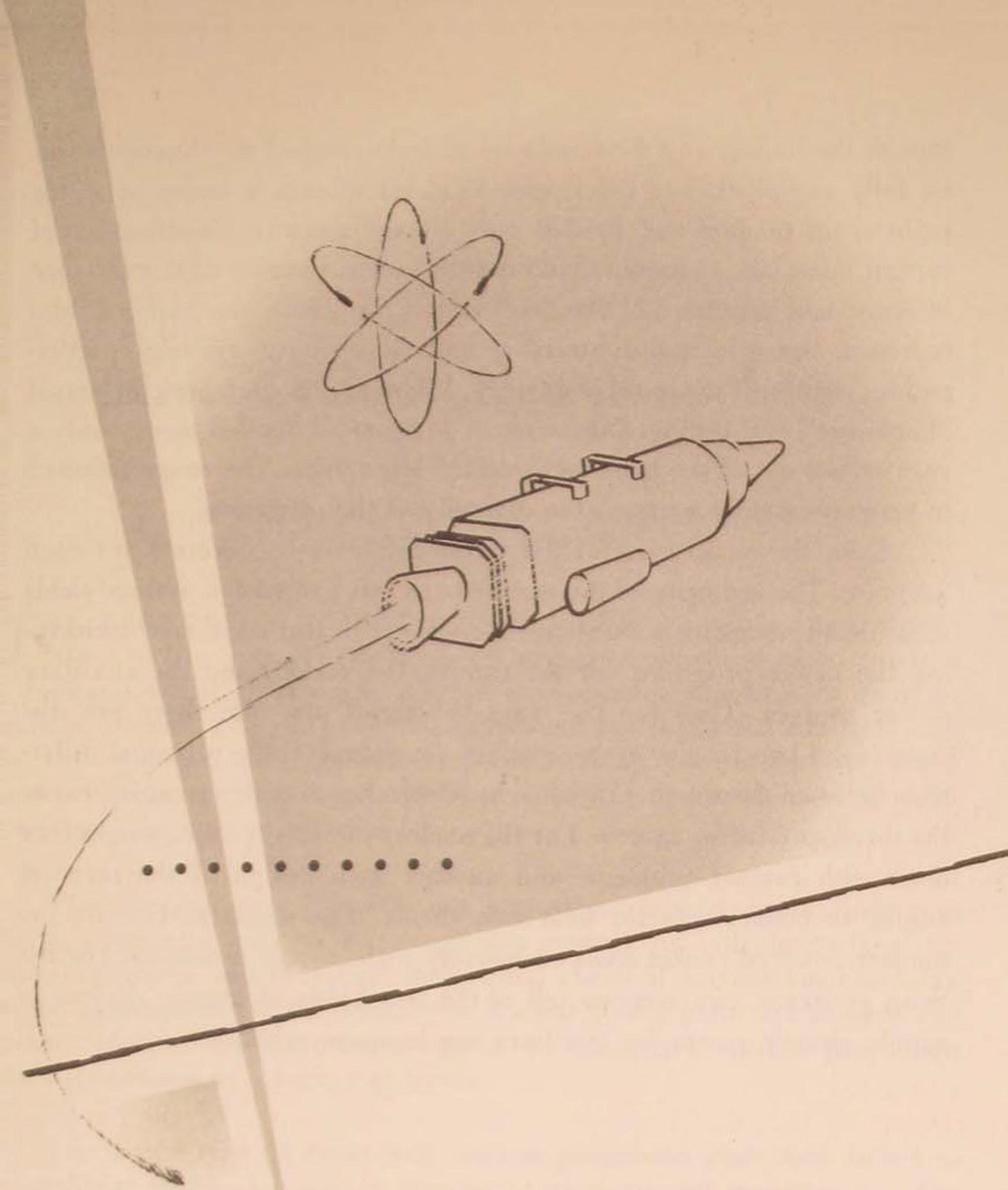
To predict the angular and the energy distribution of the radiation impinging on the crew shield, once again unique microscopic and macroscopic data are necessary. Calculations of the effects of extended media on radiation are divided between neutrons and gammas, each contribution treated separately. These in turn are divided into scattering and absorption events by air, ground, or structure. Before such calculations can be undertaken, knowledge of how the radiation will probably interact with the media is essential. This raises the experimental problem of separation of the scattering and absorption contributions of each medium from the other two for each type of radiation, neutron and gamma.

To gain experimental evidence, the equipment used may be reactors slung high in the air between towers or reactors mounted in aircraft and operated on the ground or in the air. The separation of variables may be accomplished by a process of elimination. Thus a reactor operated in an aircraft on the ground yields a measure of all three contributions—air, ground, and aircraft structure. Operated in the air, the ground parameter is eliminated. If the same reactor is run outside the airplane, the structure contribution is missing. Other macroscopic behavior of radiation in the extended media results from this process. A measure is possible of such complications as the decrease of air density with altitude and the activation of structural material by impinging radiation. The decrease in air density with altitude benefits the shield designer because then there is less air-scattered radiation hitting the crew compartment. Structure activation, on the other hand, raises a maintenance problem because of the high residual radiation level that may exist about the fuselage.

The radiation arriving at the crew compartment is reduced to the defined permissible level by the final barriers of crew-shield material. This nuclear problem is once again one of penetration, and considerations applicable to the reactor shield apply here. In the design of this shield, it is important to cut down the fast neutrons because they are biologically more damaging. Care too must be taken for the attenuation of capture gammas generated in the neutron shield, as this is the last opportunity to stop them before they bombard the crew. Because the size of the crew compartment is large, the geometry of the surrounding shield is very important with regard to weight. Here again, shield-material thicknesses are placed preferentially to take care of the anticipated greater intensities. Use of the shadow principle permits a considerable saving in weight.

Throughout the application of the maze of factors that must be considered in aircraft shield design, shield optimization is a constant goal. Thus, for a specified dose rate the choice and arrangement of materials should be such as to provide minimum weight. This involves optimization of the separation distance, the distribution of material at both the reactor shield and the crew shield, and the shape of each of these shields. The utilization of intervening nonradiosensitive equipment, such as landing gear and bomb load, between the reactor and the crew compartment augments the shields in attenuating the direct beam and scattered flux. These processes draw the shield designers and the aircraft designers even closer together.

Aircraft Nuclear Propulsion Office



PART III

Status of Program

THE actual engineering, laboratory, fabrication, and testing work on the four Air Force nuclear propulsion programs is carried on by an extensive network of civilian contractors and AEC and Air Force facilities. Some of these endeavors are as much as eight years old and for much of that time have had substantial financial support. Others only a few years old still pose many basic research problems and are not ready for enlarged development programs.

The key instrument that links the advanced systems planner to the advanced systems engineer is the project status report. Through these reports the impact and the timeliness of technological developments can be fully exploited. For the reader Part III affords a series of status reports, up to date and limited only by the security classification of certain materials, techniques, and developments. Because of the variance in stage and problems of the four major programs, the authors, who represent the principal contractors and Government agencies participating, approach their subjects very differently. Some speak of actual "hardware" and testing. Others speak in terms of applied theory only a year or two out of the book and into the laboratory. The range reflected in progress simply portrays the diversity of the programs.

Even the structuring of the treatment must be different for each program. The seniority of the manned-aircraft propulsion system yields more detail about work on its components than can be offered concerning the newer programs for the ramjet, the rocket, and the auxiliary power sources. Thus for the manned-aircraft program there are discussions of two reactor systems under development, the principal difference between them being the way in which they transfer reactor heat to the thrust-producing system. For the nuclear-powered ramjet, one author deals with reactor problems and another with design of the turbojet engine to convert reactor heat into thrust. The single section on the nuclear-powered rocket deals exclusively with reactor problems. For the Snap program, two sections tell of the two kinds of atomic devices to supply electric power for auxiliary use in space vehicles.

Direct-Cycle Nuclear Propulsion

D. R. Shoults

*General Manager, Aircraft Nuclear Propulsion Department,
General Electric Company*

THE GENERAL ELECTRIC Aircraft Nuclear Propulsion Department (GE-ANPD) is engaged in research and development work to produce a nuclear-powered, direct-cycle, turbojet propulsion system capable of flying manned aircraft. This work is being carried out under parallel contracts with the United States Air Force and the Atomic Energy Commission, the USAF sponsoring the turbojet engines and auxiliary components and the AEC sponsoring the reactor and shield.

The direct-air-cycle system is not limited to turbojet application; it is also applicable to turboprop and turbofan engines. As with the turbojet engine, the reactor would replace the normal chemical combustion chambers. Other applications for the direct-cycle nuclear power plant are ramjets and rockets. Much of the basic technology of the direct-cycle nuclear propulsion plant is common to a variety of forms.

The actual type of direct-cycle nuclear propulsion plant best suited to a particular application will be dependent upon mission requirements. The turbojet version will be attractive for penetration-type bombers, including supersonic ones. Turbofan and turboprop versions look promising for a number of subsonic planes including long-range logistic, AEW, and ASW planes.

power-plant explanation

The direct-cycle nuclear aircraft engine, in simplest terms, substitutes a nuclear reactor for the conventional combustion chambers in an ordinary turbojet engine. Air, entering through the compressor, is forced into the reactor, where it is heated by the hot fuel elements. This heated air then passes through the turbine, where energy is extracted to drive the compressor. Beyond the turbine the air is accelerated to high velocity by expansion and is finally expelled from the turbojet exhaust nozzle. The jet of high-velocity exhaust air provides the thrust that propels the aircraft.

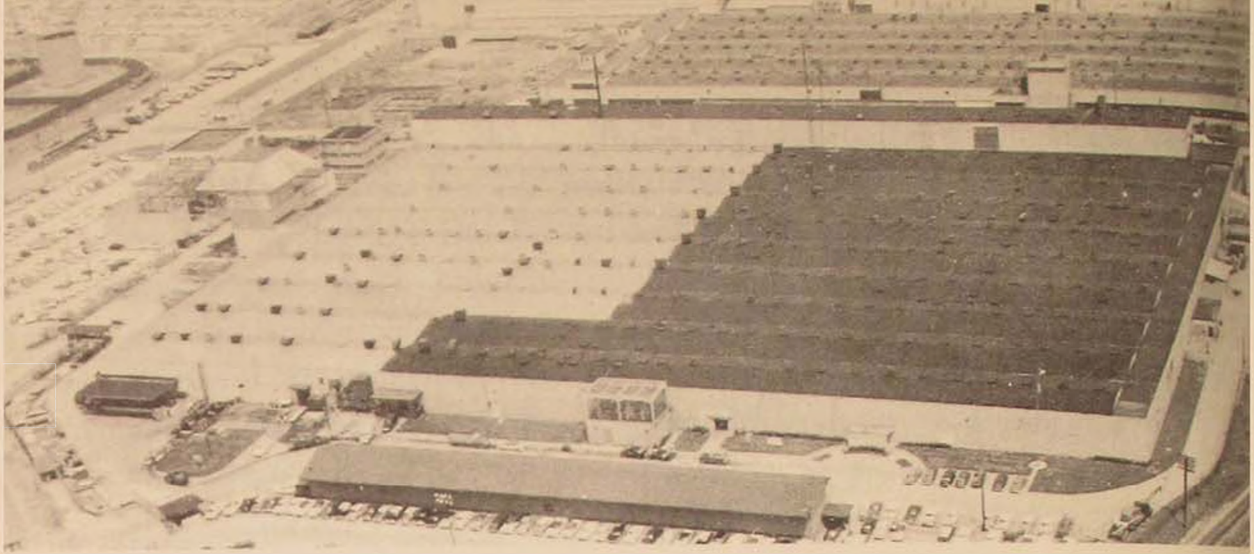


Figure 1. The Aircraft Nuclear Propulsion Department of the General Electric Company occupies several buildings in the Evendale area near Cincinnati, Ohio.

The major research and development work in the direct-cycle program is carried on at GE-ANPD in the Air Force-owned-and-GE-ANPD-operated plant at Evendale, Ohio. This facility, funded by the USAF, is a 40-million-dollar plant complex. The work on the turbojet engine is also carried out in the shops of General Electric-owned-and-operated Flight Propulsion Division, also at Evendale. The development effort at Evendale is supported by extensive tests conducted at the Idaho Test Station, an AEC facility operated by GE-ANPD at AEC's National Reactor Test Station in Idaho.

When General Electric's ANP Department was formed in 1951, extensive studies were conducted to determine which of the many theoretically possible aircraft nuclear propulsion cycles should be developed. On the basis of these studies the direct air cycle was chosen for aircraft application. Factors considered in initial study, and subsequently reviewed at periodic intervals, indicated that the direct cycle has certain unique characteristics:

- Simplicity. The direct-air-cycle nuclear engine is inherently the

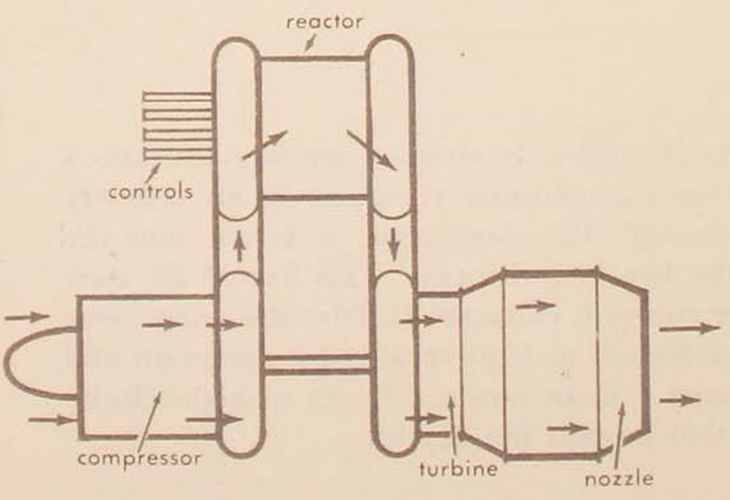


Figure 2. Schematic of direct-air-cycle nuclear propulsion system. Air enters through the compressor, is forced into the reactor, and heated by the fuel elements. After passing through the turbine, where energy is extracted to drive the compressor, the heated air is expelled at high velocity through the exhaust nozzle.

simplest type of nuclear propulsion system, since it has the fewest possible major components.

• Reliability. Simplicity in engine design with the fewest possible components is desirable from the reliability aspect, particularly in an aircraft engine. Because this system uses an open air cycle, the reactor could tolerate a leak at its flanges or casing with only a slight performance loss, since the compressor is supplying a continuous air flow through the reactor.

• Service suitability. The direct-cycle nuclear-aircraft engine lends itself to an integral power package containing turbomachinery and reactor-shield assembly. This compact feature will allow removal of the entire power plant from the airplane as a single package for maintenance. If the turbomachinery failed in flight on a multiengine aircraft, the aftercooling requirements for the affected reactor would be automatically supplied by ram air while the aircraft returned to its base on its other engine.

• Quick starting ability. The direct-cycle nuclear engine will be started in a manner similar to present turbojets and can be brought up to operating condition very rapidly. Thus the quick starting ability of the direct cycle will permit quick aircraft response time without the need for elaborate auxiliary ground equipment.

power-plant development program

The engineering challenges in the development of an aircraft nuclear propulsion system are many. The radioactive materials must be contained within the reactor; shielding must be provided around the reactor to localize the radiation; sensitive, reliable controls for the power plant must be provided; and long-life components must be developed, made of high-performance materials that can withstand high temperatures and nuclear radiation.

The state of development of an aircraft nuclear power plant can best be appreciated by noting the progress made to date on the major components of the system:

Fuel elements. Since the fuel elements must generate the heat to produce the propulsive power, they must be constructed to optimize heat transfer to the air flowing through the reactor. In the final analysis the air temperature and rate of air flow to the turbine inlet determine the engine thrust. Extensive work has been carried out with both metallic and nonmetallic fuel elements, and metallic fuel elements are now available that can provide adequate turbine-inlet temperature for a flight-test aircraft.

Reactor control system. The ability to control a direct-air-cycle reactor has been demonstrated continuously since 1956. Effective control rods have been developed that can damp or increase the reactor operating power level to meet the performance requirements for a flight-test aircraft. Many hundreds of hours of operation of direct-cycle reactors at the Idaho Test Station have proved the stability and controllability of the reactor.

Shielding. Technology now exists for the design and construction of the necessary flight shields for operational power plants. These comparatively lightweight shields will permit the carrying of larger payloads for missions requiring long range or endurance than those of equivalent chemical aircraft. Weight of course is a most important consideration in the design of any aircraft nuclear propulsion system. Conventional shields for stationary power-plant reactors are extremely heavy. For the aircraft system, special shielding arrangements and materials have been developed.

Since the allowable radiation level for the airframe components usually is considerably higher than for the crew, it is possible to employ the divided-shield concept. Only enough shielding is placed around the reactor to protect the airframe and other components immediately adjacent to it. The aircrew is housed in a separately shielded compartment. This crew shield, in combination with the shielding around the reactor and the attenuating effect of the distance of the crew compartment from the reactor, reduces the radiation received by the crew to a safe dose rate.

Turbojet engine. Although turbojet machinery was not new, the size of the engines required for a nuclear turbojet prompted a major development effort to meet the performance requirements for flight-test aircraft and later possibly those for operational aircraft. Prototype engines (designated X-211) have been developed and have logged many hours of ground testing on chemical fuel. Ground tests of this turbomachinery on nuclear power are also scheduled.

Advanced technological research and development are continuing in the various component areas. Fuel elements are being developed that operate at higher temperatures and improve aircraft performance beyond that presently anticipated. New fabrication techniques are being devised to produce shield and structural components that will provide long life for the reactor in operational use.

Heat Transfer Reactor Experiment program

The major test program to determine the characteristics and feasibility of the reactor core, shielding, and control designs for the direct-cycle nuclear turbojet has been conducted at the GE-ANPD-operated facility at the National Reactor Test Station in Idaho. This program, termed Heat Transfer Reactor Experiment (HTRE), has consisted of ground tests of direct-cycle nuclear reactors coupled to turbojet engines.

For reasons of economy and time it was decided to demonstrate first the feasibility of nuclear-turbojet operation. The initial step was to revamp a GE J-47 turbojet engine so that the expected reactor pressure drop could be simulated on chemical operation. The successful modification of this engine (redesignated X-39) in 1952 resulted in a portion of the development effort being directed toward ground-testing turbojet engines at NRTS. The first test of this type was designated HTRE-1. The unique requirement in HTRE-1 was the addition of heat to a turbojet from an external source. So far as is known, the first turbojet engine to be driven by a nuclear reactor was operated at NRTS in January 1956. This series of tests culminated in

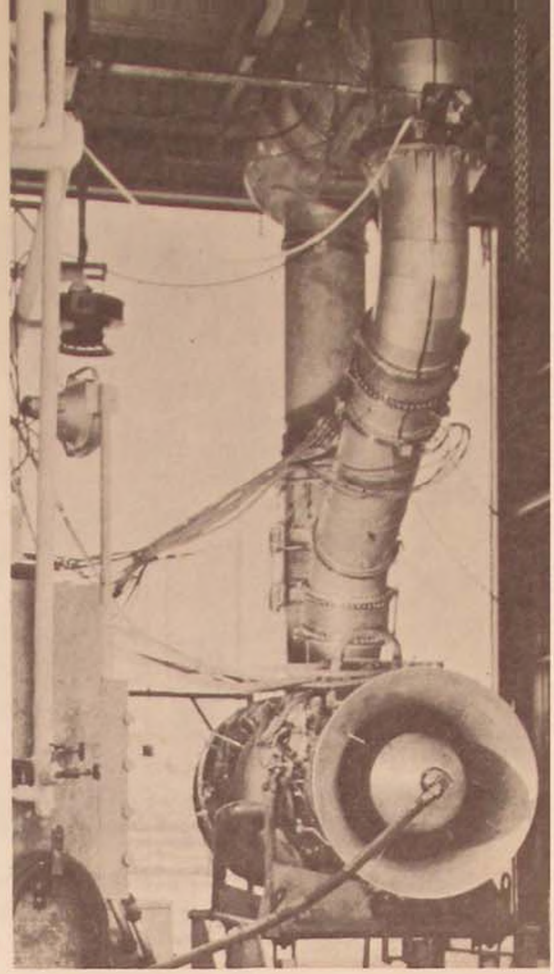


Figure 3. Idaho Test Station (above) at the National Reactor Test Station near Arco, Idaho. The nuclear test facilities are in the foreground. Railroad tracks connect with the shop area at right in the background. Left of the shop are the office and engineering buildings. The early X-39 engine (right), shown with its initial overhead, external, chemical heat source, was a modified GE J-47 turbojet engine.

1957 with approximately 150 hours of successful operation.

The reactor used in HTRE-1 was air-cooled and water-moderated and utilized metallic fuel elements. The shield surrounding the reactor was made of water, lead, and steel. It should be noted that HTRE-1 represented the early state of the art for aircraft reactors and was designed for ground-test experience. Solid moderators and shielding are programed for direct-cycle aircraft reactors.

the HTRE-1 test operation

The HTRE-1 test assembly was mounted on railroad trucks. It consisted of a reactor, a radiation shield, two turbojet engines, ducting, control components, chemical combustion systems, various accessories, an auxiliary power source, afterheat removal equipment, and necessary instrumentation for obtaining detailed information about all aspects of the tests. This assembly of equipment, which is a veritable laboratory on wheels, is called the Core Test Facility because it was designed for the insertion of different types of reactor cores as they are developed.

No attempt was made to restrict the size and weight of the Core Test Facility equipment to approximate a flight version. Rather the assembly was deliberately made large for ease of access and for the extra data-collection equipment. An additional engine was provided to guard against delay if engine trouble were encountered.

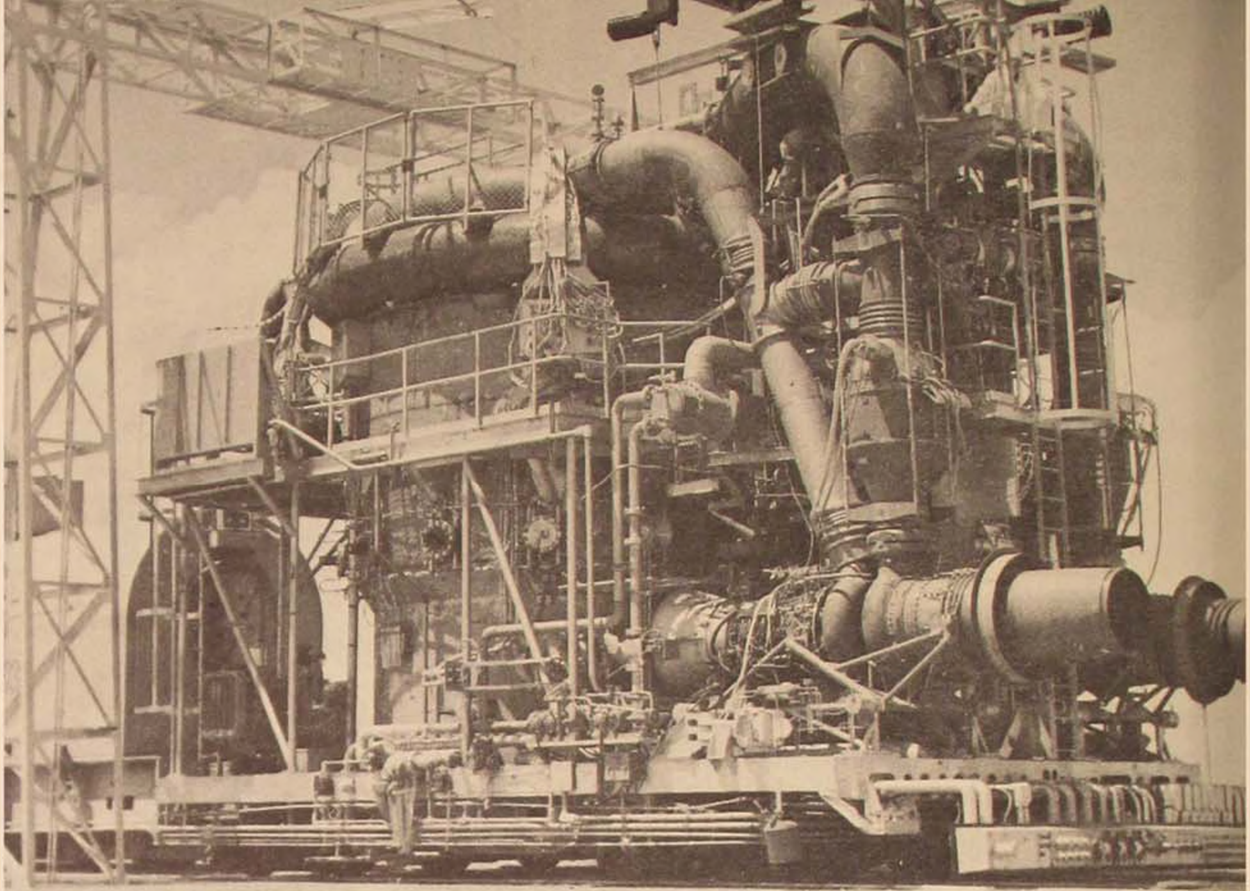


Figure 4. Core Test Facility at the Idaho Test Station, NRTS, showing the developmental assembly for HTRE-1 with its two turbojet engines protruding at the right.

The shield surrounding the reactor is unusually thick, so that post-operative radiation levels around the reactor permit manual contact with the engine and the external parts. A shielded locomotive moves the dolly on which the entire HTRE-1 power system and test assembly are mounted for transportation between test and maintenance areas. In this test facility, engines not only operate solely on nuclear power but also are tested at power levels below those necessary to sustain engine operation. This is made possible by a chemical-fuel combustion chamber placed between the reactor and the turbine.

The developmental assembly for HTRE-1 was first operated on chemical power only. No attempt at nuclear operation was made until a checkout of the entire system was completed. Then early in 1956 the transition from chemical to all-nuclear operation was realized. The engine was always started on chemical power. As the reactor heat increased, chemical heat was decreased to maintain a constant temperature at the turbine inlet. Finally when the air from the reactor was hot enough to operate the system, the chemical heat was no longer needed.

After the first transfer to all-nuclear power was made, operation continued for six hours. The total energy output from nuclear sources during the subsequent 150 hours of all-nuclear operation was over 5000 megawatt-hours. If converted to electricity, this energy could have lighted the homes in a city the size of Pasadena, California, for an entire month.

Once the engine was operating completely on heat from the reactor, changes in reactor power decreased or increased engine speed and air temperatures throughout the system. Preliminary experiments and tests were made at low power, and then the reactor was raised to full power. After a few hours of operating, fission products appeared in the exit airstream, indicating damage to the heat-transfer surface of the fuel elements. The reactor was returned to the "hot shop," where it was dismantled and the fuel

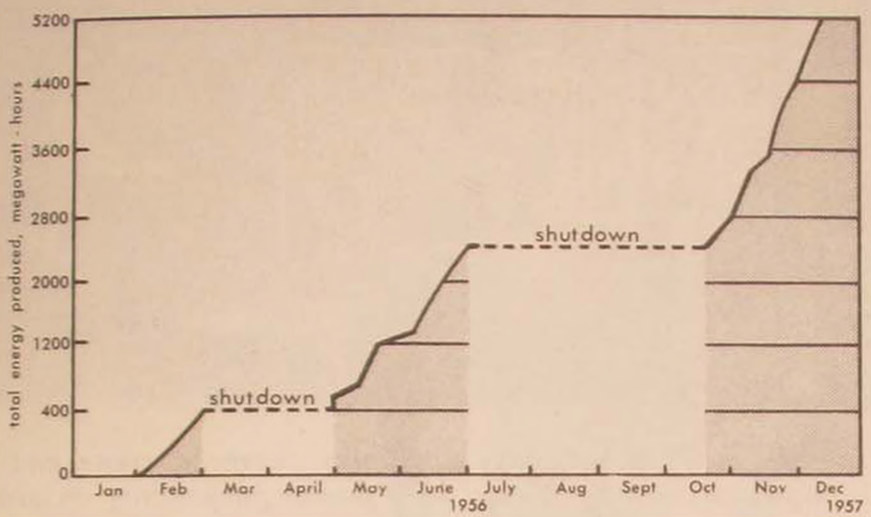


Figure 5. Range of energy produced by HTRE-1 during operation. Initial engine tests indicated over-all HTRE-1 system performance to be consistent with design.

elements removed for inspection. The source of trouble was quickly discovered. This reactor resembled a calandria or "fire-tube boiler," with fuel elements in the tube, through which the air passed, and water in the interstices between the tubes. The water not only served to moderate the neutrons but also acted as a coolant for the aluminum calandria. To prevent undue drainage of heat into the water moderator, a layer of thermal insulation had been placed between the fuel elements and the aluminum tube walls. Aerodynamic forces, instead of permitting air to pass over the outer surface of the fuel elements, had caused the insulation layer to collapse against them in places. The surface of some of the fuel elements, deprived of their cooling air, became overheated, with resultant release of fission products. Minor changes were made in the design of the insulation layer, and the reactor was put back on test. Although these tests were essentially successful, further changes in design of the insulation liner were indicated. A second period of shutdown occurred while these changes were made. The reactor was again returned to test and ran successfully until the planned conclusion of the test period. In all, several hundred hours of operation at significant power were logged.

Two interesting observations were made as a result of this initial test:

• The reactor continued to run after fuel elements were damaged and fission products released. It exhibited no instabilities and in fact operated smoothly for several hours after the damage had occurred. This indicates that fuel-element trouble in a direct-cycle aircraft reactor will not

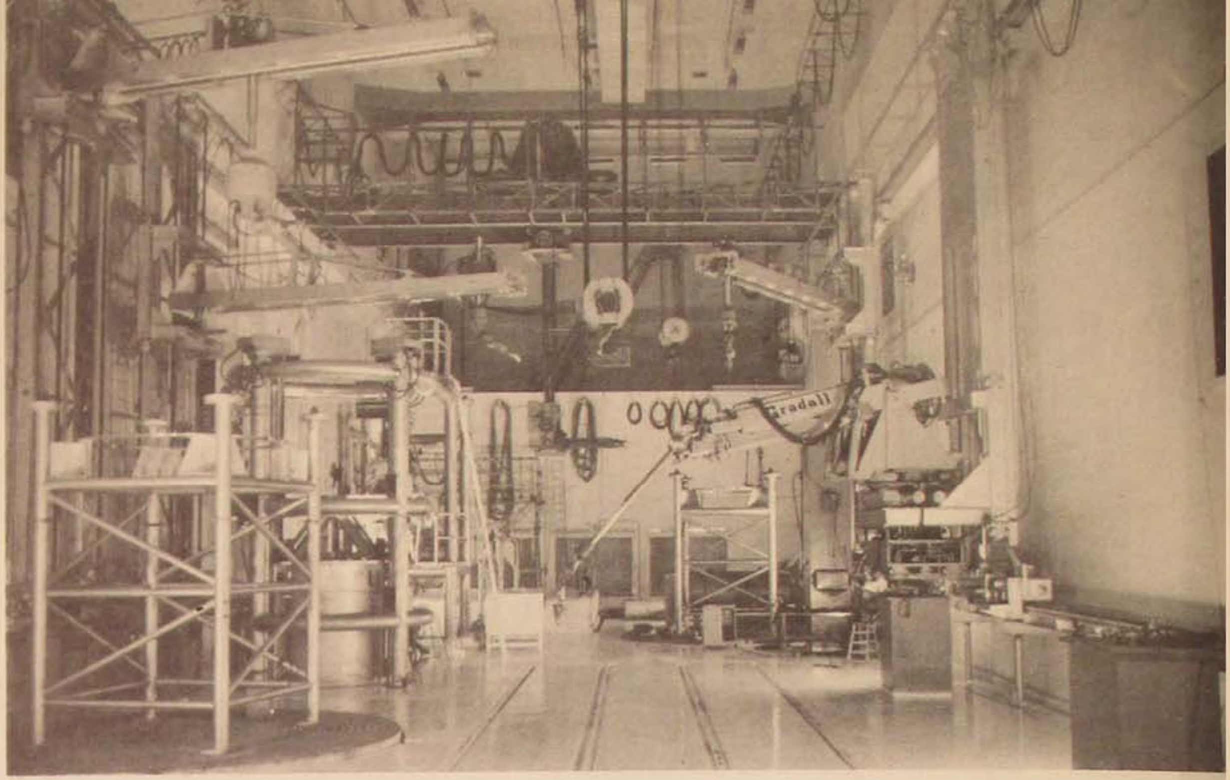


Figure 6. Interior view of hot shop, containing overhead crane and turntable. Overhead manipulators will lift 500 to 3000 pounds, depending on arm position.

necessarily interfere with completion of the mission, at least not with the return flight to base.

• Although fission products were released, contamination of surroundings was insignificant.

The HTRE-1 test was invaluable in that it verified the feasibility of the direct-cycle power-plant design. Furthermore it demonstrated the predicted performance of the power plant, the lifetimes of key components, and the operation of control components. The results were qualitatively and quantitatively close to pretest predictions.

Reactor test work is continuing at the Idaho Test Station in the HTRE-2 and HTRE-3 programs. Their purpose is to determine nuclear-turbojet control response, nuclear design parameters and feasibility, and the suitability and life of various materials for such major reactor components as fuel elements, moderators, shielding, and controls. Results being obtained in these programs remain classified.

other test facilities at Idaho Test Station

The original Core Test Facility with its thick shield produced relatively moderate radiation levels, but testing of reactors equipped with highly divided shields produces higher external radiation levels. For this reason testing of divided-shield reactors is conducted on a remote test pad called the Initial Engine Test Facility, the same pad used in the HTRE-1 tests. The isolated location of this pad permits continuous operations at the main test installation while reactor tests are in progress.

Maintenance of the HTREs is conducted in a hot shop that accommodates the entire Core Test Facility, flatcar and all. In the hot shop the Core Test Facility, including the reactor, can be completely dismantled with the aid of versatile cranes, remote-handling manipulators, slings, and other specially designed tools. The room is encased with 7-foot-thick concrete walls and has 6-foot-thick viewing windows. Dismantling operations are accomplished largely by remote control, without exposure to excessive radiation levels. The Core Test Facility has been opened, a portion of the reactor removed, a substitute portion installed, and the Core Test Facility returned to the pad ready for test—all within two days and without subjecting any individual to radiation doses higher than generally accepted laboratory tolerance values.

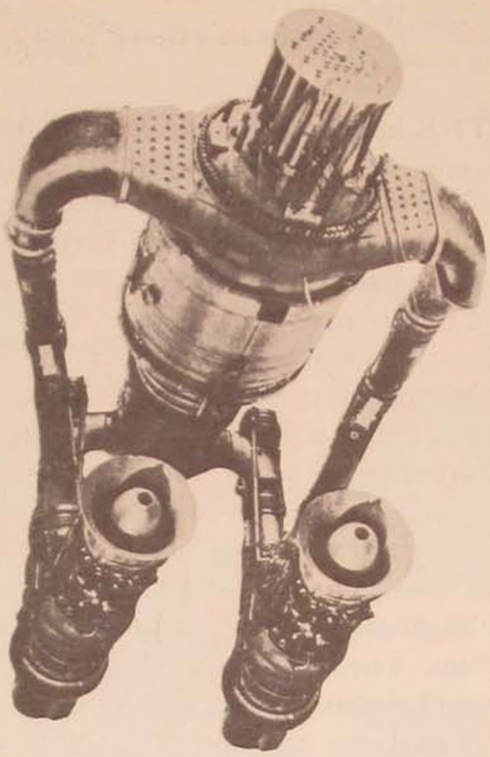


Figure 7. HTRE-3, showing essential components of the system—the reactor and the two jet engines.

We are currently fully engaged in our HTRE-3 testing, which employs a flight-type shield system, a solid moderator for high-temperature operations, and a configuration more in keeping with a propulsion system. Figure 7 shows HTRE-3 stripped of all its test equipment and supporting structure. It is easy to visualize how the next logical step would be the testing of the solid moderated reactor as an integral part of a propulsion package in a flight-type geometry.

NUCLEAR PROPULSION plants are now feasible that would permit nuclear flight. The Department of Defense has, however, indicated that it desires attainment of higher-temperature reactors prior to flight scheduling. GE-ANPD is therefore concentrating its effort on propulsion plants incorporating high-temperature reactor materials which will permit higher-performance direct-air-cycle nuclear propulsion.

Evendale, Ohio

Indirect-Cycle Nuclear Propulsion

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IN THE indirect-cycle nuclear propulsion system, the heat generated in the reactor is absorbed by liquid-metal coolant flowing through the reactor core. The hot liquid metal is then pumped to the propulsion units, which may be turbojets, turboprops, turbofans, or ramjets. The propulsion units contain radiators, where the heat is given up by the liquid metal and imparted to the airstream.

Development of the liquid-metal, indirect-cycle system has been actively pursued by Pratt & Whitney Aircraft since 1951 under sponsorship of both the U.S. Air Force and the Atomic Energy Commission. Initial studies and experimental work were conducted at Oak Ridge National Laboratory and at leased facilities near East Hartford, Connecticut. In 1953 Pratt & Whitney Aircraft began an intensive fundamental research program with several promising liquid-metal coolants that could be used in an indirect-cycle flight-propulsion system. Primary efforts were directed at two main problems. The first was to determine accurately the physical, chemical, nuclear, and thermal characteristics of a selected group of liquid-metal coolants. The second was to conduct basic metallurgical studies to develop a metal for piping, valves, and pumps that could successfully contain high-temperature liquid metals. After thorough and exhaustive studies these tests culminated in the choice of a very promising liquid-metal system for development. The indirect-cycle program was then ready to advance into a component research and development phase. Since May 1957 this work has been carried on in the Air Force-owned Connecticut Aircraft Nuclear Engine Laboratory (CANEL), a 55-million-dollar research and development facility located on an 1100-acre tract in central Connecticut. The program under way at this facility is the subject of the following discussion.

advantages of liquid metal

The basic components of a one-loop, indirect-cycle nuclear propulsion system are shown in Figure 2. For schematic simplicity only one propulsion unit is shown, but it is more likely that multiple units will be powered from a single reactor. The turbojet application illustrated is also only one example. Application to other types of propulsion units is possible.

Administration Building

Figure 1. Over-all view of the research and development facilities comprising the Air Force-owned-and-Pratt-&-Whitney-operated Connecticut Aircraft Nuclear Engine Laboratory (CANEL) near Middletown, Connecticut. Surrounding this photograph are pictures of eight of the key laboratories and buildings.

Heat Exchanger Laboratory

Pump and Turbine Laboratory

Radiator Laboratory

Machine Shop

Pilot Radiator Laboratory

Nuclear Physics Building

Air Laboratory

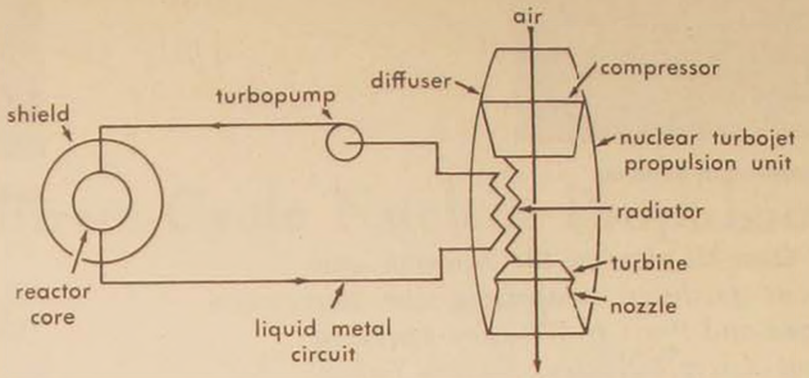


Figure 2. Single-loop, liquid-metal, indirect-cycle propulsion system.

Figure 3 illustrates a two-loop system, in which the liquid-metal coolant flows through an intermediate heat exchanger, where its heat is transferred to a secondary liquid-metal loop. There are two reasons why a two-loop system might be required. First, the liquid metal passing through the reactor may become radioactive by neutron activation. If so, a small, easily shielded, primary loop is needed. A second possible reason would be the inability of a single material simultaneously to contain the high-temperature

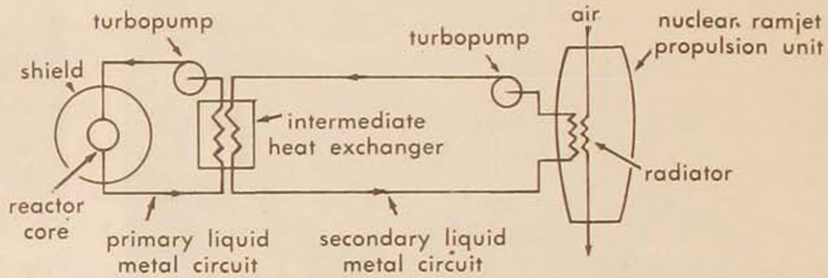


Figure 3. Two-loop, liquid-metal, indirect-cycle propulsion system.

liquid metal and to resist oxidation by the air in the radiator. In this event, the primary loop would contain the corrosive liquid metal, and the secondary loop, of oxidation-resistant material, would contain a noncorrosive liquid metal.

Certain advantages result from the use of liquid metals as heat-transfer fluid in the reactor. Liquid metals are the most efficient heat-transfer fluids known. They have low densities and high volumetric specific heats. These properties permit large amounts of heat to be removed at high temperatures from a small reactor volume. Since the weight of the reactor shield is strongly dependent upon the volume to be shielded, the use of liquid metals permits comparatively lightweight shields.

The final transfer of heat from the liquid metal to the air is made in a radiator outside the reactor-shield assembly. Air is a relatively poor heat-transfer medium, but this may be compensated for in the radiator by using extended surfaces (fins) on the air side. Since the radiator does not have to be shielded, the weight penalty for enlarging the air passages to obtain low air velocities and hence low pressure losses is small.

One of the serious concerns about nuclear-powered airplanes is the possibility of release of fission products into the airstream. An important advantage of the liquid-metal cycle is the greatly reduced probability of this. Failure and subsequent penetration of several metal walls (fuel element, intermediate heat exchanger, and radiator) by the fission products would have to occur before fission products could escape into the airstream.

power-plant components

Reactor. The core of the reactor contains a highly enriched, fissionable material in the form of fuel elements, within which the fission process takes place. Heat produced by the fission process is removed from the fuel element by the liquid-metal coolant. The reactor is controlled by rotating drums that contain boron in one segment of the drum periphery. Boron is called a "poison" because it captures neutrons, thus decreasing the number available to cause fission. Rotating the drums varies the position of the boron relative to the reactor core, regulating the rate of fissioning and consequently the power production. The reactor must be shielded, of course, to protect personnel, instruments, lubricants, and other materials from neutron and gamma radiation. The heat generated in the reactor shield as a result of this radiation is removed by a separate cooling system. The weight of the reactor shield can be minimized by alternating the layers of neutron and gamma shielding, by dividing the shielding between the reactor proper and the crew compartment, and by "shadow shielding."

Reactor development areas under active investigation include power distribution, the critical fuel mass, the liquid-metal flow distribution, and the structural integrity of all reactor components under operating conditions. The latter entails consideration of pressure loads, steady and transient thermal stresses, creep, and aircraft acceleration loads. All these problems are being investigated experimentally in critical facilities, heat-transfer analogs, and materials-development laboratories.

Radiator. The radiator occupies the annular space between the compressor and turbine of the engine or, for the ramjet, fills the entire duct. The desirable but conflicting characteristics of a good radiator are a reliable, lightweight structure, a large air-temperature rise, low pressure drops of both air and liquid metal, and a small frontal area. Thus the radiator is a good example of a component in which trades in characteristics can be made. If its depth is increased, there are increases in the air-pressure drop through the radiator, in the exit air temperature, and in the radiator weight. Increasing air-pressure drop and increasing exit air temperature have opposite effects on the thrust of the engines, with the result that a particular depth occurs at which maximum thrust is obtained. Yet this depth would not necessarily be the most desirable to use because of the weight of the radiator. The optimum depth of the radiator must consequently be chosen in terms of the desired airplane-performance criteria, such as in payload or speed.

Analytical studies are quite useful in selecting suitable heat-transfer surfaces for radiators. These studies have shown that the best power-plant

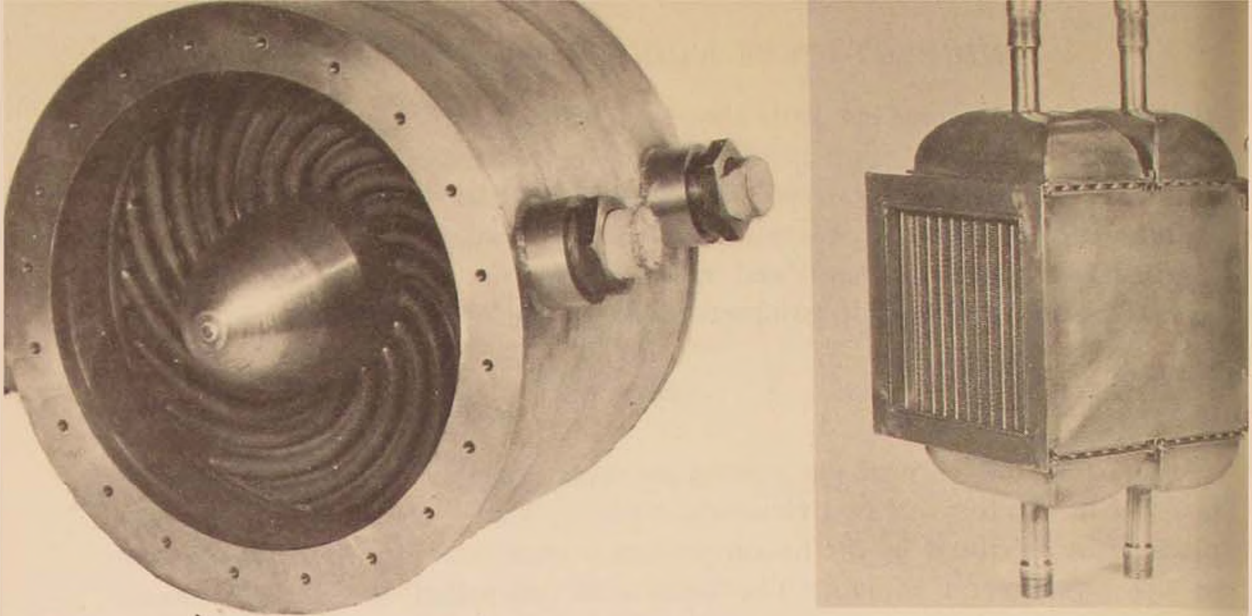


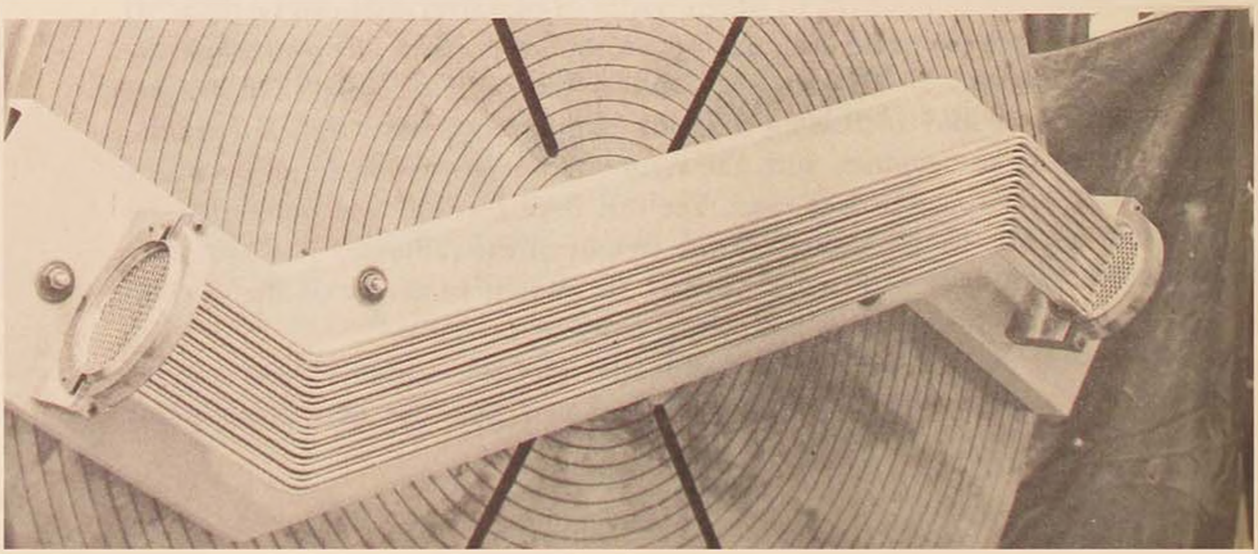
Figure 4. Two experimental extended-surface radiator test units. At left is a tube-and-spiral-fin radiator and at right a flattened-tube-and-plate-fin radiator.

performance results from using heat exchangers with bare prime surface on the liquid-metal side and fins on the air side. Two such extended-surface types that have merited construction and experimental testing are the tube-and-spiral-fin and flattened-tube-and-plate-fin radiators. Radiators are developed by the normal procedure of fabricating, endurance testing, and performance testing, first of small-scale units, then of larger models or sections, and ultimately of prototype radiators.

Intermediate heat exchanger. If an intermediate heat exchanger is used, both fluids will be liquid metals, and in consequence it is likely that the exchanger will be given a direct heat-transfer surface, without fins. Figure 5 shows a typical intermediate heat exchanger constructed during the development program, a shell-and-tube type using bare tubes. Problems concerned with flow distribution, thermal stress, and tube-to-header joints are under investigation.

Turbopump. A centrifugal turbopump, powered by bleed air from the engine, circulates the liquid metal in each loop. The turbopump must be

Figure 5. Intermediate heat-exchanger test unit.



capable of circulating hot liquid metal at high flow rates and at substantial heads with reasonable efficiency. Figure 6 shows all the essential components of a typical development pump. Considerable analytical and experimental

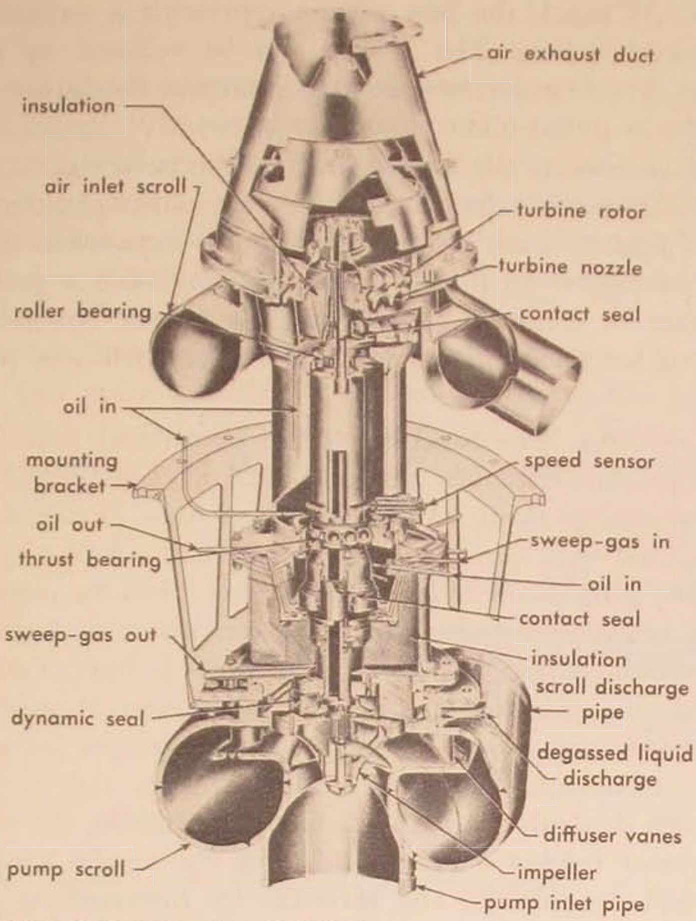


Figure 6. Liquid-metal turbopump TP-1.

study of the liquid-metal flow in the pump inlet, impeller, diffuser, and scroll is required.

Valves. There are three types of valves in the liquid-metal power plant. Control valves are used to regulate the liquid-metal flow in the reactor. Isolation valves may be used wherever there are branching subloops—a sectionalized radiator, for example—so that a leaking section can be sealed off while the remainder of the power plant continues to function. Fill-and-drain valves are needed for servicing the power plant. The valves in contact with liquid metal should be capable of repeated operations at high temperature without self-welding or other damage to the valve seat. Absolutely no leakage is permitted along the valve stems of any type of valve. In addition, shut-off or isolation valves must not leak past the valve seat. When the valve is open, the liquid-metal pressure drop should be low. Operational and endurance tests are required to develop all these features.

Piping. Like the other power-plant components, the piping must contain hot, flowing, liquid metal. Each pipe fitting—elbows, branches, and expansion joints—must be developed for stringent operating conditions. A single piping material capable of both containing the liquid metal and resisting oxidation by the atmosphere is preferred. Otherwise a bimetallic system will be required, perhaps in form of a coating, a cladding, or a dual-wall jacketed type. As usual, the best piping represents a compromise between conflicting considerations. The weight can be reduced by decreasing the pipe diameter, but this decrease in turn increases the liquid-metal pressure drop and reduces power-plant performance.

Inert gas system. As the temperature of the power plant changes, there is differential volumetric expansion between the power-plant components and the contained liquid metal. To provide for this expansion, there must be a free surface somewhere in the liquid-metal system and a gas blanket above this free surface to maintain pressure on the system. An inert gas, such as helium, is used for the blanket so that the system will not become contaminated.

Propulsion units. The function of the propulsion units, or engines, in a nuclear propulsion system is to convert the heat generated in the reactor into useful propulsive thrust. This conversion must be accomplished with a high efficiency and with a minimum of weight and complexity in the engine. There are many propulsion cycles to choose from, but the most desirable ones are generally variations of the Brayton cycle, which consists ideally of the following thermodynamic processes: isentropic compression, constant-pressure heat addition, isentropic expansion, and constant-pressure heat rejection. The engines using this cycle that are of interest for aircraft propulsion are the turboprop, the turbojet, the turbofan, and the ramjet. Which engine is chosen depends on the particular applications, the turboprop being generally superior for low-speed applications, the ramjet for high-supersonic application, and the turbojet and turbofan for intermediate speeds.

The turbojet engine illustrated in Figure 7 scoops up air through the inlet, compresses it in the compressor, heats it in the radiator, and expands it through the turbine, which drives the compressor by means of the connecting shaft. The air is further expanded through the nozzle to a high velocity to produce useful thrust.

The turboprop differs from the turbojet in that the air is expanded further in the turbine to produce additional shaft power, which is used to drive the propeller. A reduction gear is interposed between the engine and propeller so that each may operate at its most efficient speed. The turboprop derives most of its thrust from the propeller and only a small amount from the jet.

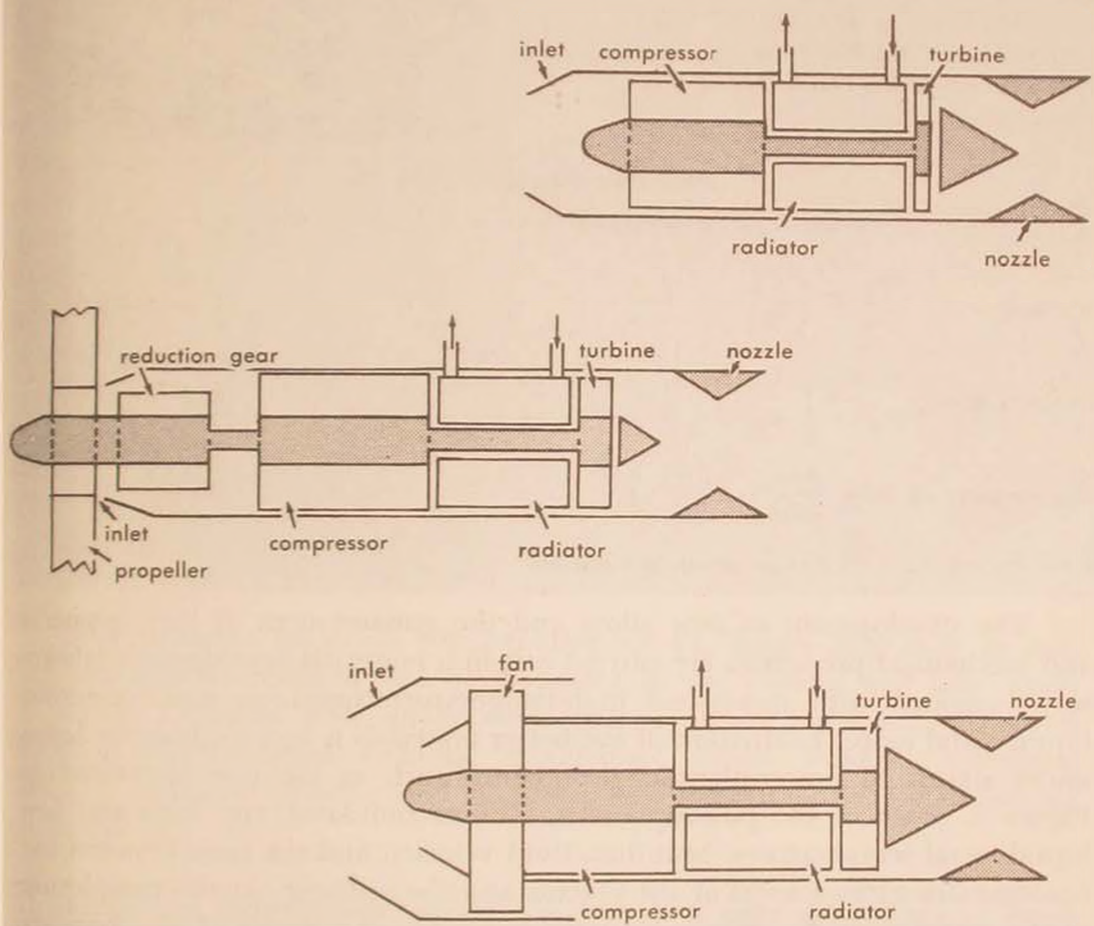
The turbofan may be thought of as a turboprop with the propeller in a duct. There are several possible versions of this engine; in the one shown the fan blades are extensions of the first few compressor blades. The fan blades may also be extensions of the turbine blades, or the fan may be on a separate rotor driven by a separate turbine through a concentric shaft. Regardless of the arrangement, the thermodynamic cycle is the same.

The simplest of the propulsion engines is the ramjet, which has no rotating parts and obtains the compression of the air solely by the forward motion of the engine through the air. The airplane or missile using this engine must be boosted to very high speed before it becomes self-sustaining.

materials

Materials capable of functioning under extremely exacting environments are being developed. Without specific statement of their applications or relative merits, it can be revealed that some of the materials under consideration or now being worked on are beryllium and its compounds, boron compounds, europium and gadolinium compounds, hydrides, molybdenum, tungsten, and zirconium. Alkali metals are among the liquid metals of interest as heat-transfer fluids.

Among the desired properties of structural materials are high-temperature strength and good ductility at all temperatures. The materials must also withstand corrosion of liquid metals and, for certain applications, must resist oxidation by the atmosphere. They should not be significantly



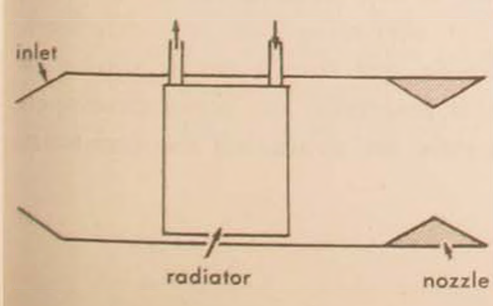


Figure 7. The four engines using the Brayton cycle which are of interest for nuclear propulsion systems are (from top to bottom): turbojet, turboprop, turbofan, and ramjet.

damaged from irradiation by neutrons or gamma rays. Special-purpose materials such as shields, moderators, reflectors, and poisons must possess the above properties to varying degrees, in addition to their particular characteristic of absorbing, reflecting, or moderating radiation.

The liquid-metal reactor coolant should not become radioactive. It should have a reasonably low melting temperature and a low vapor pressure at high temperature. It should have a high specific heat, a high thermal conductivity, and a low viscosity.

The basic physical properties and certain performance parameters of some of the liquid metals considered can be compared in tabular form.

Comparison of Liquid-Metal Coolants

	lithium	*sodium*	*potassium*	*sodium-potassium alloy*
melting point, °F	354	208	147	66
density, lb/ft³ (ρ)	28	47	41	45
specific heat, Btu/lb-°F(C_p)	0.99	0.3	0.19	0.25
volumetric heat capacity, Btu/ft³-°F(ρC_p)	28	14	7.8	11
vapor pressure at 2000°F, psi	2.1	77	156	96
thermal conductivity, Btu/hr-ft-°F(k)	18	35	20	18
viscosity, lb/hr-ft(μ)	0.56	0.44	0.32	0.38

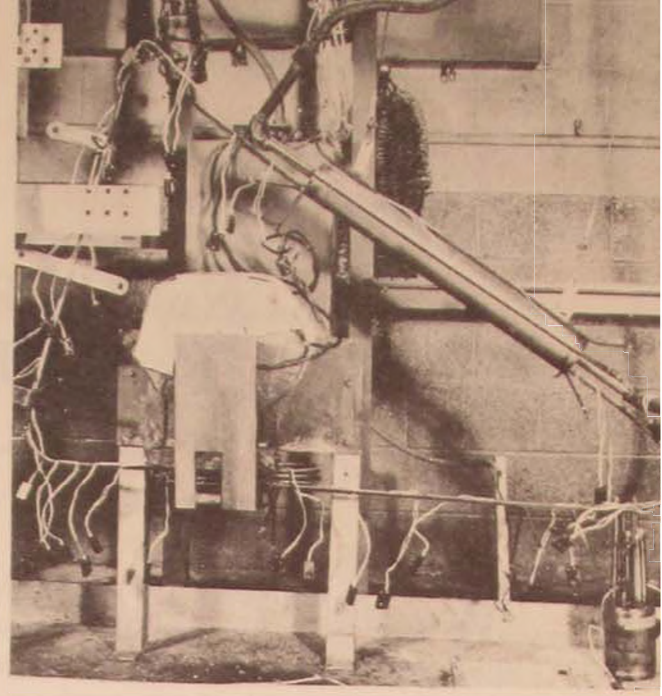
Relative Performance
(Constant Size System and Thermal Conditions)

	lithium	*sodium*	*potassium*	*sodium-potassium alloy*
pressure drop, $\frac{\Delta P_1}{\Delta P_2} = \left(\frac{C_{p2}}{C_{p1}}\right)^{1.8} \left(\frac{\rho_2}{\rho_1}\right)\left(\frac{\mu_1}{\mu_2}\right)^{0.2}$	1.0	4.89	11.9	6.85
pumping power, $\frac{hp_1}{hp_2} = \left(\frac{C_{p2}}{C_{p1}}\right)^{2.8} \left(\frac{\rho_2}{\rho_1}\right)^{2}\left(\frac{\mu_1}{\mu_2}\right)^{0.2}$	1.0	9.63	43.7	16.9
film temperature drop, $\frac{\Delta T_{f1}}{\Delta T_{f2}} = \left(\frac{k_2}{k_1}\right)^{0.6}$	1.0	0.671	0.939	1.0

Note: Properties at 1450°F unless otherwise indicated.

The development of new alloys and the measurement of their physical and mechanical properties are carried out in a materials-development laboratory equipped with specialized high-temperature apparatus and numerous liquid-metal loops. Evaluation of the better materials is accomplished in loops under simulated power-plant environments, such as the one illustrated in Figure 8. Some of the power-plant conditions simulated are: high and low liquid-metal temperatures, heat flux, fluid velocity, and the ratio between the heat-transfer surface areas of the reactor and the radiator. At the completion of the test, which may run several thousand hours, sections of the loop are metallurgically and chemically examined for corrosion and erosion effects. The loops are operated either in atmospheric test stands or, as shown in Figure 9, in inert-atmosphere stands. Special materials are being developed for bearings, seals, and valves. These materials are evaluated for corrosion, erosion, and self-welding characteristics.

Figure 8. Corrosion-test loop, triangular in shape, through which a liquid-metal coolant is pumped in a clockwise flow. The heater electrical lugs are on the triangle's vertical leg, and the cooler is on the hypotenuse. The multipass electromagnetic pump is on the base of the triangle, the sump tank at the lower right, and the surge tank at the upper left. The many white wires attached to the loop are thermocouple leads.



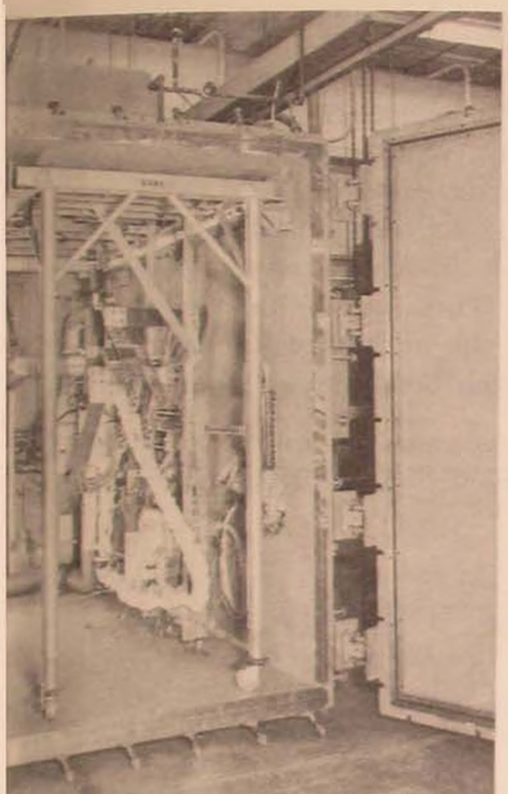


Figure 9. Forced-convection, liquid-metal corrosion loop, triangular shaped, installed in inert-atmosphere chamber.

The stringent materials requirements set by design objectives necessitate considerable research and development in the joining and fabrication of metals. Processes now under development include solid-state diffusion bonding, electron-beam welding, shielded-arc fusion welding, ultrasonic welding, extrusion pressing and sintering, and various other metal-working techniques.

Although the indirect-cycle propulsion system is only now ready to enter the initial experimental test reactor phase, the characteristic features of the liquid-metal, indirect-cycle power plant—light weight, excellent performance, good growth potential, and versatility—are well suited for application to manned aircraft as well as other possible uses at later dates.

Middletown, Connecticut

Nuclear Reactors for Ramjet Propulsion

DR. THEODORE C. MERKLE

Associate Director, Lawrence Radiation Laboratory

WHILE nuclear-ramjet propulsion systems have been imagined in many forms over the past thirteen years, it is generally considered that the most practical device consists of a suitable inlet diffuser system followed by a single-pass-straight-through heat exchanger, which of course couples into a typical exhaust nozzle. Figure 1 illustrates such an "engine."

The nuclear reactor in such a system usually is conceived to be identical with the heat exchanger. Within this simple framework several possibilities present themselves to the reactor designer. These possibilities are governed by the aerodynamic requirements of flight, the nuclear requirements of the reactor, the chemical problems associated with breathing air (both wet and

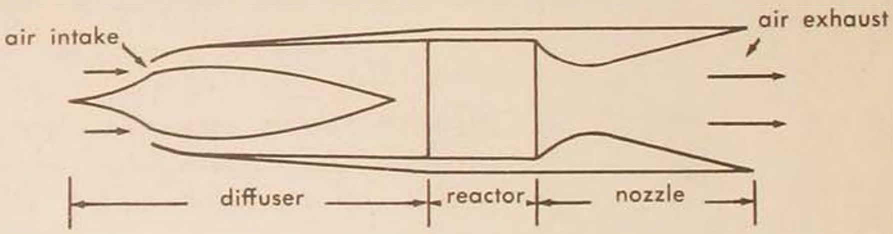


Figure 1. Basic elements of a nuclear-ramjet "engine."

dry), and the mechanical properties of materials at rather elevated temperatures.

The aerodynamic requirements of flight are illustrated in a qualitative manner in Figure 2, which gives some typical relations between flight mach number, heat-exhanger wall temperature, and net thrust coefficient, for a duct containing a reasonable reactor. Although qualitatively given, the curves illustrate two major points that directly determine reactor design. First, net thrust—and therefore presumably performance of a given missile—will be improved rather rapidly with increasing wall temperature. Furthermore, since some minimum value of the net thrust will be required to fly the missile at all, there is a corresponding minimum reactor wall temperature (for a given geometric configuration) that must be attained. This minimum turns out to be rather high in terms of materials normally associated with reactor construction. Thus for nuclear-ramjet reactors there is an enormous premium in performance to be attained by developing systems that can operate satisfactorily at the highest possible temperatures.

The second major point to note is that, other quantities being equal, the net thrust coefficient tends to maximize near mach 3. Thus if a reactor wall temperature is determined by the behavior of a material at elevated temperatures, the best missile performance could be anticipated near such a mach number. This fact in turn indicates that the reactor must be designed to stand a considerable pressure across its face. At sea level, for example,

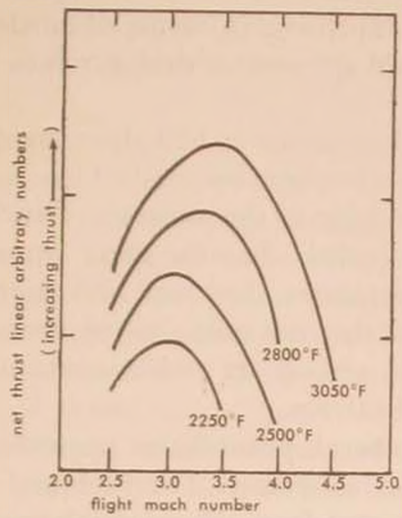


Figure 2. Qualitative presentation of aerodynamic factors that help solve reactor design problems. The four temperatures are heat-exchanger wall temperatures.

the stagnation pressure for mach 3 is approximately 550 pounds per square inch (psi). Such a pressure is not very formidable when structural weight is unimportant. When coupled with high temperatures, weight limitations, and the peculiar structural materials appropriate to the reactor neutronics, it can be supposed that many new research and development problems will be encountered.

choice of reactor system

The wall temperature requirement, when joined with the oxidizing effects of hot air, narrows the choice of wall surfaces to materials at least capable of withstanding oxygen attack for long periods. Such materials are high-melting-point metals, certain intermetallic compounds, and the oxides. It is true that a few other types of materials will resist oxidation by forming oxide surface layers while in use, but these materials may be conveniently classed with the oxides. It is also true that oxides will withstand higher temperatures in air by several hundred degrees Fahrenheit than the best of the present metals. Furthermore it is desirable but not mandatory to avoid thin coatings of oxides on air-passage walls to protect an otherwise combustible structural substrate. Thus from the chemical point of view alone, it might be desirable to form the reactor body of solid oxides or from those materials that could be counted on to form a self-generating protective oxide coating.

Chemistry and aerodynamics are not in themselves sufficient. The reactor must also live with the behavior of neutrons. Here the choices become a little more complex because we must select the way in which we wish to distribute the nuclear fuel and determine the amount of such fuel that may be invested in a given propulsion system. The amount of fuel to be spent also influences design by deciding the choice between a "fast" reactor and a "moderated" reactor. It turns out that for any reasonable missile size a fast reactor is extremely expensive in terms of nuclear fuel. Thus an economic argument has coerced the reactor designer into a serious consideration of moderated reactors.

The slowing down of neutrons is best done by atoms that individually are as close as possible to a neutron in mass. Thus for moderating a ramjet reactor the elements that suggest themselves are hydrogen, beryllium, and carbon. Helium has been omitted because there is no known way to render it solid at elevated temperatures. Lithium and boron have been omitted because in the natural state they not only slow neutrons but also devour them. The elements heavier than carbon are rather unattractive, since they do not slow the neutrons very effectively.

At this point two general possibilities present themselves: the heterogeneous or the homogeneous reactor. The fuel, and with it the heat transfer to the air, can be separated from the materials used to slow the neutrons. Such a reactor is called a heterogeneous reactor. Or the nuclear fuel can be mixed with the moderating material so that the moderation and the heat transfer to the gas are carried on by the same substance. However, while uranium forms the very refractory oxide UO_2, it also forms a volatile oxide when heated to a high temperature in the presence of air. So if a heterogeneous reactor is selected, the uranium fuel (presumably in the form of UO_2) must be protected against direct contact with the airstream.

Selection of this alternative forces the development of some suitable canning procedure. If the cans are metal, then the aerodynamic performance is restricted to that obtained with high-temperature metals. As indicated earlier, such temperatures are not very attractive for nuclear-ramjet-engine applications. It is possible to consider "cans" or fuel elements consisting of a high-temperature ceramic. Such a selection again forces the development of new materials techniques and presents more complications than the remaining general possibility, which is the homogeneous reactor. If a homogeneous reactor is selected, its core may be imagined to be a right cylinder of height roughly equal to its diameter. This cylinder is drilled with close-packed holes such that the open area is roughly half the area of one end of the cylinder. The length-to-diameter ratio of the holes might be approximately 200.

problems in a homogeneous reactor

At this point in the analysis the demands of flight thermodynamics, chemistry, a portion of reactor physics, and a brief consideration of the economics of uranium-235 have indicated that a nuclear-ramjet reactor might logically be a homogeneous moderated reactor fabricated of a high-temperature oxide of a light metal or that it might possibly be fabricated of a carbide which will form a self-protective oxide coating. Among the light metal oxides there exists only one that is a good moderator, namely, BeO. Among the carbides the most reasonable from the chemical point of view would be SiC, although it is well known that BeO is a far superior neutron moderator. It is also possible that certain of the intermetallic compounds of beryllium could be used in such a homogeneous reactor. The main point is that the choices which can be made in the foreseeable future are indeed severely limited.

The mechanical design of such a homogeneous reactor must include means of carrying three major classes of stress. To begin with, there are the stresses associated with the pressure drop through the reactor. As indicated earlier, this stress is in the order of hundreds of pounds per square inch when spread over the entire reactor. When concentrated at various support points it contributes loads of thousands of psi. To transfer heat from the fuel to the airstream, there must be a temperature drop in the fuel-bearing materials; and for typical ceramics and power densities that would be of interest in possible missile applications, stresses of many thousand psi result from these temperature differences. Such stresses are referred to as "thermal stresses" when occurring in the steady state and as "thermal shock" when occurring under transient conditions. Finally there are the stresses resulting from gravity forces associated with flight. Since in principle ramjet power plants must operate from sea level to quite high altitudes, rather large "gust loadings" must be anticipated.

Now it is certainly true that most of the technology of Western civilization rests on the fact that metals yield. In a given mechanical device small and inevitable errors in design, fabrication, and material properties can equalize under large loads because overstressed areas can yield without major loss of strength. On the other hand the oxides and carbides, selected up to this point as suitable ramjet reactor materials, are all very hard, brittle substances. Even when these materials are fabricated in such a way that suitable strengths are obtained for high temperatures, they do not ordinarily possess the familiar yield characteristics of metals. Clearly, then, two areas of work are indicated: (1) by ingenious design to minimize the need for yield in the material and (2) by ingenious research to impart at least some "give" to otherwise recalcitrant substances. All this must be done, of course, without vitiating the high-temperature and neutronic properties of these substances.

If, somehow, materials are developed and fabricated so that a useful ramjet reactor might be built, a few annoying problems still remain. The first has to do with the variation of the degree of criticality of a homogeneous moderated reactor as the temperature varies from ambient to the very high operating temperature desired. Such variations may be equivalent to having to increase the amount of fuel in the reactor by fifty per cent or more to maintain criticality during warmup. Since no "hot moderator" reactors have been run to date, it is desirable to run a "critical measurement" program on a variety of systems constructed inside a large high-temperature oven. Such an oven has been built in Nevada by Lawrence Radiation Laboratory and has been measuring hot "crits" since February 1959. This large negative temperature coefficient of reactivity has a good and a bad future. On the good side it makes the reactor rather safe, since if it "runs away" it will get too hot and shut down the power increase. On the bad side it makes necessary a very large "control swing," associated with a large excess reactivity potential built into the system. If improperly handled, such a large excess reactivity can lead to a very short reactor period, which can have embarrassing consequences. Otherwise this large swing in control as the temperature rises would not appear to be very troublesome.

Another annoying problem in a nuclear propulsion system has to do with the large flux of neutrons and gamma radiations given off by the reactor. These radiations contribute a large heat load to structural materials inside the reactor and also create an unpleasant environment for materials outside the reactor. Even though the missile is unmanned, the heating effects of these radiations must be taken into account very carefully. Furthermore, the radiations are intense enough to make it necessary to avoid certain materials altogether or to shield them heavily. Thus many components of the propulsion system, even though not directly involved in the reactor design, must be specially developed for the environment. Since the stagnation temperature of mach-3 air at sea level is about 1000°F, environmental problems are severe even without the reactor radiations.

The reactor radiations, although intense, do not lead to problems with persons on the ground when such a power plant passes overhead at flight speed, even at very low altitudes. Also, persons near the launching point need not be exposed to excessive radiation even though unprotected, as the reactor can be brought up to power during the boosting phase subsequent to launching.

The question of launching necessarily suggests the question of regulating the reactor power during flight. If it is desired to use a homogeneous reactor in a ramjet, it will be necessary to live with a power plant that turns off and on rather slowly. The heat capacity of the reactor is of course quite large, and this feature makes variations of power in the gas stream quite sluggish, even though reactor power-generation rates can be relatively rapid.

In addition to the sluggish response to demands for power change, a nuclear reactor cannot be turned off in a very short time because of the heat liberated by radioactive nuclei created during the operating period. If it is desired to land or recover a ramjet missile, this power-plant feature will require special provisions for aftercooling, or "shutdown" cooling as it is called, once the normal ram-air cooling has stopped. For typical types of ramjet power plants the heating rate is in the order of megawatts immediately after shutdown, and it decays rather rapidly from this value.

Nuclear-ramjet propulsion systems have essentially one advantage over chemical systems of the same weight (including fuel)—a relatively long cruising range. Contrary to popular belief, this range is not infinite. Several factors can limit the life of a reactor for ramjet applications to periods of time from a few hours to a few days, depending on the methods of construction. The most obvious limit is actual fuel consumption. If accumulation of reactor poisons can be avoided, many days of operation would be reasonable from the standpoint of fuel burnup.

However, when a uranium atom fissions in a material, the material near the fissioning atom is disrupted by the fission fragments. Such radiation damage in power reactors operating at lower temperatures than required for ramjets can limit the structural life of these materials to a few-per-cent burnup, depending on the detailed nature of the material. For ramjet reactors an interesting by-product of the high-temperature operation is the possibility that at least some of this sort of damage can "anneal" out of the material, thus appreciably increasing the reactor life.

One problem that bothers the designer of reactors is the necessity of confining all the fission products to the reactor fuel elements. In the case of a nuclear-ramjet missile it is interesting to note that this problem is not severe. A typical mission might produce somewhat less than 100 grams of fission product. It might be expected that some large percentage of this product would naturally remain in the fuel elements and the quantity released into the airstream be only a few grams. These few grams will, by the very nature of the ramjet, be distributed over the thousands of miles of its flight path. Consequently the fission activity introduced locally into the atmosphere is minute compared with that of even the smallest atomic weapon. For actual military use a ramjet power plant need not be designed for complete retention of fission activity. For routine testing, however, and for training missions in peacetime it is desirable to develop materials that really hold the emission of fission fragments to extremely small values.

I BELIEVE that the nature of the challenge facing the designer of a ramjet-engine reactor has been illustrated rather completely by the discussion up to this point. It may be of further interest to itemize the major research and development areas that must be entered to actually produce such an engine:

- High-temperature ceramic materials must be developed to a high degree of reliability—both in the laboratory and in production—with respect to mechanical properties.

- Techniques for distributing the fuel in appropriate amounts in such materials have to be evolved. These techniques must provide that the material will not leak fuel at high temperatures. It would be nice if the material did not leak fission fragments either.

- These materials must be developed with such characteristics that chemical attack by the various components of air on the flow-passage walls does not unduly limit the useful life of the reactor.

- Ingenious mechanical design features must be evolved to enable effective exploitation of these novel materials.

- The nuclear physics of hot moderator systems must be explored in great detail, both experimentally and theoretically.

• Novel control systems, compatible with flight requirements, must be developed. In some cases new materials must be evolved for portions of such systems.

• Since the cost of testing a complete, full-sized reactor is quite high, methods for fully testing components and subassemblies must be worked out.

• A series of reactors must be built and tested to "evaluate" a satisfactory finished product. It might be expected that the first reactor of such a type would define new problems rather than provide answers to existing questions.

• Since many fabrication methods of a new sort are required, it will be necessary to develop manufacturing practices, product-control methods, and inspection techniques with a sharp eye on the various cost factors involved, if such reactors are to become suitably inexpensive. This feature might turn out to be no small order, since many of the materials of interest are by no means items of commerce today.

• Finally every item in a proposed missile must be engineered to be compatible with an intense radiation environment and must be tested in such environments.

It has been publicly announced that the Atomic Energy Commission's Lawrence Radiation Laboratory, operated by the University of California, is presently constructing facilities at the Nevada Test Site for the purpose of operating engineering test reactors in connection with Project Pluto. The development of a reactor to test in these facilities would clearly indicate a serious start upon this development road rather than the end of the journey.

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Design of a Nuclear Ramjet

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THE RAMJET engine has received increased attention for airplane and missile applications in recent years as flight applications for air-breathing propulsion have advanced further into the supersonic regime. Sometimes referred to as a "flying stovepipe," the ramjet is in principle the simplest of the air-breathing engine class, which includes reciprocating, turboprop, and turbojet engines. This superficial aspect of simplicity is unfortunately lost when we consider that a ramjet does not operate always at precisely its design point. A great deal of sophisticated engineering is required to permit it to operate successfully over the wide range of flight conditions—mach number, altitude, ambient temperature, rate of climb, etc.—required for practical application.

Conceptually the ramjet consists of three major components: a diffuser for decelerating and compressing the inlet airstream and recovering its kinetic energy in the form of "ram pressure" with good efficiency; a heat addition region where heat is added to the airstream by means of a nuclear reactor (or radiator or chemical combustor); and an exhaust nozzle for expanding the heated airstream back to essentially the ambient pressure. Propulsive thrust arises from the increase in momentum imparted to the airstream by the engine. In other words the airstream leaves the exhaust nozzle with a higher velocity (relative to the engine) than the velocity of the airstream entering the diffuser, and the engine's thrust per unit mass of airflow is equal to the difference between these velocities.

Because the ramjet depends on its own forward motion for compression of the incoming airstream, the engine produces no thrust at zero speed. In fact the ramjet must be brought to fairly high speeds (typically slightly supersonic) to produce enough thrust to make up for internal losses and vehicle drag. Thus ramjet-powered vehicles must be boosted or accelerated to ramjet-takeover speeds by auxiliary means, such as by the use of turbojets or rockets or by launching from a mother aircraft. For manned aircraft or for recoverable missiles, some auxiliary means such as turbojets or parachutes must also be employed for landing. Most of the current ramjet applications are for rocket-boosted missiles, for which the ramjet's freedom from large turbomachinery presents major cost advantages. Hybrid combinations of the ramjet with the turbojet and the rocket have also been considered.

the nuclear ramjet

Primary attention is focused in this discussion on the open-cycle nuclear ramjet, in which air is passed directly through a nuclear reactor. As with the turbojet cycles considered in preceding pages, it is also possible to design a closed-cycle nuclear ramjet system. Here the reactor is cooled by, say, a liquid-

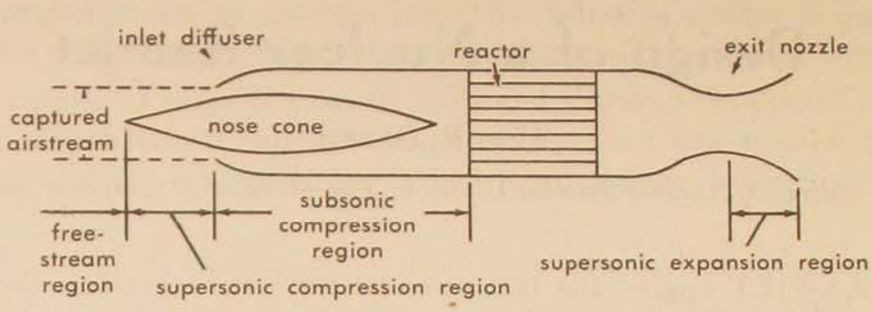

Figure 1. Simplified schematic of a nuclear-ramjet engine.

metal coolant, which in turn heats the engine's airstream in a liquid-metal-to-air radiator.

Some fundamental aspects of nuclear-ramjet performance analysis will be discussed first, with special attention to the importance of the inlet diffuser. Results of typical performance calculations will be shown graphically. These will be followed by discussions of reactor requirements, control considerations, and the special problems in ground-testing nuclear ramjet engines.

nuclear-ramjet performance analysis

The inlet. Quite large pressure ratios are potentially available from ram compression at supersonic speeds. For example, complete isentropic deceleration (i.e., without losses) of a mach-2 airstream gives a pressure ratio of 7.8/1; mach numbers of 3 and 4 give pressure ratios of 37/1 and 157/1, respectively. The inlet designer must provide a system that recovers as much as possible of the available pressure ratio.

The most obvious way to decelerate a supersonic stream would be to allow it, or to cause it, to undergo a normal shock. This is indeed a satisfactory procedure for mach numbers up to about 1.5. Above mach 1.5 the inefficiency associated with a strong normal (perpendicular) shock becomes objectionable. For example, a normal shock at mach 1.5 is 93 per cent efficient, but a normal shock at mach 3 is only 33 per cent efficient.

At the higher mach numbers the general approach is to pass the airstream through one or more oblique shocks to decelerate the air to a lower (but still supersonic) velocity, followed ultimately by a weak (efficient) normal shock. Take three design configurations—a normal shock inlet, a conical spike inlet (single oblique shock), and an isentropic spike inlet. As the number of oblique shocks is increased and the mach number ahead of the normal shock decreases, the inlet becomes a more efficient pressure-recovery device. The limiting case is the so-called isentropic spike inlet in which the spike is shaped to produce an infinite number of oblique compression waves followed by a weak normal shock. Such an inlet offers attractive pressure recovery at higher mach numbers, but it is very sensitive to off-design conditions. For most cases up to mach 3 or thereabout the simple conical spike (or equivalent) is adequate, and the later discussions of control will be focused on this type. In practical situations inlet design is profoundly in-

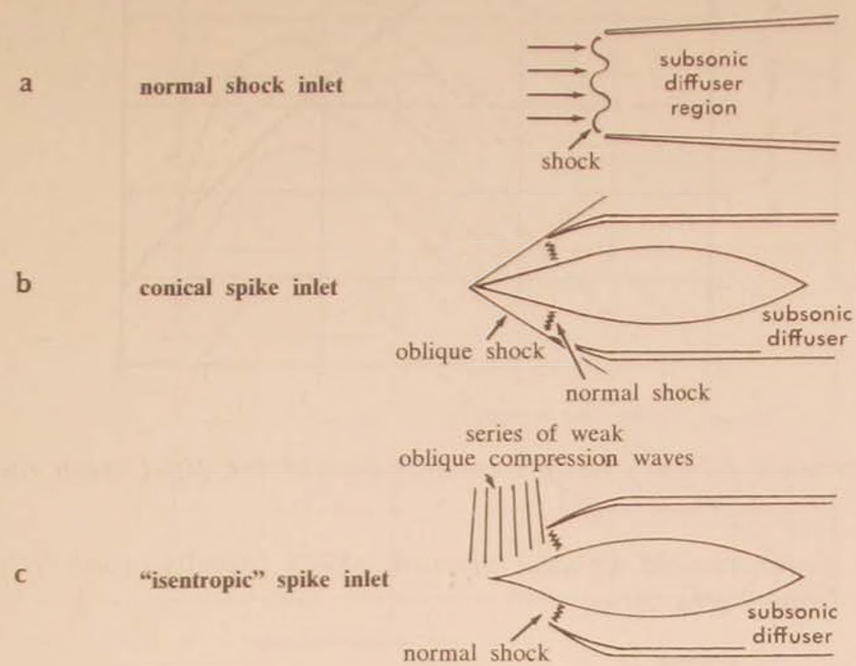

Figure 2. Three typical supersonic inlets. The simple normal shock is the least efficient and the isentropic spike the most efficient for pressure recovery.

fluenced by such considerations as the effect of the installation on over-all missile drag, payload or fixed equipment packaging, structural design, etc.

Results of performance analysis. The propulsive thrust of a nuclear-ramjet engine depends mainly on several factors:

- mach number
- altitude (or ambient air pressure and temperature)
- pressure recovery of the inlet diffuser
- temperature to which air can be heated by the reactor
- pressure drop incurred by air in going through the reactor
- efficiency of expansion process in exit nozzle

Sample calculations are presented below which show the interplay of these factors. For simplicity it is assumed that the pressure drop through the reactor is 30 per cent of the total pressure at the reactor inlet face. A perfect (isentropic) exit nozzle is assumed, with the air being expanded back to ambient pressure in all cases regardless of nozzle size or airframe installation considerations. AIA pressure recoveries (i.e., accepted by Aerospace Industries Association) are assumed (Figure 3).

Ramjet thrust is conventionally stated in terms of a dimensionless thrust coefficient, C_F, which is defined as the net thrust divided by the product of the

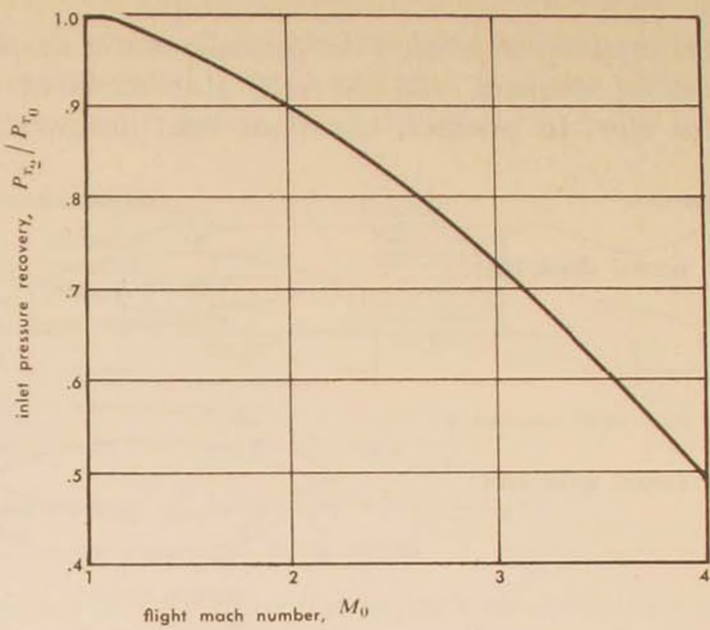

Figure 3. Inlet pressure recovery (AIA standard) plotted for flight mach number.

free-stream incompressible dynamic pressure, $\rho V^2/2$ (usually called "q"), and a reference frontal area, A, or

$$C_F = \frac{\text{thrust}}{(\tfrac{1}{2}\rho V^2)\,A}$$

In selecting a reference area, two different areas are of interest for the nuclear ramjet. These are (1) the free-stream capture area, A_0, which is the cross-sectional area of the tube of air swallowed by the engine, and (2) the reactor cross-sectional area, A_R. For the purpose of the results shown here, it is assumed that the air mach number in a reactor passage at the reactor inlet is 0.25. The reactor is further characterized by its free-flow area or void fraction, which is the fraction of its frontal area that is open to airflow. A void fraction of 0.5 was assumed. Some of the problems of reactor design are touched on later.

Figure 4 shows thrust coefficients (based on free-stream capture area) versus mach number for three air temperatures at sea level and at altitudes of 36,089 to 82,000 feet (tropopause). Figure 5 shows thrust coefficients based on reactor frontal area. It should be emphasized that these engine data are "rubberized"; that is, each point on a curve represents an engine designed for operation at that point, so that each point represents an engine physically different from that at another point.

For a given real engine—designed for operation at a specific condition—performance at flight conditions other than design point will be poorer than that indicated by the results on rubberized engines. At each flight mach number the engine's inlet supplies a specific amount of air. Figure 6 shows inlet airflow versus mach number for a 30° conical inlet designed for mach-3 operation. Usual practice is to specify airflow in terms of a "capture area ratio," which is the ratio of the cross-sectional area of the tube of air swallowed by the engine to the cross-sectional area swallowed by the engine when it is just

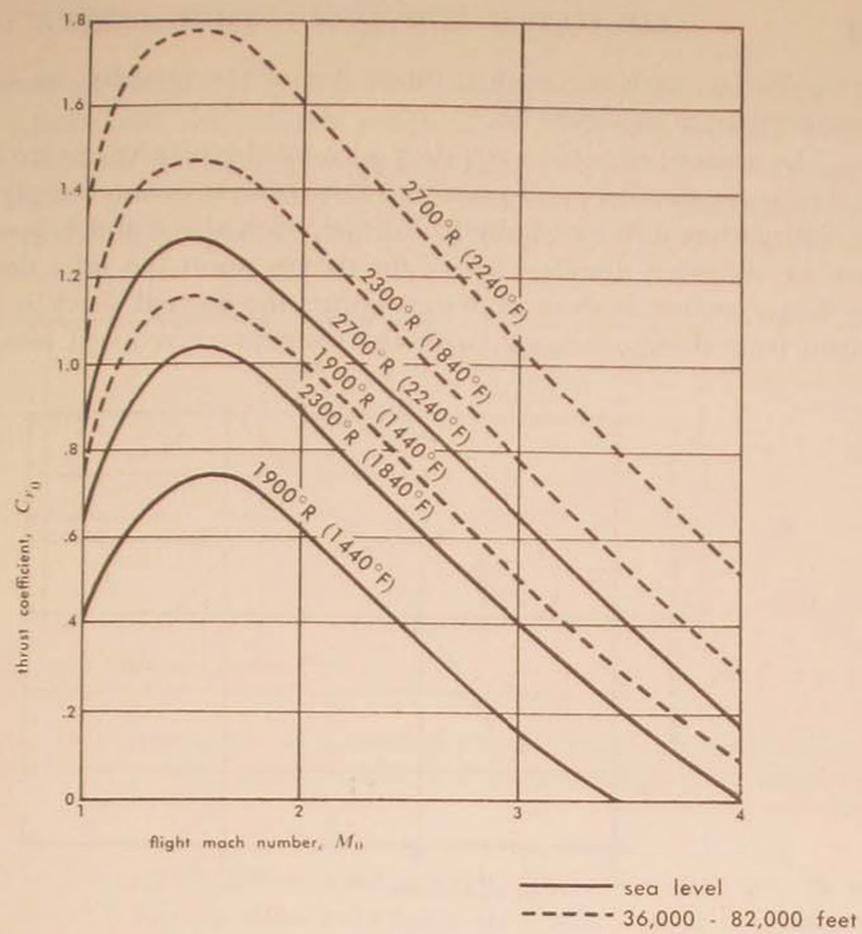

Figure 4. Thrust coefficients (based on free-stream capture area) of a nuclear ramjet versus mach number at sea-level flight and at 36,089 to 82,000 ft altitudes. The six air temperatures shown on the curves are those at the reactor outlet.

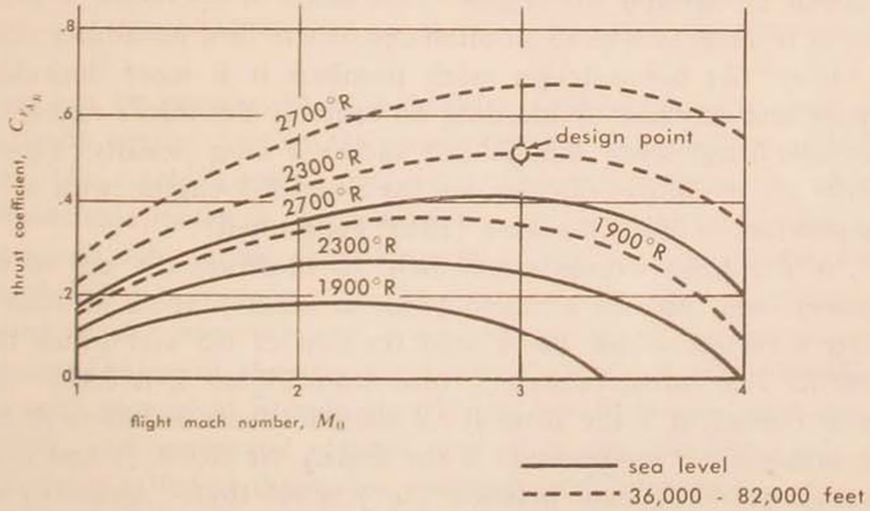

Figure 5. Nuclear-ramjet thrust coefficients of Figure 4 based on reactor frontal area instead of free-stream capture area, for flights at sea level and at 36,089 to 82,000 ft altitudes. The six temperatures shown are reactor temperatures.

"critical"—i.e., with the normal shock just at the cowl lip, or minimum flow area location, as in Figure 2b.

The amount of airflow required by a fixed-geometry engine is determined by the air temperature and pressure at the reactor outlet. Supply and demand get balanced in different fashions for operation above and below design mach number. At mach numbers above the design point the inlet does not supply any larger airstream than at design point; the normal shock is sucked downstream from design location, with the consequent reduced pressure recovery

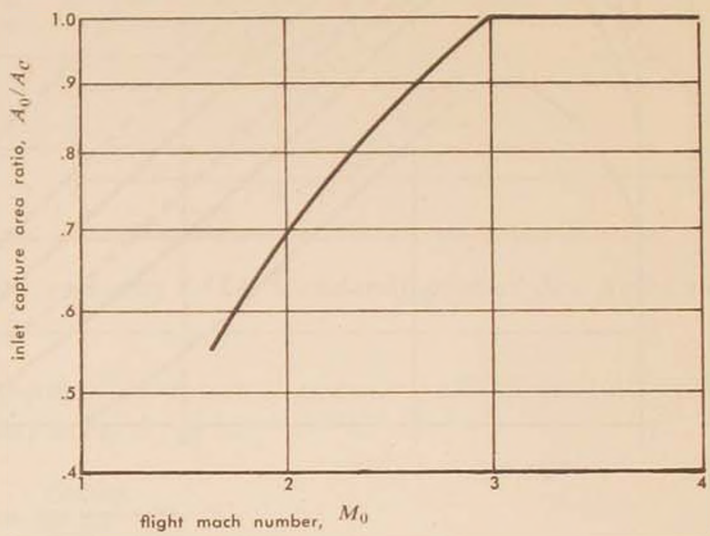

Figure 6. Curve showing the assumed inlet airflow (or inlet-capture-area ratio) versus the mach number for a 30° conical inlet designed for mach-3 operation.

leading to a large enough reduction in engine demand to balance supply and demand. At mach numbers below design point the normal shock would tend to move upstream onto the inlet cone, with consequent spillage of part of the subsonic air around the engine. This mode of operation is avoided in practice, as it tends to lead to an often-destructive flow instability situation known as "buzz." At below-design mach numbers it is more desirable to balance supply and demand by bleeding off some of the inlet's excess supply within the inlet itself, even though this incurs a drag penalty. Figure 7 presents results on off-design calculations for a mach-3 engine with a reactor outlet temperature of 2300° Rankine (1840° Fahrenheit).

A simplified example may help to illustrate the use of the thrust coefficient data. Assume a design point of mach 3 at an altitude of 60,000 ft, using a reactor which has a void fraction of 0.5 and which delivers air at 2300°R. The thrust coefficient, read from Figure 5, is 0.495. (Note that the thrust coefficient is the same at all altitudes from 36,089 to 82,000 ft because the ambient air temperature is the same.) At 60,000 ft and mach 3, the air incompressible dynamic pressure ("q") is 945 lb/ft^2. Assuming a reactor with an over-all diameter of 6 ft, or a frontal area of 28.3 ft^2, the engine thrust is then equal to $0.495 \times 945 \times 28.3 = 13{,}200$ lb. Assuming that a lift/drag ratio of 4 could be achieved for a missile with this engine installed, the missile's allowable gross weight would be 52,800 lb. If we further assume that the missile structure weighs 35 per cent of the gross weight, or 18,500 lb, and that the engine and its controls weigh 20,000 lb, then we find that a balance of 14,300 lb is available for useful load (payload, armament, electronic equipment, auxiliary power or cooling equipment, etc.). This engine would have a total airflow of 376 lb/sec and a reactor heat output of 130,000 kilowatts at

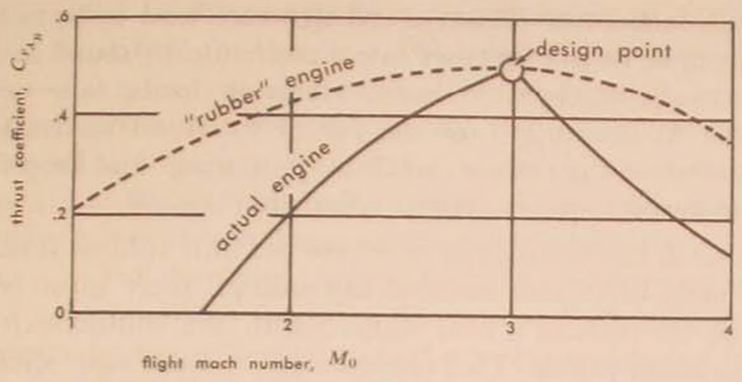

Figure 7. Off-design performance of a mach-3 engine with a reactor outlet temperature of 2300°R, and comparative rubberized performance data from Figure 5.

design point. The air specific thrust is 35 seconds (or 35 lb thrust per lb/sec airflow). This figure is low by chemical-engine standards, but it is characteristic of nuclear ramjets, which are limited in temperature and which have large pressure losses in the reactor.

Reactor considerations. In the foregoing engine-performance data, the nuclear reactor was treated only in terms of its influence on the airstream. That is, the reactor was simply a device for heating the air to a certain temperature at the cost of a certain pressure loss. Internal reactor parameters (void fraction and inlet mach number) were included primarily to give a feeling for reactor cross-sectional area as it compares with the free-stream capture area.

The reactor can be assumed to be a cylinder, with air flowing along its axis, installed in the engine duct in the place otherwise occupied by a chemical-fuel burner. The reactor consists essentially of a solid structure, in which is embedded fissionable material (such as U^{235}), with many small-diameter ducts along the axis for airflow. The fraction of the reactor frontal area available for airflow has been defined as the void fraction. Heat is generated within the fueled reactor structure and is transferred, largely by forced convection, to the air. Design of the reactor involves a very complex interplay of technologies such as nuclear physics, metallurgy, aerodynamics, heat transfer, stress analysis, and automatic control, and it is possible here only to mention qualitatively a few of the major problems and interplays:

• To produce high air temperatures in a reactor of reasonable size, a very large amount of heat-transfer surface must be provided so that the required surface-heat flux is lowered and the temperatures and the thermal stresses of the reactor fuel-element surfaces are kept within the allowable limits of the materials. At the same time too much heat-transfer surface would cause too large an air-pressure drop and adversely affect performance. Also, small-scale passages can create difficult tolerance problems in manufacture and assembly.

- Because of the high operating temperatures characteristic of ramjet performance and because of the presence of oxidizing atmosphere, materials for fuel element, moderator (if any), and structure tend to be rather brittle. These materials must be put together into a mechanically sound structure that can stand air loads, acceleration loads, vibration loads, large temperature differentials, etc. At the same time the use of structural material is limited by the desire to reduce the reactor's nuclear "poisoning" and keep the amount of fissionable material required within reasonable bounds.

- In general, the reactor's heat release per unit volume is not uniform. To make the most of reactor-material capabilities, there must be a careful coordination of the reactor's heat output with the diffuser-exit characteristics, such as pressure profile. This coordination is made more difficult by the fact that both reactor and diffuser are influenced by such things as control-system functioning, off-design operation, etc.

Reactor materials for the nuclear ramjet pose problems essentially similar to those of the nuclear turbojet. However in the ramjet attention is focused on a somewhat higher temperature range, and—if the ramjet is intended for missile application—endurance and maintenance problems are somewhat eased.

Control considerations. The reactor of the nuclear ramjet can be controlled by moving neutron absorbers in such a way that the power is held constant or is changed at a desired rate. The reactor control system is coupled with equipment that controls the position of aerodynamic surfaces, inlet bleed doors, etc., and the combination constitutes the engine's flight-control system.

In a chemical ramjet the flight-control system attempts to create a stable interaction between the inlet and the fuel-flow control. For example, the control system can sense the location of the normal shock in the inlet (by measuring static pressure at various locations along the inlet), and then it can adjust the rate of fuel flow in such a way that the shock tends to stay at the desired location. Control of the nuclear ramjet is, unfortunately, more difficult:

- The radiation environment severely restricts selection of systems and components and also aggravates equipment-cooling problems. In general, hydraulic systems cannot be used near the reactor. Here systems are limited to pneumatic components or to certain types of electronic components.

- The reactor's limitations on rate of response place more of the control burden on the inlet. In other words, the reactor is inherently sluggish, because of its large mass and correspondingly large heat capacity, thus ruling out very rapid changes in its heat output or temperature. The reactor's response rate might be even further limited by thermal-shock problems associated with its brittle materials of construction.

ground-testing the nuclear ramjet

Development of new engines reliable enough for military use requires an extensive shakedown or "de-bugging" program of ground-testing prior to flight test. Facilities for ground-testing ramjet engines are unusual because of the ramjet's inability to pump air through itself when it is not moving. Air is typically supplied to the ramjet by air compressors or high-pressure air-storage tanks, the latter (known as a "blowdown" system) being used for high-flow tests of relatively short duration. The air-supply system should also include a heater to simulate the temperature rise that accompanies deceleration of the incoming airstream in flight. For example, to simulate a flight condition of mach 3 at 50,000 ft altitude, the test air should be heated to about 620°F. For simulation of very high altitudes, for which the air pressures in the engine can be less than one atmosphere, it is necessary to employ either exhausters or compressors to compress the used test air back to atmospheric pressure. A general-purpose facility, to perform tests simulating both high and low altitudes, would include both high-pressure air supply and exhauster installation.

Nuclear-ramjet test facilities differ from conventional ramjet facilities primarily in their isolated location, their protection of test personnel from radioactivity hazards by distance and shielding, their use of remotely operated equipment, such as air-pipe disconnects, in handling the test item, and their special instrumentation requirements.

Van Nuys, California

Nuclear-Rocket Propulsion

DR. RAEMER E. SCHREIBER

Leader of N Division, Los Alamos Scientific Laboratory

AS A RESEARCH program, the development of nuclear-rocket propulsion has the excitement and challenge of applying the enormous potential of nuclear energy to the new field of space exploration. As a practical application, nuclear rocket propulsion must offer the promise of accomplishments beyond the reach of chemical rockets or of doing the same job better or cheaper.

Before considering the practical aspect, it is necessary to review some basic ideas of rocket propulsion. Any change in velocity—that is, change in speed or direction—of a vehicle involves reaction with a second object. In most methods of travel that object is external to the vehicle. Automobiles have traction on the road, ships thrust against the water, and aircraft pull or push themselves by interactions with the air. Unlike such vehicles the rocket in free space must carry with it not only a source of energy but a material which it can eject to provide the interaction necessary to change its velocity: that is, to accelerate, decelerate, or turn. This interaction satisfies the basic law of conservation of momentum.

Momentum is the product of mass and velocity. Thus a desired change in momentum can be obtained either by a large mass ejected at low velocity or a small mass ejected at high velocity. In the classical illustration of the man stranded on a frictionless ice pond, the man can move himself, for example, either by the recoil produced by throwing rocks or by firing bullets from a gun in the direction opposite to his desired travel. If he can throw at 50 feet per second but fires a gun at 2000 ft/sec, he need only carry 1/40 as much weight in bullets as in rocks. Of course if he only needs 10 pounds of rocks to accomplish his objective and the lightest gun he can find weighs 25 lb, he will not believe the gun to be worth while regardless of the fact that the bullets weigh only 1/4 lb. On the other hand he may require 1000 lb of rocks and find it impossible to carry them, in which event he would be happy to carry a 25-lb gun and 25 lb of bullets.

In the case of long-range ballistic missiles and space vehicles, the virtue of high-velocity recoiling material—e.g., propulsion systems with high specific impulse—is enhanced as the demands of the mission increase. Specific impulse is defined as the pounds of thrust produced per pound per second of propellant flow rate. Through the relationships between force and momentum, specific impulse is also proportional to the exhaust velocity of the propellant relative to the vehicle, being equal to that velocity divided by the earth's gravitational constant, $g_0 = 32.2$ ft/sec^2. By applying the law of conservation of momentum to the case of a vehicle exhausting propellant at constant specific impulse, it is easily shown that, for a fixed ratio of initial to final vehicle weight (fixed vehicle mass ratio), the velocity achieved is proportional to the specific impulse. Similarly, for a given desired final velocity the mass ratio is an exponential function of the specific impulse.

As an illustration, consider a system with a specific impulse of 250 seconds or exhaust velocity of about 8000 ft/sec. Present liquid-chemical rockets have specific impulses somewhat higher than this, and solid-chemical rockets somewhat lower. For an IRBM requiring about 16,000 ft/sec of velocity, the mass ratio theoretically can be as low as 7, allowing 15 per cent of the initial mass to be delivered. For an increase to 32,000 ft/sec, which, taking air resistance into account, might be required for an extreme-range ICBM or a low earth satellite, the theoretical mass ratio is over 50. An earth escape requires a velocity equivalent of between 40,000 and 45,000 ft/sec. The minimum mass ratio for this case is between 150 and 300. It is clear that one cannot build a vehicle that is 99.5 per cent propellant, so the rockets are staged—that is, the flight is broken up into increments and hardware is dropped off along the way. The over-all mass ratio is thereby increased, but it becomes possible to get some small fraction of the initial mass to the desired velocity.

If one can attack the same missions discussed above with a device having a specific impulse of 750 sec, the mass ratios are reduced from 7, 50, and the 150–300 range to 2, 4, and 6 respectively. This is the argument for high specific impulse.

The trouble with increasing specific impulse is that it requires more energy. The power required to produce a fixed thrust is proportional to the specific impulse. In chemical systems it is this energy requirement that limits specific impulse. With the most energetic fuel-oxidizer combinations known, this limit is reached at about 400 sec.

nuclear potentialities

Since the energy available in a pound of U^{235} is some ten million times that of the most energetic chemicals, there is no problem in carrying along an essentially unlimited supply of power for nuclear propulsion. The trick is to convert it into useful thrust at a high performance level—in other words to transfer a large amount of energy to each pound of propellant.

Materials can store up energy in a variety of ways. The most common is in the form of specific heat, and for this case the energy is roughly proportional to the absolute temperature. A change of state, such as melting or vaporization, can also store energy. Looking at the more energetic processes, dissociation of molecules and ionization of atoms are possible energy sinks if the requisite temperatures can be reached. To be useful in propulsion, these processes must involve large amounts of energy, must be reversible so the energy can be recovered, and must take place rapidly.

There have been many schemes proposed for the utilization of nuclear energy for rocket propulsion. The most straightforward is a solid-fuel heat exchanger consisting of a nuclear reactor with channels or flow passages through which the propellant can be pumped and heated. The propellant then is expelled through a convergent-divergent nozzle. An extension of this idea is the gaseous reactor, in which the nuclear fuel and propellant are both high-temperature gases. Nuclear reactors also may be used to generate electrical power that can be applied to accelerate plasmas or ions. In addition, many novel schemes have been suggested, ranging from radioisotope sails to multiple, external, nuclear-bomb drives.

Let us consider the basic concepts of these various ideas.

the solid-fuel heat-exchanger reactor

The basic scheme of the solid-fuel heat-exchanger reactor embodies a reactor core with a number of parallel channels through which the propellant is pumped. Heat is transferred to the propellant by convection and radiation, and then the propellant flows out through a nozzle similar to that for a chemical rocket.

The simplicity of this system makes it attractive as a first approach, so that it is useful to examine its capabilities. The specific impulse depends primarily upon the exit-gas temperature and the molecular weight of the propellant, varying directly as the square root of the absolute temperature and inversely as the square root of the mean molecular weight. Thus a propellant at a temperature of 3000° Kelvin (about 4940°F) will have about 1.4 times the specific impulse of one heated only to 1500°K (about 2470°F). The propellant cannot be hotter than the nuclear fuel elements that provide the heat, so the temperature limit is set by solid materials and probably cannot exceed that attainable by chemical combustion—at least in the simple solid-fuel system. On the other hand the propellant to be used in nuclear systems can be chosen with considerable freedom, whereas it is necessarily the product of combustion in chemical systems. The best chemical fuels now in use have molecular weights in the range of 18 to 25. If one can choose a propellant

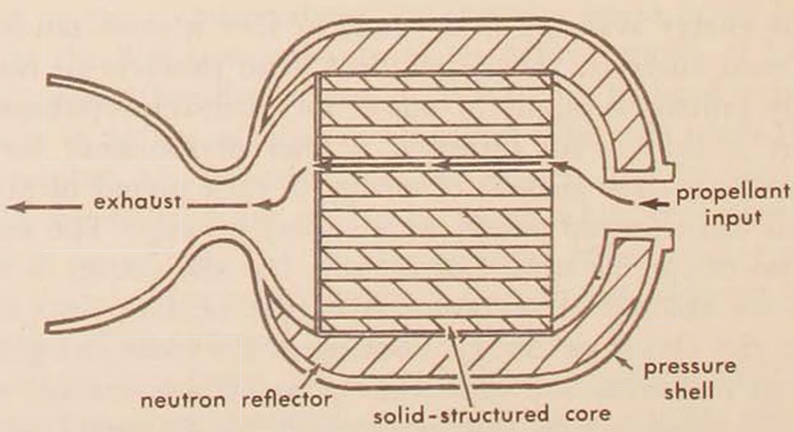

Figure 1. Schematic diagram of the solid-fuel heat-exchanger propulsion reactor. Propellant is pumped through a number of parallel channels in the reactor core and removes heat generated in the nuclear fuel plates. It then expands through a convergent-divergent nozzle to exert thrust by virtue of its momentum. Not shown here are the control rods, methods of support, methods of cooling the pressure shell, or the nozzle—all of which are essential to an actual propulsion reactor.

such as hydrogen, with a molecular weight of 2, there is a potential increase in specific impulse of a factor of three simply from this change.

Some idea of the temperatures that can be attained in solid-fuel nuclear systems can be obtained from science handbooks. Graphite retains its strength up to about 2800°C, molybdenum melts at about 2600°C, and tungsten at about 3400°C. Among the compounds, there are niobium and zirconium carbides with melting points as high as 3500°C. Since uranium in some form must be a constituent of the fuel material, the melting points of its compounds are of interest. As the metal itself melts at about 1100°C, it is not very attractive. Uranium carbide melts at about 2400°C and uranium oxide (UO_2) at above 2800°C.

The choice of fuel elements and operating temperatures is a basic design consideration in nuclear-rocket propulsion. The higher the temperature, the better the performance, although it should be noted that hydrogen has a specific impulse of 400 sec at only 350°C—just above the melting point of lead. As the temperature requirements increase, the problems of corrosion, changes in physical structure, and diffusion of materials increase. Yet temperatures between 1500 and 2500°C should be attainable with the heat-exchanger reactor, yielding specific impulses in the 700- to 800-sec range. This level of performance is interesting if reactors can in fact be made to operate at such temperatures.

The power required to produce a pound of thrust at a specific impulse of 800 sec is about 20 kilowatts. A 50,000-pound-thrust engine therefore requires about 1000 megawatts of power. Since the engine must accelerate itself, low specific weights—that is, high power densities—are desirable. High specific power implies large heat fluxes and thermal stresses. Also the reactor starts cold but must reach very high temperatures, so that provision must be made for adequate controls to override the changes in reactivity as a function of temperature. The amount of propellant in the core of the reactor also affects its reactivity. Thus the control of the engine involves a complex interplay of many effects that may occur simultaneously and somewhat independently. These questions are not entirely new, and many have been solved in the development of stationary power reactors or other propulsion reactors. For nuclear-rocket propulsion the need is for a lightweight package, a rapid start-up, and a relatively limited life.

The translation of a propulsion-reactor concept into a working device involves the development of many items of hardware. The reactor core containing the fissionable material must sustain a pressure load caused by the flow of the propellant through the coolant channels. The heat transfer from the interior of the fuel elements to the surface and the transfer from the solid to the gas must be adequate to permit high power generation without burning out the fuel elements. The power generation throughout the volume of the reactor must be matched to the cooling capacities of the coolant channels. The whole reactor must be enclosed in a pressure shell, and this shell will be heated by the absorption of neutrons and gamma rays from the reactor. The nozzle will also have a heat load from the absorption of nuclear radiation as well as from contact with the heated propellant gas.

Control of the reactor itself is provided by neutron-absorbing rods that are inserted into the core or reflector. Withdrawal of these rods increases the reactivity of the system and permits the reactor to generate power. As the reactor heats up, the control rods must be continuously adjusted to maintain the desired power level. These rods also absorb nuclear radiation and must be cooled. The propellant flow and the reactor power are therefore independent variables that determine the operating temperature of the reactor. Fairly accurate sensing of flow and power is required for maximum performance levels.

Finally, developmental tests require that diagnostic measurements be made to find out the actual conditions of pressure, temperature, flow, displacement, and vibration during the operation of the reactor.

The individual design and hardware features affecting the conditions just listed are relatively straightforward problems when taken singly. Lumped together, they represent a fairly complex system that can be proved to work only by conducting an integral test.

This conclusion was the basis for the decision to design and build the Kiwi-A test reactor as a part of the Rover program. Kiwi-A was never intended to fly. It is an experiment exploring the feasibility of a nuclear propulsion reactor. This permits the designers to incorporate features that capitalize on existing technology, shortens the development period, and provides economies in testing. For example, a water-cooled pressure shell and water-cooled nozzle are used to avoid the development problem of regeneratively cooled components. Heavy water (D_2O) moderation is used to minimize both the fuel volume and the propellant flow rate.

The testing of rocket propulsion reactors may be illustrated by the Kiwi-A program. A test area was selected at the Nevada Test Site (NTS) of the Atomic Energy Commission, and a complex of test facilities was constructed. There are three areas: the reactor test area itself, a control area, and a maintenance-assembly-disassembly (MAD) area. These are separated by distances of one and one half to two miles. The reactor is assembled on a

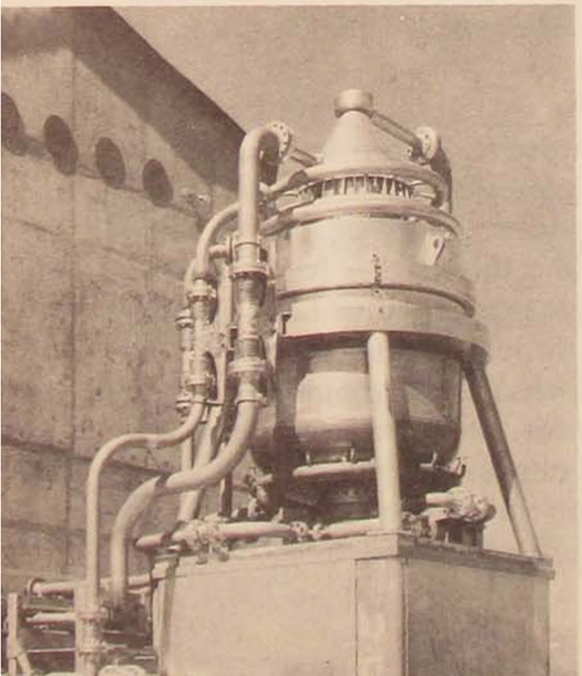

Figure 2. Kiwi-A mockup positioned before test cell for alignment of water and propellant fittings. The reactor itself is in the large cylindrical pressure shell and is mounted on a cubical chamber that contains control and instrumentation gear. Supply lines plug into the face of the test cell at left. During the testing operations the reactor car is supported on outrigger rails.

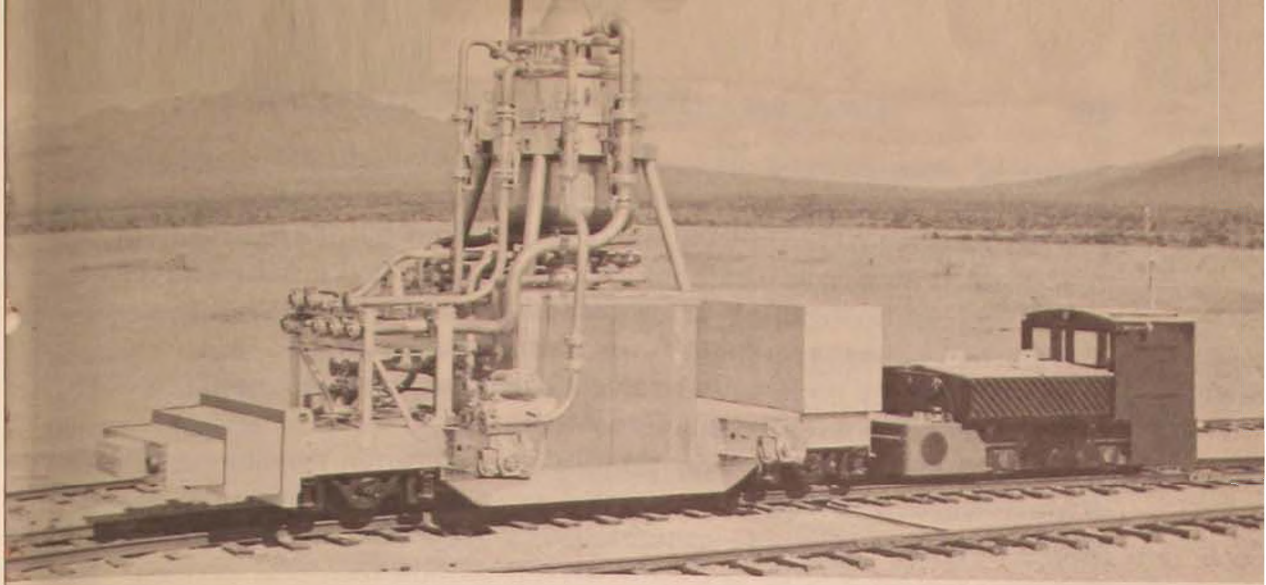

Figure 3. The Kiwi-A mockup, mounted on its test car, being moved by rail from the MAD area to the reactor test area by the radio-controlled electric locomotive. The concrete umbilical plug on the nose of the test car carries the control and instrumentation lines and fits into an opening in the face of the test cell. The locomotive is removed from the test area during operation of the reactor.

special test car in the MAD area, transported by railroad to the test cell, and attached to it by means of a shielded umbilical plug that fits into a port in the wall of the test cell. The reactor itself is unshielded and operates on an open cycle: that is, the coolant or propellant is discharged into the atmosphere through a nozzle. Inside the test cell are located the propellant controls, auxiliary coolants, some of the reactor controls, and the instrumentation lines. The walls of the cell are made of heavy concrete for protection of equipment from nuclear radiation. This shield is not adequate for personnel during reactor operations, although a re-entry may be made between tests for servicing and calibration. The reactor and its attachments are not accessible after a fairly modest level of operation. After the test is completed, the reactor is jacked away from the test cell by remote control and is trundled back to the MAD building by a radio-controlled electric locomotive. The disassembly bay of the MAD building is heavily shielded and equipped with remote manipulators, viewing ports, etc., where the reactor can be dismantled for postmortem analysis. The Kiwi-A test was completed in July 1959.

The control building is located approximately two miles from the test-cell area, so that there is no requirement for shielding. Buried cables carry instrumentation and control signals between the two areas. Conventional signal transmission and recording are used, but fairly elaborate instrumentation is necessary for the remote reactor operation.

The basic layout for Kiwi-A should be applicable to the testing of a variety of rocket propulsion reactors and engines. Additional test stands could be serviced from the MAD building and the control-point area.

Nuclear radiation. The use of nuclear reactors for power carries with it the problem of nuclear radiation in the form of leakage neutrons and gamma rays. Neutrons captured in the reactor or adjacent material can induce radioactivity that will persist after shutdown. Fission products in the fuel elements or escaping from the reactor will also continue to emit radiation after shutdown. All these effects deny access to the reactor itself and to materials immediately in its neighborhood for some period after a power operation. In the case of Kiwi-A, the reactor is decoupled from the test cell and removed to a shielded disassembly building by remote-controlled mechanisms. The test cell is expected to "cool off" within a few days and to be re-usable.

During power operations with the reactor, radiation levels are very high. The reactor itself must be made of materials not susceptible to radiation damage, this problem being about the same as for more conventional power reactors. Since the flight propulsion application demands a minimum of shielding weight, equipment located near the reactor must also be highly radiation-resistant. At a distance of 10 feet the radiation level from a 1000-megawatt reactor may be as high as several million roentgens per hour. Both the inverse-square law and air absorption cut down the radiation level rapidly with increasing distance. At a distance of one mile the level is essentially down to tolerance levels for human exposure.

In terms of flight application the nuclear radiation represents a real but not insoluble problem. Unmanned vehicles probably will require a shadow shield for protection of equipment during extended operations. In the case of ground launch, air scattering makes a shadow shield relatively ineffective during the early part of the flight. For manned flight fairly heavy shields would be required for ground launch, but shadow shielding for nuclear operations outside the atmosphere does not appear to be expensive. The discovery of the Van Allen belts of intense radiation around the earth raises some interesting questions concerning the need for radiation shielding of all manned space vehicles.

Reactor weights. The range of useful thrust levels from heat-exchanger reactors is a complex subject, but a few general statements are possible. A propulsion reactor will have a certain minimum weight regardless of its power rating because of the necessity for a critical mass in the nuclear materials. This "fixed" lower limit is on the order of a few thousand pounds. As the power level is increased, the size and weight of the reactor will increase somewhat because of larger propellant flow areas and structural strength requirements, but the thrust-to-weight ratio will also increase. As the thrust and reactor size increase, economies might be effected by changing to a design that is suitable only at high thrust levels. Detailed studies are required to attach specific numbers to these general statements, but it appears that payloads must be on the order of a few tons to make the simpler nuclear-rocket propulsion systems compete successfully with chemical systems.

gaseous reactors and other high-temperature concepts

The temperature limits imposed by solid-fuel elements could be avoided by building a reactor in which the fuel—possibly uranium vapor—is held in a critical configuration at a very high temperature. The walls of the reactor and the nozzle could be regeneratively cooled by the propellant. Such a reactor could operate at temperatures at which propellant gases would be dissociated—adding a mechanism for pumping energy into the propellant.

The idea of a gaseous reactor is not new, and many concepts have been presented. The key to a successful design is the development of an effective scheme for retaining the expensive nuclear fuel, while transferring its heat to the propellant.

A variation of the gaseous reactor is the extremely high-pressure reactor in which the reacting mixture (i.e., mixed uranium and hydrogen gas) is exhausted as the propellant and is replenished by a new reacting mass either in a pulsed or continuous flow. This is also a variant of the "fizzling bomb" concept. Such devices become highly efficient only at the pressures and short time scales appropriate to bombs. It is not necessary to point out that these conditions lead to a somewhat rough ride. If explosions are to be used, it is probably better to use external explosions with a shock-absorber mechanism between the "engines" and the vehicle, such as the concept being explored in Project Orion sponsored by ARPA.

The investigation of reactor schemes involving temperatures beyond the range of solid-fuel elements brings in many new problems of heat transfer, thermal radiation, and the interaction of materials. It probes into the region where ionization phenomena become important and may very possibly upset predictions based on low-temperature experience. It is a difficult field, but it is intriguing because of the enormous performance levels that are possible. For example, the specific impulse of hydrogen is about 1000 sec at 2750°C; that of ionized hydrogen is 6700 sec at 25,000°C. With the latter specific impulse the mass ratio of an earth escape vehicle is only about 1.25.

nuclear-electric space drives

To achieve the highest specific impulses, it is necessary to abandon schemes for heating propellants and to go to electric or magnetic acceleration of particles. The energy of a particle accelerated by a one-volt potential difference is equivalent to a temperature of about 12,000°C, so that a very modest electrical acceleration can lead to very high velocities. A 50-volt proton (hydrogen nucleus), for example, has a specific impulse of about 10,000 sec. Heavier atoms require more potential for the same specific impulse. Even so, rather modest acceleration voltages lead to enormous performance figures. So where is the gimmick?

There are several gimmicks. High specific impulse requires proportionately large electrical power for a given thrust. At a specific impulse of 10,000 sec, a pound of thrust requires an output power of about 600 kilowatts. This is net electrical output. The power production requirements will be from three to five times higher because of the inefficiency of the power plant. The waste heat must be dumped, and the only way of dumping heat in space is by radiation. The power plant might therefore consist of a nuclear reactor heating a working fluid that circulates through a turbine and a radiator. The turbine drives an electrical generator that powers some form of electromagnetic accelerator.

Because of the large power requirements, nuclear power is essential to this type of system. Yet the weight of the equipment involved means that even the nuclear-electric system can work only in very weak gravitational fields. It seems unlikely that accelerations can exceed a milli-g—that is, the thrust-to-weight ratio will be 1 to 1000 or less. On the other hand, such accelerations are not at all trivial if they are coupled with low propellant consumption. The sun's gravitational field at the earth's orbit is only 0.6 milli-g. A net acceleration of 0.5 milli-g continued for ten days gives a velocity increment of 14,000 ft/sec, covers a distance from a standing start of about

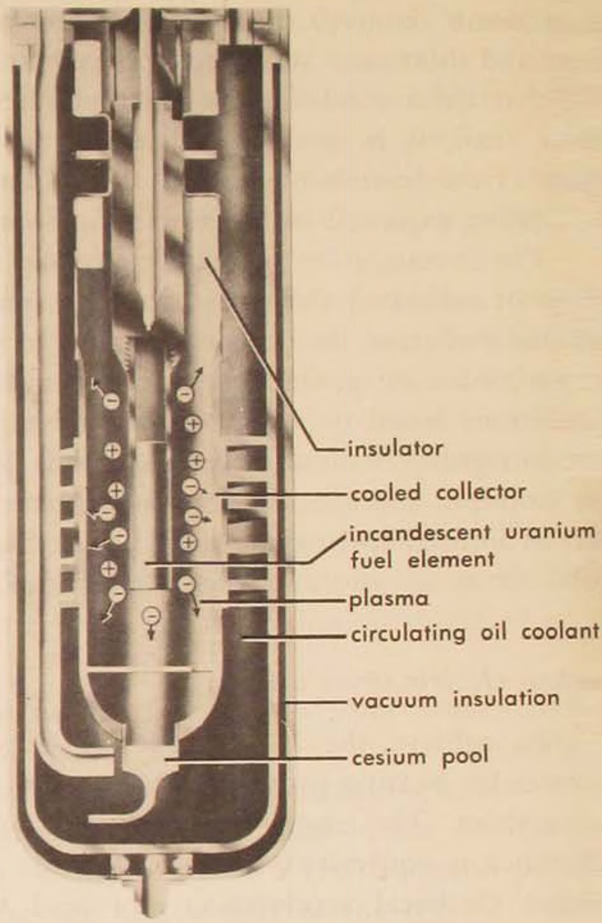

Figure 4. In-pile test of plasma thermocouple. The uranium fuel element was about ¼ inch in diameter and the active portion about ⅝ inch long. The small circles with positive and negative symbols represent the cesium ions and electrons carrying the current. The whole assembly was inserted in a 2-inch-diameter port in the Omega West Reactor at Los Alamos. It operated at an output of about 40 to 50 watts for ten hours before removal for post-mortem examination.

a million miles, and expends an amount of propellant that is only 5 per cent of the gross weight of the vehicle. In free space one can of course coast along at this speed indefinitely.

There are two major problems in nuclear-electric drives. One is to produce a lightweight electrical generating system, complete with heat dump, that can operate for many months. The other is to produce ion or plasma accelerators capable of handling many thousand amperes of current. It is interesting to note that equal numbers of positive and negative ions must be emitted by the space vehicle in order to prevent a net space charge on the vehicle. The effect of such a space charge is that the ions of opposite sign simply will not leave the vehicle but will follow it along, creating a drag that nullifies the propulsive force.

A development at the Los Alamos Scientific Laboratory that might have important applications in nuclear-electric space drives is the investigation of the plasma thermocouple. It is well known that metallic thermocouples can be used for electrical power generation but that their efficiencies are very low. The use of special materials such as semiconductors (as in the Snap program) can improve efficiencies to a considerable extent. The plasma thermocouple accomplishes higher efficiency by making one leg of the electrical circuit a plasma (mixed positive and negative ions) that has a theoretical electrical efficiency of perhaps 30 per cent.

In the Los Alamos experiments a mixture of zirconium and uranium carbides forms the emitter of the plasma thermocouple cell. This mixture is heated to temperatures above 2000°C. A collector surrounds the emitter, and the space between is filled with cesium vapor. Cesium is easily ionized, and with the electrons boiled out of the emitter electrode it forms a plasma. Under suitable loading, such a cell has demonstrated power outputs of about 25 watts/cm^2 at about 1 volt. By the use of U^{235} in the emitter electrode it is possible to make the cell self-heating in a neutron flux.

This cell was demonstrated by an in-pile test at Los Alamos in April 1959. With suitable U^{235} loading, an array of plasma thermocouple cells could constitute the reactor itself. The plasma thermocouple can also be used as an attachment to a high-temperature reactor. To obtain more suitable voltages, the cells can be arranged in series. For space applications the fact that the whole cell can operate at a temperature in excess of 1000°C is a definite advantage in terms of disposing of the waste heat, since the effectiveness of radiators increases as the fourth power of the absolute temperature.

Although much more work needs to be done both to understand the detailed mechanisms of plasma thermocouples and to develop practical hardware, it is intriguing to observe that one square meter of plasma thermocouples will develop 250 kilowatts of electrical energy.

Los Alamos, New Mexico

Radioisotopic Power Sources

DR. JEROME G. MORSE

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THE OMNIPRESENT military need for small, compact, and reliable electrical generators, now heightened by requirements extending beyond earth-based applications, has provided technology with a major challenge. The advantages of radioisotopic power sources—principally light weight and long life—have been outlined by an earlier author. These advantages must be weighed against inherent limitations in fulfilling the military need.

radioisotopic power

The principles underlying radioisotopic power are simple. Heat is generated when the particulate and electromagnetic radiations emitted by a sealed quantity of radioisotopes are absorbed in the surrounding containment material. The heat is then partially converted into electricity by a suitable energy-conversion device, the remaining heat being dissipated to the external environment.

Advantages and disadvantages. Radioisotopes are sources of energy in relatively high power densities whose natural decay rates determine, in major part, the lifetime designed into the power plant. Radioisotopic power plants lend themselves appropriately to remote, unattended application. Against these advantages are the considerations that present-day availability of radioisotopes is low and that the practical upper limit of their power-producing capability, based on today's energy-conversion efficiency, is of the order of only several hundred watts. Regarding availability, it is noteworthy that the lack today is not in quantities of radioisotopes but rather in facilities to separate, purify, and process the active materials into forms useful for power application.

Fuel selection. Fuel selection for the radioisotopic power source is governed by the manner in which the power supply will be used, considering power density in watts per gram, halflife, cost, availability, shielding, and safety in use. General analyses may define the first four of these parameters. The last two reflect the specific mission or application requirements.

To calculate the specific power (thermal) of radioisotopes, the following relationship is used:

$$\frac{P}{M_0} = 7.75 \times 10^5 \, \frac{E}{A T_{1/2}} \, e^{-\lambda t} \text{ watts/gram}$$

where P = power, watts (parent) λ = decay constant, days^{-1}

M_0 = mass at time zero, gm $T_{1/2}$ = halflife, days

A = isotopic mass, gm (parent) t = decay time, days

E = average energy per decay, mev e = 2.71828, a constant, the base of natural logarithms

If the radionuclide decays directly to a stable isotope, only the decay energy of the radioactive isotope need be considered. But if the parent isotope decays to a daughter that makes a considerable contribution to the decay power, the energy of decay of the daughter must also be considered. In the case of radioisotopes decaying to nuclides of very short halflife (e.g., ruthenium-106 to rhodium-106, cerium-144 to praseodymium-144, strontium-90 to yttrium-90, cesium-137 to barium-137) the daughter may be considered to assume the decay rate of its parent. The total energy per decay of the radioisotope can then be approximated by adding the energy per decay of the daughter to that of the parent. For calculating, it is assumed that all the average beta energy and 50 per cent of the gamma energy are absorbed and converted into heat in the containment vessel.

Two other important areas to consider in fabricating power packs are cost and availability. As technology improves, so do these parameters. If uses are found for more of these fission products, production facilities will be increased, with resultant increased availability and reduced cost of radioisotopes.

radioisotopic power-system components

Heat source. Heat generation in radioisotopic power systems stems from containment of two major types of radioactive source materials. The first is the waste material resulting from the controlled fission of uranium, and the second results from irradiation of suitable target materials in nuclear reactors.

More than 200 radioisotopes are formed in the fission process, but it is reasonable to consider only those with halflife longer than 100 days as potential fuels for energy-conversion systems. It is estimated that a thermal output greater than 0.01 watt/gram is required to keep the heat source to a practical size. This criterion is necessary to convert the heat efficiently to useful work and to minimize the shielding requirements necessary to allow personnel access to the proximity of the power unit. It limits the number of potential fuels to only a few.

Fission wastes are a major projected disposal problem of the nuclear power industry. Predictions for 1975 indicate the accumulated formation of 12 billion curies. Since pure fission products must be used as the fuel, this amount represents about 50 megawatts of usable thermal power. Therefore an anticipated problem may be partially converted into a useful form of energy.

There are applications where the use of fission-product fuel materials is seriously limited. These limitations stem from the size and weight of the shielding that must be used to allow biological specimens to exist for long periods close to these sources or to prevent radiation damage to electronic components or film during the mission. These problems may be circumvented by using alpha emitters as the heat source. With proper selection of the alpha emitters, a kilowatt of heat can be safely contained in a volume of 3 cubic inches.

After extensive examination of the alpha emitters available, it appears that there are only three isotopes having merit as heat sources. These are curium-242, polonium-210, and plutonium-238. Potential availability, cost,

Isotope Power Sources

							estimated costs		
				specific power		current		projected
isotope	halflife	element or compound	density (gm/cc)	(watts/cc)	(curies/watt)	($/curie)	($/watt)	($/watt)
polonium-210	138 days	Po	9.3	1320	31.2	5.0	156	—
curium-242	162 days	Cm.30 Ni	8.7	128.5	27.2	2.9	80	45
cerium-144	285 days	CeO_2	6.4	12.5	128	0.7	87	14
promethium-147	2.6 years	Pm_2O_3	6.6	1.1	2700	1.1	2990	1630
strontium-90	27.7 years	$SrTiO_3$	4.8	0.54	153	3.0	455	23
plutonium-238	86.4 years	PuC	12.5	6.9	30.3	—	—	1600
		Pu	16.0	9.3	30.3	—	—	—

and the lack of high-energy gamma radiation are the deciding factors in the selection of these isotopes. Two of them, curium and polonium, are in the short-life, high-power category, while plutonium-238 has an 86.4-year halflife and will answer the problem of long-lived heat sources.

Energy-conversion devices. The second component in an isotopic power source is the energy-conversion device. Three methods of energy conversion will be noted: thermoelectric, thermionic, and turboelectric.

- The principle upon which *thermoelectric conversion* is based is the Seebeck effect, in which an electrical potential is established by a difference in temperature within a material. The principle is basically the same as that observed to operate in thermocouples. The materials being investigated for the thermoelectric conversion system are semiconductors, which offer a significant improvement in efficiencies over the simple thermocouple. The schematic, Figure 1, of a thermoelectric couple illustrates how positive-type and negative-type semiconductor materials are connected electrically and thermally to produce a current I through an external load Q_{in}, which represents the heat (Btu's) entering the thermoelectric device from the heat source at a hot-junction temperature T_h. Q_{out} is the waste heat (Btu's), which must be dumped and which leaves the cold-junction temperature of the couple at T_c. These couples are connected thermally in parallel and electrically in series to provide a conversion device with the voltage and power output required.

- In *thermionic conversion* two materials of different work functions (i.e., in respect to the energy required to free an electron from the surface

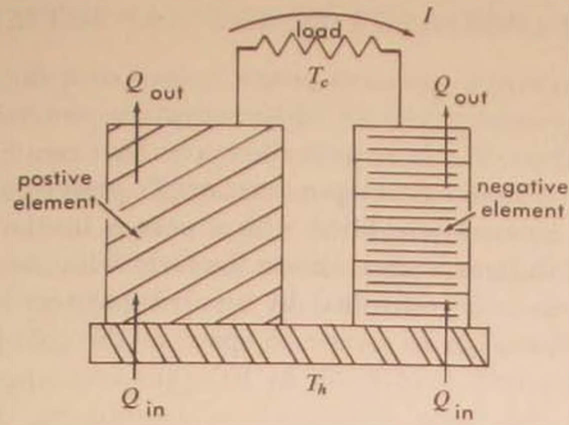

Figure 1. Thermoelectric conversion device.

of a material) are placed in close proximity with a vacuum between and the emitting material is heated. Electrons "boil off" the surface of the emitter and collect at the cooler, low-work-function surface. The hot cathode with a high work function (ϕ) serves as the electron emitter, while the cold anode with a low work function acts as the collector. With the flow of electrons an electromotive force is established between the two surfaces and can cause a current to flow through an external load. A thermionic conversion system can achieve high efficiencies (up to 15–20 per cent) at relatively high heat-source and radiator temperatures. In space, excess heat must be radiated away from the vehicle. The amount of heat radiated is a function of the fourth power of the radiator temperature. Such a conversion system, therefore, has a very high potential for space applications.

- In *turboelectric conversion* the heat generated by a radioisotope is converted into electrical energy by a conventional turboelectric device. The thermodynamic Rankine cycle is the principle used in boiling a cycle fluid with the isotope heat and driving a turbine generator by the expansion of the vapor through a nozzle. This process can be effected at high efficiency for high power outputs, but the efficiency decreases rapidly when the electrical power output drops below a few kilowatts. The extensive technology and experience available on such systems still make turboelectric conversion relatively attractive for many applications, even at low power outputs.

heat sink

Only a small percentage (upper limit approximately 30 per cent) of the heat generated by the radioisotope can be converted to electricity. It is therefore necessary to "dump" the remaining heat to the external environment. The means used to get rid of this excess heat depends on the operational environment of the power unit. Since for space applications the heat must be radiated away, radiator design is a major consideration in space-oriented power systems. For terrestrial applications the heat may be lost through radiation, conduction, or convection. The heat sink is determined by the application, and any of several means can be used to release the unused heat.

Because radioactive decay falls off logarithmically with time, a means must be provided to obtain constant power output over the life of the power unit. The method generally used to achieve constant power involves dumping through a controlled parallel heat path the excess heat created early in the life of the unit. A method under development controls power output by adjusting the gas pressure in an enclosure filled with a porous insulation. The conductivity of such an insulator varies almost linearly with the gas pressure enclosed. The gas pressure is controlled by a valving system which requires no power and which allows gas to escape to space as the cold-junction temperature decreases.

Snap-3

To provide an example of what can be expected from radioisotopic power sources, the Atomic Energy Commission awarded a contract in April 1958 to the Martin Company for production of a proof-of-principle device. The first power unit produced was demonstrated by President Eisenhower in January 1959 and attracted wide attention by its very small size and weight. This device uses a thermoelectric converter made by the Minnesota Mining and Manufacturing Company. To facilitate handling and demonstration, polonium-210 was selected as the fuel for the generator because of its high specific power and low gamma activities. Isotopes of longer halflife would greatly increase the output life of these power units for operational use.

The accompanying cutaway view of the Snap-3 prototype thermoelectric generator indicates the radial position around the contained heat source of

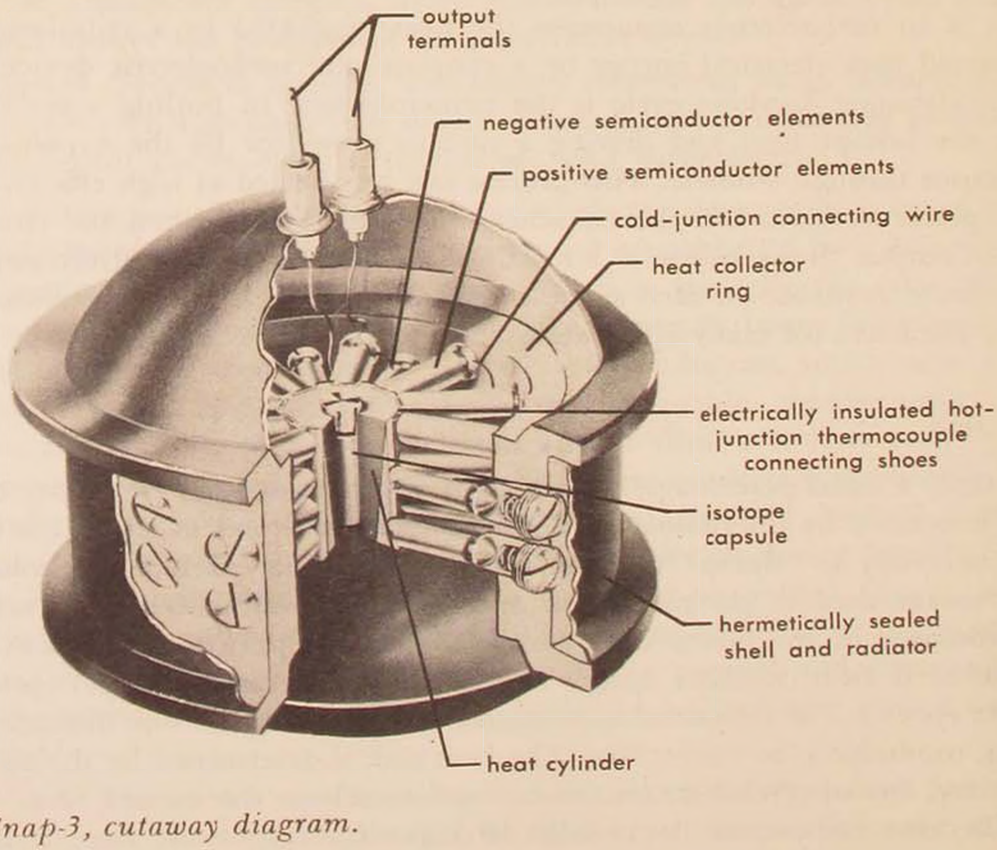

Figure 2. Snap-3, cutaway diagram.

the 27 couples of doped lead-telluride elements. These elements are doped with bismuth or sodium to provide negative- and positive-type semiconductors, one negative and one positive thermoelement defining a couple and all couples connected in series. Each of the elements provides a parallel path for heat flow from the heat source to the container-radiator. The thermocouples are electrically insulated from each other at the hot and cold junctions. Each element is spring-loaded at the cold junction to ensure positive, low-resistance electrical contact.

The radioisotope was supplied to the Martin Company in encapsulated form. Each of the two stainless-steel cylinders contained about 800 curies of

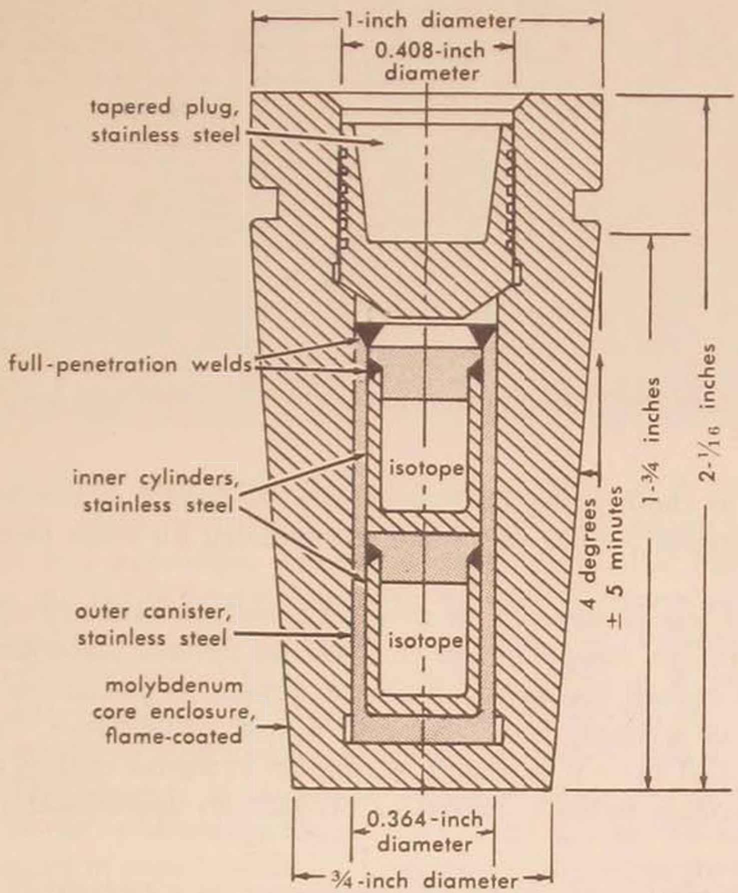

Figure 3. Internal containment of radioisotope in Snap-3.

activity and was closed with a tapered plug. The plug was sealed by heliarc welding with 100-per-cent penetration. Each capsule was carefully tested for alpha activity and helium leakage. The two cylinders were inserted into a close-fitting third canister, which was sealed and tested using the same techniques. The third canister was enclosed in a molybdenum core that had been flame-coated to prevent oxidation and sealed with a stainless-steel, tapered pin plug under helium pressure. The seal provides a thermal bond between the steel capsule and the molybdenum core. Closure with a pin plug eliminates the need for a high-temperature seal, which could adversely affect the heliarc welds. Tapering the molybdenum block ensures good thermal contact with the hot-junction ring of the thermoelectric converter.

In an accompanying graph, Figure 4, the variation in power output with

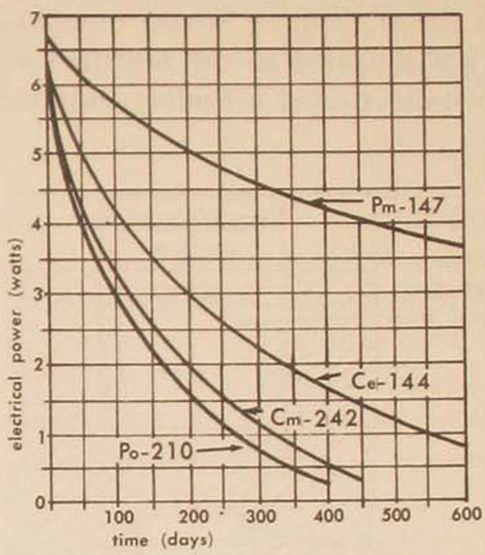

Figure 4. Isotope electrical power versus time.

the lifetime of the existing Po^{210} generator of Snap-3 is extrapolated over projected lifetimes. Similar curves are extrapolated for other potential radioisotopic fuels.

As Snap-3 was constructed for proof of principle, little attempt was made to minimize weight. Simple design changes and optimal materials in the container would reduce the weight from the present 4 pounds to less than 3 pounds without seriously affecting power output or efficiency. But with this milestone behind us, it is necessary to conduct extensive testing, optimize designs, and perform hazards analysis to produce an operational radioisotopic power unit.

Development testing. Although functioning in a zerogravity field is particularly attractive for static energy-conversion devices, a number of environmental tests must be performed to simulate launching and operational conditions. These tests include thermal shock, vibration, acceleration, mechanical shock, and heat-transfer tests. Determination of the primary and secondary radiation spectra must be made to design suitable shielding of the sensitive equipment carried for the mission. The existence of the Van Allen radiation belts will also require that sensitive equipment be shielded, and this shielding will mitigate the quantity and significance of the shielding weight required for the radioisotopic power unit itself. Finally, ground-handling techniques must be evaluated to integrate the power unit into the missile launch countdown.

Hazards analysis. Two basic biological hazards are associated with using radioisotopes. First, there is a direct-radiation hazard from the penetrating

Snap-3 Characteristics

dimensions	4.75-in diameter; 5.5-in height
weight	4 lb
source	1700 curies (0.38 gm) of polonium-210
thermal output	60 w
electrical output	3.3 w to optimum load of 1.7 ohms
efficiency	5.5%
total electrical power output over 280 days (approximately 2 halflives)	10,000 w-hr
conventional battery equivalent (over 2 halflives)	160 lb of zinc-silver cells
open-circuit voltage	5.0 v
closed-circuit voltage	2.5-v to 1.7-ohm load
thermoelectric elements	lead telluride: positive-type doped with bismuth, negative-type doped with sodium
hot-junction temperature	496°C
cold-junction temperature	107°C
copper-shell temperature	99°C
dose rate at shell surface	500mr/hr
dose rate at 1 ft	50 mr/hr
dose rate at 5 ft	<1 mr/hr

Note: Performance data are for unit at beginning of first halflife of polonium-210 source.

radiation associated with alpha and beta decay, such as X radiation from bremsstrahlung, alpha-neutron reactions, and gamma photons from decay products and fuel impurities. Second, there is a potential hazard from the possibility of the radionuclides dispersing into the biosphere and subsequent biological uptake by humans through inhalation and ingestion. There are direct and effective countermeasures. Biological shielding is provided to attenuate the direct radiation to tolerance levels. The shields are solid or liquid materials, generally of high density, which are integrated into the structure of the device. The absolute containment principle is employed to ensure encapsulation of the radioisotope under any conceivable condition. The source material is sealed in capsules of high-temperature, high-strength material such as molybdenum, and zero leakage is maintained so that isotopic power devices can be safely utilized in any environment, be it terrestrial, marine, or space. It is important to evaluate environmental hazard conditions to determine the design criteria for the source capsule. Hazards tests must represent transient environmental conditions, which appear to be the most stringent conditions imposed on any isotopic power device.

Exhaustive hazards-test programs were conducted to determine the integrity of the radioisotopic capsule under a variety of extreme conditions simulating those of a space mission. Integrity is defined as the ability of the capsule to retain the fuel and allow no leakage of the fuel to the atmosphere during operational and postoperational conditions.

Baltimore, Maryland

Nuclear Reactors as Auxiliary Power Sources

JOSEPH R. WETCH

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SPACE flight, with its tremendous extension of distances, of flight time, of communications requirements, has posed many formidable problems. Not the least of these is providing the electrical energy needed to run the diversified systems in a space vehicle for the length of time that the mission will last, yet at a minimum weight to reduce loss of payload and at a cost per watt-hour that is in proportion to the total investment in the space vehicle.

Until now flight systems have satisfied their internal electric requirements by carrying along stored electrical energy as in batteries, or by operating a generator that in turn used the continuously operating main propulsion system as its energy source. Neither of these conventional means is suitable for the requirements of extended space flight. Chemical and fuel cells have short life spans and are so heavy per watt of power that they become prohibitive for the higher electrical energy requirements.

Solar cells as demonstrated on the Vanguard satellite can produce small amounts of power for a long period of time. The cost of this power is difficult to appraise because in the Vanguard program the power requirement was only a few watts and program costs have been abnormally high—about $5 million per pound of payload that has achieved orbit. The cost of power, on the other hand, will become an important consideration in the future, where vehicle costs of less than $600 per pound of payload in orbit are projected and many thousands of watts of power are required.

For a space vehicle that is placed in continuous sunlight and maintains perfect orientation with respect to the sun, the cost of solar cells is ideally estimated to be about $400 per watt.

Nonoriented solar cells in an earth sunshade orbit would cost more nearly $3000/watt, or $3,000,000 per kilowatt.

area requirements

Nuclear power sources promise greater performance at reduced cost without requiring special orientation and without imposing restrictions in regard to orbit or trajectory.

Figure 1 indicates that the radiator area requirement for nuclear power sources will be only one tenth to one hundredth as great as the collector area requirement for solar systems. The reduced area requirement of nuclear systems will permit the design of much more compact, rugged, and reliable power systems.

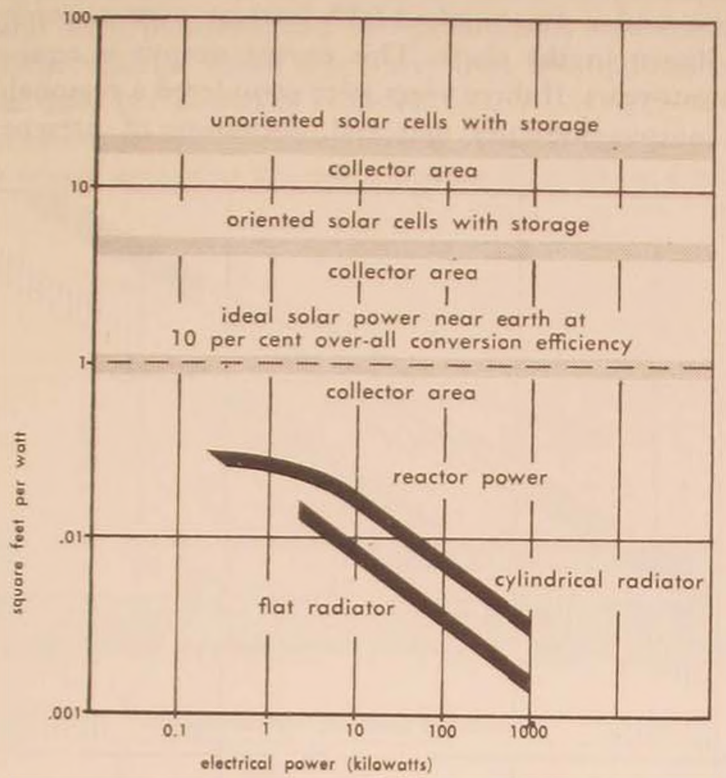


Figure 1. Radiator-area and collector-area requirements for satellite APUs.

weight and costs

Small nuclear reactors can serve as the heat sources to produce electrical energy in the large amounts needed for more ambitious and useful space missions and to provide power for the redundancy of circuits that will increase system reliability. Ideally the fissioning of 1 pound of U^{235} would produce 1 thermal megawatt-year or 3×10^{10} Btu per pound, which at 10% conversion efficiency will produce 900 million (9×10^8) electrical watt-hours per pound of fuel. This energy–weight advantage is potentially over a million times greater than advanced chemical systems and a hundred thousand times greater than the nonoriented solar-cell system. We have not yet learned how to take full advantage of this enormous potential, but significant strides have been made toward the attainment of this potential in nuclear fuel.

For instance, small nuclear reactors may be built weighing less than 200 pounds with critical masses of U^{235} ranging from a few kilograms to tens of kilograms. Thermalized systems would have only a few kilograms of fissionable fuel. In such a system 1 pound of U^{235} might easily be fissioned without causing unreasonable metallurgical or control problems. Assuming reasonable vehicle configuration and a transistorized payload, some 300 pounds of shielding could be adequate for at least 1-year life. If an additional 400 pounds were allowed for the power-conversion system, heat-rejection system, and structural-support weight, one could consider a nuclear reactor system that would produce 9×10^8 watt-hr/900 lb or on the order of one million watt-hr/lb, for a two-thousand-fold increase in performance over an advanced chemical system and a two-hundred-fold increase over a nonoriented solar-cell unit, as shown in the chart. This energy output is equivalent to 100 electrical kilowatt-years. If three years were considered a reasonable maximum lifetime, this output indicates that full utilization of present nuclear ca-

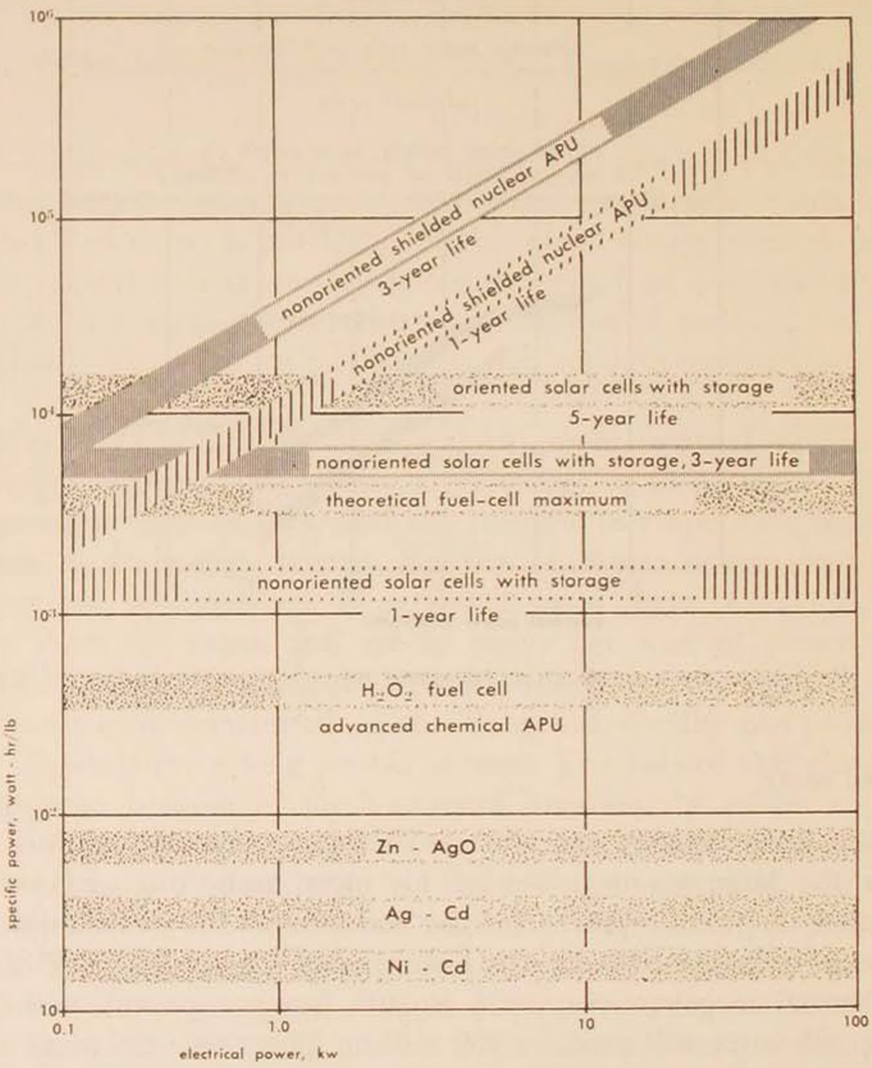


Figure 2. Specific power (watt-hours per pound of APU weight) of various satellite auxiliary power units for production of 0.1 to 100 kilowatts of electric power.

pability will require the use of about a 30-kw unit. At higher power further increase in power and energy density is possible. In the range of hundreds of kilowatts of power, weights of about 10 lb/kw for nuclear auxiliary power units (APUs) appear to be attainable with present developmental approaches. This would correspond to one to five million watt-hours per pound of power plant, depending upon power level and fuel loading.

A very preliminary estimate of projected space nuclear electric power costs indicates that costs of $500 to $1000 per pound may be anticipated. Thus a decrease in cost from nearly $1000/watt in the hundred-watt power range to $10/watt in the megawatt power range may be expected.

From Figures 3 and 4 it can be seen that a 30-kilowatt nuclear unit weighing about 1000 pounds could be operationally and economically considered for large vehicles which may carry over 5000 pounds to a 300-mile orbit at about $600 per pound of payload.

This discussion should not be construed to mean that we should not consider nuclear power units that are much smaller than 30-kw. Certainly nuclear

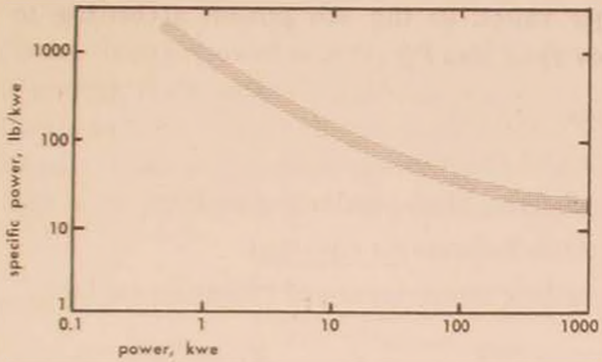


Figure 3. Specific power versus power output for currently feasible nuclear APUs.

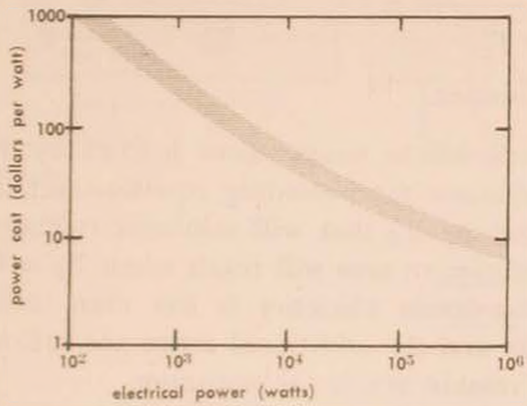


Figure 4. Projected cost of space nuclear electric power.

power need not utilize its full advantage if it can substantially outperform competitive systems at lower power. In addition it would be imprudent to presume that all the engineering problems associated with the high-power, long-life systems should or could be solved without an evolutionary process that involves the development and flight-testing of lower-power systems.

temperatures

To produce useful electrical power from a nuclear reactor some sort of device must be used that will convert reactor-produced heat into electricity.

The efficiency of this conversion will always be less than 100%; therefore the waste heat must be rejected to space by means of thermal radiation. In all nuclear space power plants the radiator is a predominant weight factor, and its area will have major significance when considered in terms of vehicle designs. To minimize this area and weight, we strive to minimize the amount of heat that must be rejected by increasing the conversion efficiency. This increase can be achieved by elevating the reactor heat-source temperature T_1 and lowering the cycle heat-rejection temperature T_2 to produce a large Carnot efficiency, $\eta_c = (T_1 - T_2)/T_1$. As the cycle heat-rejection temperature T_2 is lowered, the radiator area will increase because it is proportional to the amount of heat to be rejected, $1 - \eta_c$, divided by the absolute rejection temperature raised to the 4th power, according to the Stefan-Boltzmann radiation law $Q = A\epsilon\sigma T_2^4$

where Q = heat rejected
A = area of radiator
ϵ = emissivity of the radiating surface
σ = Stefan-Boltzmann constant
T = absolute temperature of radiating surface

That is,

$$A = \frac{K(1 - \eta_c)}{T_2^4} = \frac{K\left(1 - \dfrac{T_1 - T_2}{T_1}\right)}{T_2^4} = \frac{K}{T_1\,T_2^3}$$

where K = a constant.

If the reactor heat-source temperature is fixed by the reactor characteristics, we may differentiate the preceding equation, set the differential equal to zero, and solve for the T_2 that will minimize radiator area. When this is done, we find that minimum area will result when $T_2 = 0.75T_1$ or $\eta_c = 25\%$. When the conversion-device efficiency is less than the Carnot efficiency, a series solution results and the additional terms are sufficiently small for 25% Carnot efficiency to remain nearly the optimum.

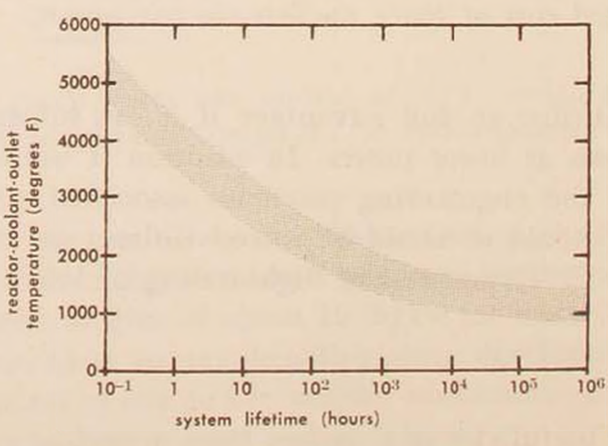


Figure 5. System lifetime versus operating temperatures.

As reactor and power-plant system operating temperatures are elevated the expected system endurance must decrease. Figure 5 presents an indication of the trend in temperature capability of nuclear reactors and dynamic systems envisaged over the next decade. If systems with greater than 1 year of endurance are required, we should consider reactors that operate at temperatures less than 1800°F. On the other hand, radiator size and weight can become unwieldy if the reactor heat-source temperature is less than about 1000°F. From the relationship mentioned above, it is apparent that radiator temperatures will preferably be about 600°F and higher.

power conversion

As in conventional electric power sources for flight systems, nuclear power can offer electrical energy from either static or dynamic conversion systems.

Figure 6 represents various attractive means of reactor cooling and power conversion for compact nuclear systems operating in the interesting temperature regions. For low power output, conductive cooling to the surface

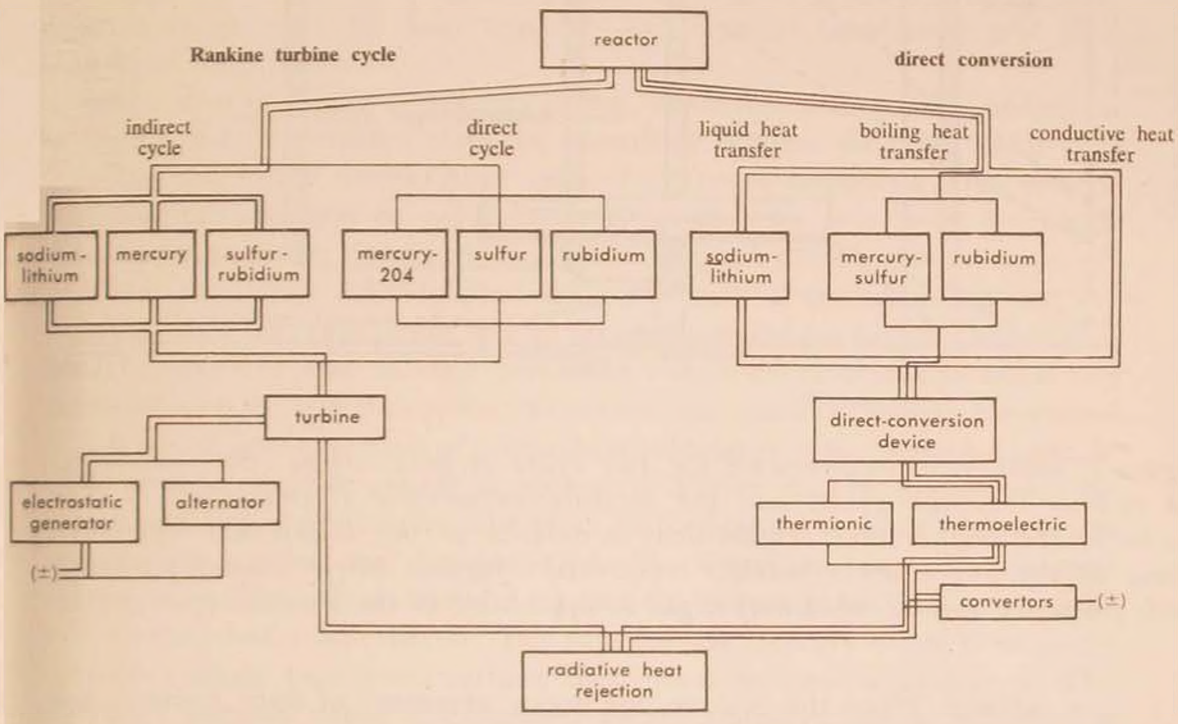


Figure 6. Advanced nuclear auxiliary-power-unit systems.

of the reactor is possible. In such a system static power-conversion systems based upon the thermoelectric or thermionic principles are very attractive. These means of conversion are not as attractive at powers in excess of a few kilowatts because they generally are less efficient under given temperature conditions than the thermodynamic turbine cycles. Their associated radiators become excessively large, or static conversion requires excessively high reactor temperatures to utilize comparable radiators. Static conversion gains its major attractiveness from the fact that it promises to be extremely reliable and free of disturbing torques. As power output is raised, it becomes necessary to circulate a fluid through the reactor to the conversion-element hot junction or circulate a fluid from the conversion-element cold junction

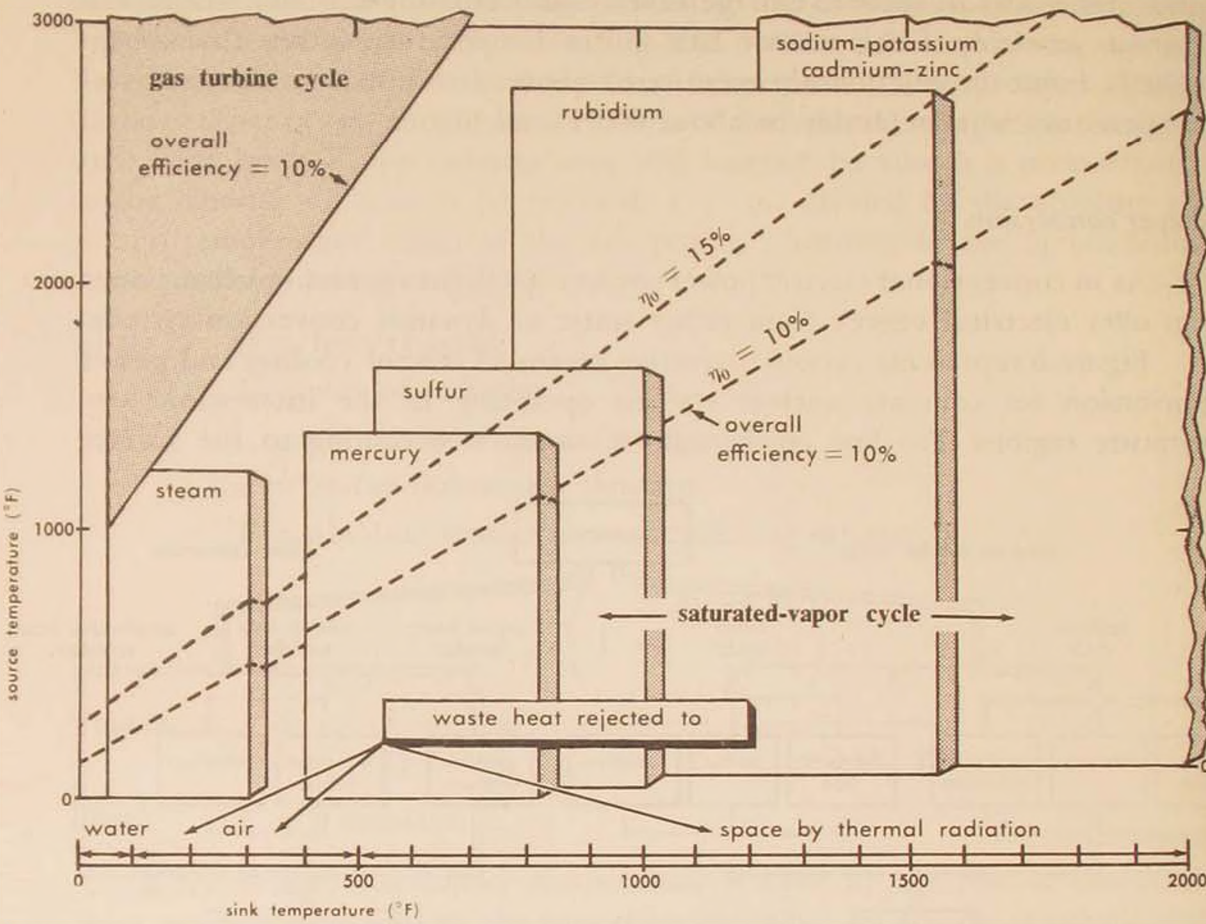


Figure 7. Heat-cycle requirements for two types of heat engine: the closed-cycle gas turbine (Brayton cycle) and the saturated-vapor-cycle (Rankine cycle). The reactor-source temperature requirement is related to the heat-sink temperature. Three of the boxed areas indicate temperature regions where several promising fluids (mercury, sulfur, rubidium) might be applicable in the Rankine-cycle engine.

to a radiator. When this is done, the major advantage of static conversion is lost, and the higher cycle efficiencies obtainable from the thermodynamic engines become worth while.

In any case the same fluids are of interest as reactor coolants, whether static or heat-engine power conversion turns out to be preferable. From this standpoint a single reactor development may provide heat for several alternative means of power conversion.

Because of the effect of reactor temperature upon endurance, reliability, and difficulty of development, it is desirable to maintain the lowest possible reactor operating temperature consistent with the power-plant requirements and consistent with achieving as great a conversion efficiency as possible. Figure 7 indicates the reactor-source temperature requirement versus the heat-sink temperature for the closed-cycle gas turbine (Brayton cycle) and for the saturated-vapor-cycle (Rankine) heat engines. The temperature regions where several promising Rankine-cycle fluids might be applicable are also shown. It is apparent here that, if reasonable radiators are desired (greater than 600°F sink), the Brayton cycle cannot be compared favorably with the Rankine-cycle systems. This is because the Brayton cycle requires excessive reactor temperatures and extremely efficient components (turbine, compressors) to produce the same results. The saturated Rankine cycle, on the other hand, can achieve better than 50% of the Carnot efficiency (25% Carnot optimum) for over-all efficiencies of better than 12%. The Rankine cycle also permits easier development because lower turbine efficiencies can be tolerated and low pump efficiencies may be used. The Rankine cycle may be very reliable because the system can be built with only one moving part —a combined rotating shaft that includes turbine, alternator, pumps, and working-fluid lubricated bearings. The Phillips engine based upon the Stirling cycle has comparable efficiency (about 50% of Carnot) but requires many moving parts, gas heat transfer, and separate lubrication and it is heavier at higher powers.

As shown in Figure 7, mercury, sulfur, rubidium, and possibly potassium lie within the temperature range of immediate interest. Of these fluids mercury has the lowest temperature capability and is consistent with present metallurgical and reactor capabilities. It is also the only fluid for which sufficient engineering data and experience exist to permit the development of a long-endurance, reliable auxiliary power unit. It is anticipated that engineering data and experience will be accumulated for the higher-temperature fluids in sufficient time to keep abreast of reactor-development progress and the requirements for higher-power, more-compact, space nuclear-electric plants.

A typical flow schematic of a liquid-cooled reactor with a Rankine turbine-cycle power-conversion system is shown on Figure 8. The reactor may be cooled with liquid sodium, because of its high efficiency as a high-temperature heat-transfer medium and because it provides simplified reactor control and development. The sodium in turn releases the heat it gains from the reactor to a mercury-boiler superheater. The superheated mercury vapor then passes through a small, high-speed turbine that drives an electric alternator. The expanded mercury vapor is exhausted to a condenser-radiator, where it is condensed to the liquid phase. A small, high-speed mercury pump then pressurizes the mercury liquid to be returned to the boiler.

Another alternative is to utilize the identical concept but eliminate the liquid-sodium loop and the boiler by boiling the working-cycle fluid directly in the nuclear-reactor core. The major advantage of this scheme is that it permits nearly isothermal reactor operation and permits boiling the working fluid at a higher temperature without elevating the reactor fuel temperature. The disadvantages include increased control complexity, loss of superheat, and the added requirement of a liquid-vapor separator and a liquid-recirculation pump. The total weight and complexity of this approach are equivalent to the two-loop system at low powers. At large powers it appears that this single-loop approach has potential of being a lower-weight system.

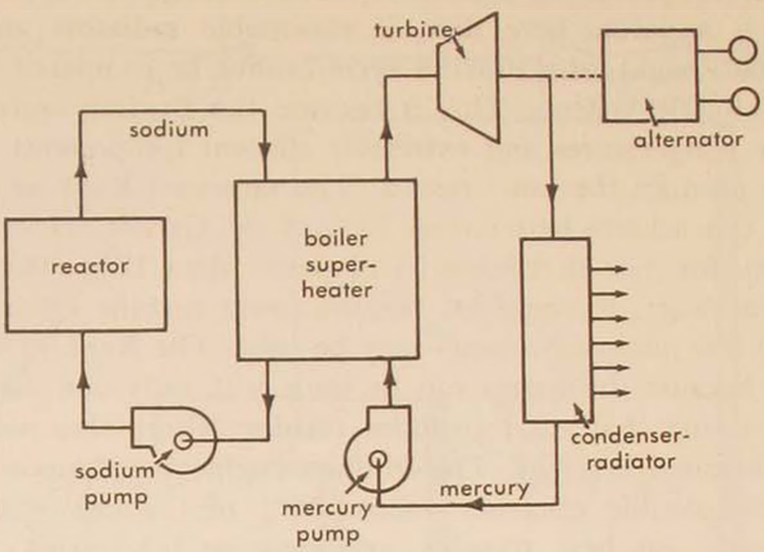


Figure 8. Flow schematic of a two-loop power system based on a liquid-sodium-cooled reactor heat source and a Rankine turbine-cycle power-conversion system.

static conversion APU

Conduction cooling is feasible for thermal power outputs of the order of 10 kilowatts. If a system would incorporate thermoelectric or thermionic power-conversion devices that utilize the reactor surface as the hot junction and a radiator fin as the cold junction, then a completely static, nonmoving-part system would be possible. A system as simple as this can be easily started up after it has been established in a satisfactory orbit. In this way special launch facilities and handling procedures can be minimized to permit early flight of a nuclear-reactor power source. This system need weigh only about 1 lb/watt and even with shielding should not exceed about 2 lb/watt. Its life can be many years. The system generates power continuously regardless of orientation or shadow. Thus it is a competitor of the nonoriented solar-cell auxiliary power units for earth satellites and deep space-probes. Not only does it exhibit a weight advantage but in production it might cost on the order of one to two hundred thousand dollars, which may be significantly less than the comparable power solar-cell system.

nuclear-generated electric propulsion

Based upon reasonable assumptions, indications of payload capability for various missions of interest are presented in Figure 9. Here the payload fraction (which is the ratio of the payload weight to the power-plant-plus-propellant weight) for 10,000-volt cesium ions is plotted versus the power-plant specific power. Reasonably short transit times have been assumed starting from 300-mile earth orbits. A 30-kw unit weighing some 30 to 40 lb/kw (Figure 3) could place about a 500-pound payload on the moon in 3 or 4 months.

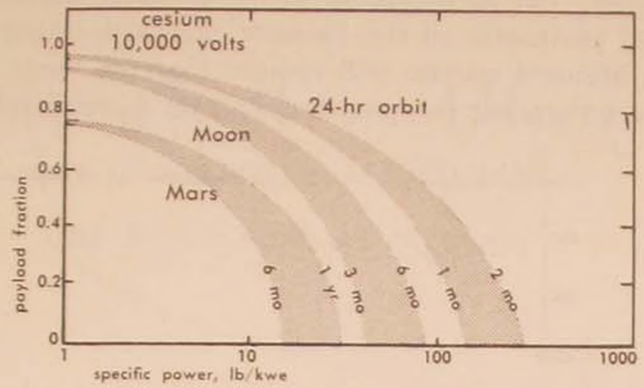


Figure 9. Assumed nuclear-generated electric propulsion requirements and payload capabilities for space missions to Mars and the moon and for a 24-hour orbit.

communications

An approximate projection of the power required for communications in space is shown in Figure 10. The broadband TV power requirement indicated would permit contiñuous TV broadcasting. Slow-motion films or "snapshots" will consume much less power and can in some cases be as low as the narrow-band continuous-voice communication requirement.

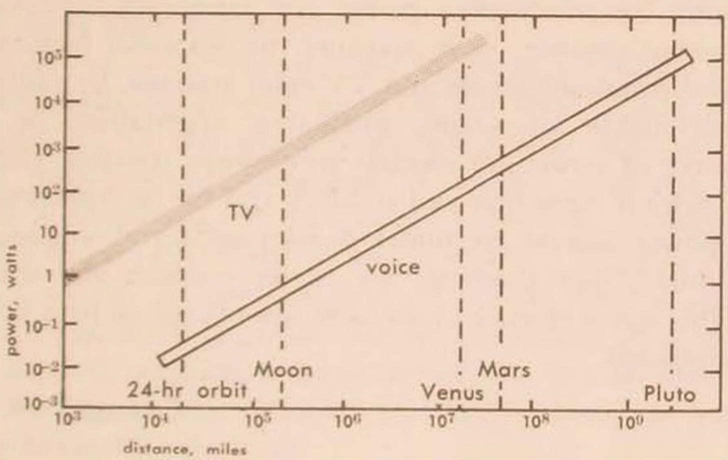


Figure 10. Projection of power requirements for space communications.

shielding

Finally an appreciation for shielding requirements can be gained from Figure 11. Here both a vehicle arrangement and a transistorized payload of 3.5 ft^3 were assumed for 1-year endurance. If transistors occupied the entire nose-cone payload section, these weights could range from 1000 to 2000 pounds. The weight could then be reduced again by permitting a lightweight, rigid telescope some 35 feet long to separate the payload section from the APU module. The arrangement of components around the reactor and the design and placement of the radiator play a deciding role in shielding requirements. Manned systems will require that the "bola" concept be used —a long cable separating the reactor from the space platform. The reactor

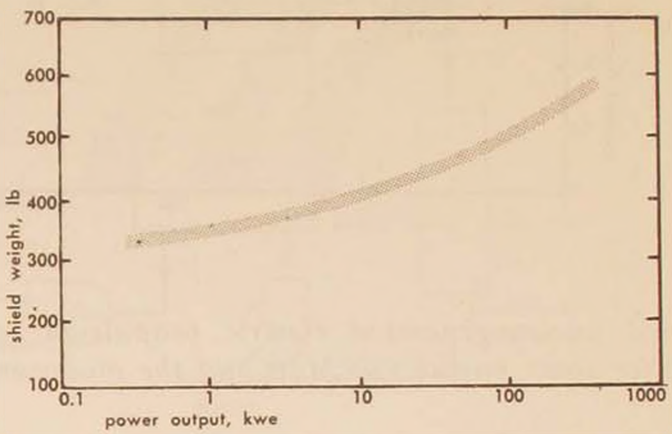


Figure 11. Reactor shielding requirements (shield weight versus power output).

can be shielded by a lightweight "shadow" shield and be removed from the space platform some thousand feet. The manned platform will then remain in the shielded shadow.

THE COMPACT nuclear power plant promises to provide an economical source of continuous, long-endurance power for numerous earth-satellite systems, including reconnaissance, early warning, navigational beacons, weather surveillance, and communications and TV relay stations. In addition it promises the only reasonable low-weight, small-area, orientation- or trajectory-independent source of power for electric propulsion systems. These systems will be used for orbital correction and stability and for interplanetary exploration. The lower-power systems are under development and will soon be ready for flight. The higher-power systems are under research and study and can be made available when electric propulsion has proved to be a preferred method of space propulsion.

Canoga Park, California

Testing Radiation Effects on Aircraft Systems

The USAF Support Program

CAPTAIN WILLIAM C. SHIEL

Project Officer, Aircraft Nuclear Programs Office, Hq ARDC

FROM the outset of the manned nuclear-aircraft program it was apparent that the presence of a nuclear reactor in an airframe would pose a unique challenge in regard to radiation effects upon airborne systems and subsystems.

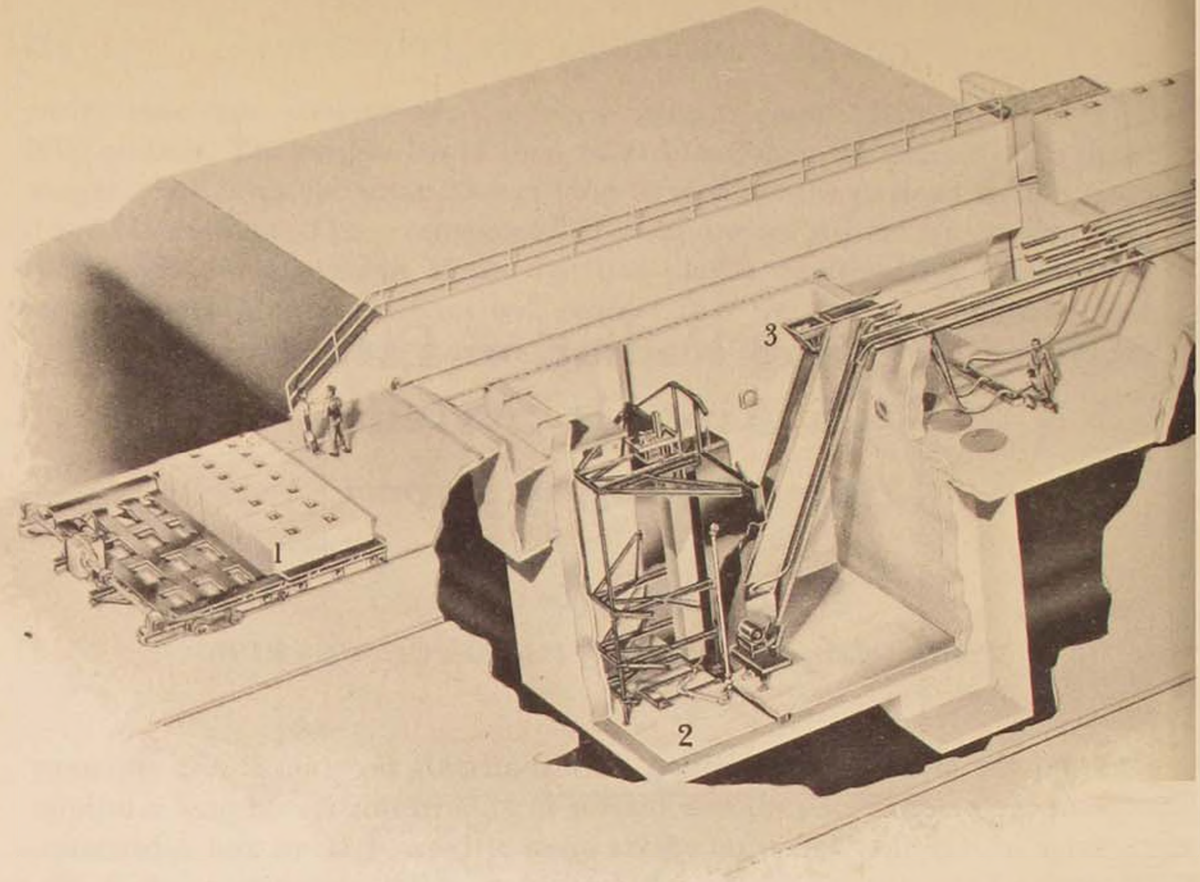
Each of the Aircraft Nuclear Propulsion (ANP) programs conducts development and testing of its own particular components. None of these programs, however, is equipped to carry out the broad studies of basic materials and components for suitability in a combined nuclear-and-flight environment. The need for such fundamental studies, prerequisite to any program of nuclear-power application, was recognized early in the formulation of the manned nuclear-aircraft program. At that time the Air Force contracted for broad, basic investigations of materials and components in relation to performance in a nuclear flight environment.

Since the radiation-effects testing effort began as a support program to the manned nuclear-aircraft project, many of the specific tests and testing facilities were tailored to the manned nuclear-aircraft concept. With the creation of the nuclear-missile programs, it became apparent that these facilities and the accumulated test data would be equally valuable to them. The complex of radiation-effects testing and specialized facilities under ANP responsibility is operated in direct support of all the ANP programs. It is the purpose of this discussion to present the unique testing philosophy of the radiation-effects support program, to explain some of the tests that have been conducted, and to describe the facilities that are in being or coming into being specifically to conduct the work.

testing philosophy

Until the present the standard practice in both aircraft and missile testing programs has been

- to select as many components as possible from the inventory of items that have been previously tested and proved satisfactory. This procedure re-

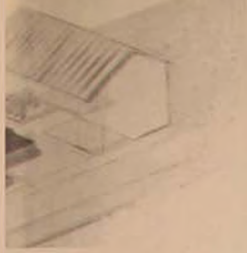


duces the expensive testing programs and increases standardization of components in the Air Force inventory.

• to test thoroughly, on the ground, those components and subsystems that have not been previously tested under the predicted environmental conditions. The latter requirement imposed a unique burden upon the nuclear-aircraft and nuclear-missile programs, since experience in the operation of aircraft and missile equipment in a nuclear environment was nonexistent. The lack of experience data made necessary the creation of new facilities for testing materials, components, and subsystems in a radiation environment combined with simulated flight conditions. When it was found that many basic materials used in components deteriorated badly under only fractional amounts of predicted nuclear environments, a broad testing program was arranged.

An extensive effort was initiated to obtain, assemble, and evaluate nuclear-radiation damage data. This was followed by experimental and analytical investigations to determine the basic changes that occur in materials in a nuclear environment, to find radiation-resistant materials satisfactory for use in aircraft and missile components, and to develop means of predicting dose rates of neutron-activated materials.

To complement the materials investigation, a component-testing program



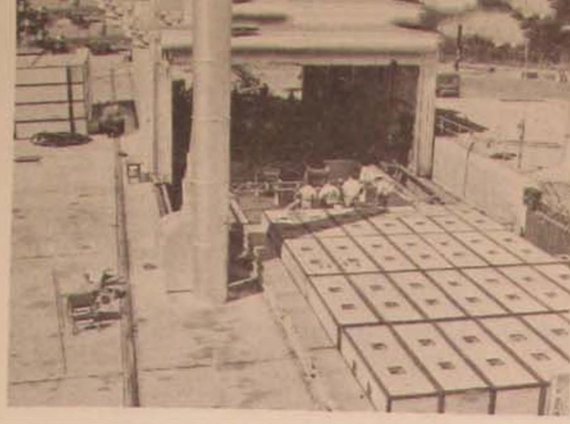
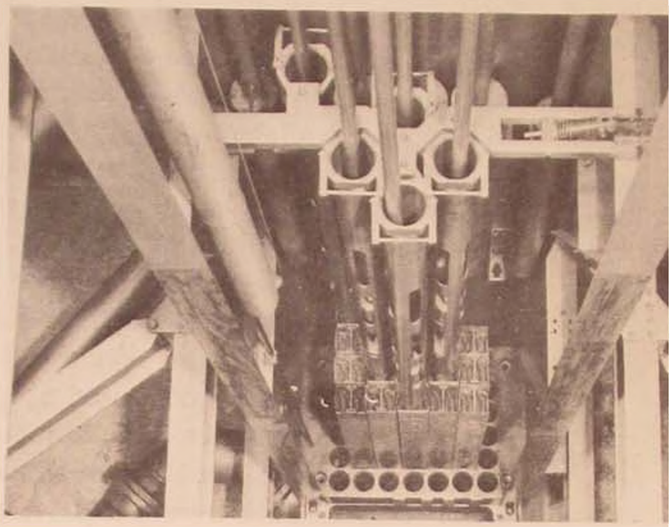


Figure 1. Cutaway of NARF ground-test reactor shows (1) rail-borne concrete-block shield (also in photo above) that covers the pit when reactor is operating, (2) reactor pit, and (3) escalator system for lowering test items into position near the reactor. View down into the 3-megawatt reactor (right) shows fuel-element control rods and channels, gridded fuel-element cells, and remaining holes in grid-plate for additional fuel elements needed to make a critical mass.



was started to determine if proposed system and subsystem components would operate under all nuclear environments. System components include tires, brakes, hydraulic lines, fuels, valves, blowers, pumps, and electronic equipment. Subsystem components include seals, bearings, valve packing, insulators, brake discs, electronic tubes, transistors, and capacitors.

A ground-test and later a flight-test program is planned, where applicable, for all new systems, since the flight test of new airborne systems culminates their development and it is toward this end that all earlier testing is directed.

The data acquired from the experience of the Atomic Energy Commission in developing atomic reactors provided a useful base from which to start the search for radiation-resistant materials. It soon became evident, however, that additional specialized information would be required in a continuing aircraft nuclear propulsion program. To this end, the Air Force contracted with the Convair Division of the General Dynamics Corporation at Fort Worth, Texas, to prepare a handbook of all available information on radiation effects upon materials, for use by anyone designing nuclear-aircraft or nuclear-missile systems. Later this contract was expanded to permit the contractor to perform an extensive radiation-testing program to find materials and to test components particularly suited for the new environment of the nuclear aircraft. This work resulted in a requirement for a new test facility.

Built at Convair and funded by the Air Force, it is designated Nuclear Aircraft Research Facility (NARF).

Nuclear Aircraft Research Facility

NARF is one of the most complete facilities available in this country for testing radiation effects. It is particularly suited to the investigations required of nuclear-aircraft programs. The Convair contract for NARF has also been expanded to require investigations of the mechanisms of damaging nuclear radiation and to test and evolve radiation shielding and methods for designing shields.

The outstanding testing device at NARF is the ground-test reactor capable of dynamically testing small aircraft components in a nuclear radiation field and in any one of three environments: pressure, temperature, or humidity. Also available is the Aircraft Shield Test Reactor, as well as a number of other sources of radiation. These devices are used not only for radiation testing but also for shielding experiments. Any contractor engaged in the ANP effort can perform tests at NARF that may be required for his own components. The contractor operates the facility for benefit of the entire industry.

In 1952 Convair was awarded a contract to construct and fly the nuclear test airplane. The plane was a B-36 modified to carry aloft the Aircraft Shield Test Reactor and given a special nose containing a shielded crew compartment to protect crew members from nuclear radiation. Studies were made to determine the effect of shielding in reducing the radiation from the Shield Test Reactor over a wide range of altitudes and to analyze the variables of direct, air-scattered, structure-scattered, and ground-scattered nuclear radiation. These studies were necessary because the absorption or scattering of radiation depends upon the material through which the radiation passes. At high altitudes the effects of ground-scattered radiation will be removed and the effects of air scattering will be reduced greatly, so that structure scattering alone can be analyzed. The tests using the nuclear test aircraft were completed in 1957. At that time the Aircraft Shield Test Reactor was removed from the aircraft and set up at NARF, where it has been a very useful ground-test device.

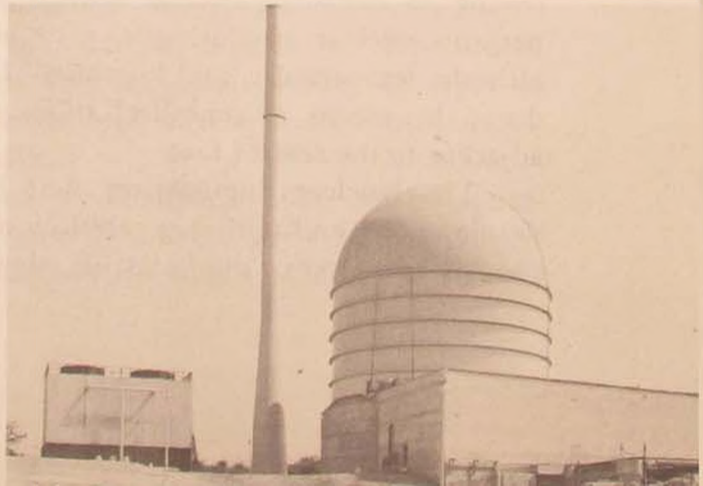
Tower Shield Facility

While flight testing with the nuclear test aircraft was in process, the Tower Shield Facility was constructed at Oak Ridge to simulate aircraft-reactor radiation patterns during flight. Four 324-foot towers were erected, with steel-cable assemblies capable of lifting large weights to various heights above the ground. A nuclear reactor was lifted aloft and operated at various heights. At the same time numerous mockups of different crew shields and shield materials were lifted to equal level with the reactor, simulating the separation of the crew compartment from the aircraft reactor. Radiation dose rates for different operating power levels at various heights above the ground were recorded in the underground blockhouse containing the reactor control

Figure 2. The Tower Shield Facility at Oak Ridge National Laboratory. Suspended for simulated flight testing with the pot-shaped nuclear reactor is a cylindrical mockup of crew shielding material.

Figure 3. Georgia Nuclear Aircraft Laboratory at Dawsonville, Georgia. Here large components and major subsystems for aircraft undergo tests in a nuclear environment.

Figure 4. Nuclear Engineering Test Facility at Wright Air Development Center permits radiation testing of complete aircraft systems by the 10-megawatt test reactor.



equipment. This work still continues, and the data compiled from the flight tests can now be applied to correct the data obtained from the Tower Shield Facility to actual flight conditions.

Georgia Nuclear Aircraft Laboratory

In 1956 the Air Force funded a new radiation-effects facility designated as the Georgia Nuclear Aircraft Laboratory from its location in northern Georgia near the Lockheed Aircraft Corporation's plant at Marietta. This Lockheed-operated facility, built to augment NARF, is designed to irradiate and test large aircraft components and major subsystems anticipated for use in nuclear-powered airborne vehicles. It is capable of testing items as large as 10 by 15 by 8 feet, in which the gamma-to-neutron ratio may be varied between 2.1/1 and 140/1. The basic tool of the laboratory is a reactor (located in the rectangular building in the photograph). Large test items can be moved into and out of this building on railroad flatcars. They ride on rail spurs that enter three sides of the building in pairs, thus providing positions for six cars to be irradiated at one time. The reactor is kept submerged in a pool of water beneath the surface of the ground when not in use and may be raised to the test area when required. This feature allowed the designers to provide a large space for positioning test items in the test area while the reactor is shielded by the pool. Operation, movement, and data recording are accomplished from an underground control building remote from the reactor building.

Nuclear Engineering Test Facility

Currently the Air Force is building a new nuclear radiation facility, the Nuclear Engineering Test Facility at Wright Air Development Center in Dayton, Ohio. It is being constructed for the purpose of establishing reliable nuclear radiation parameters, procurement specifications, and nuclear analysis techniques; conducting realistic reliability and performance testing of materials, components, and subsystems, including tests involving combinations of other environmental factors affecting the nuclear environment; developing instrumentation and monitoring techniques that will advance the state of the art in nuclear-radiation-resistant materials.

The facility will consist of a 10-megawatt research reactor joined by two 330-cubic-foot environmental-radiation test cells and a remotely operated handling system for irradiated materials. The radiation test cells permit the testing of complete aircraft systems under high-intensity gamma and fast-neutron nuclear environment, with other simulated flight environments of altitude, temperature, and humidity. These latter environments can be introduced by means of umbilical tubes and cables leading into the test cells adjacent to the reactor face.

The Nuclear Engineering Test Facility will provide nuclear research, development, and testing capabilities currently not available and will support the Air Force across the board in advancing its nuclear capability.

In addition to the airframe and propulsion contracts, the ANP program has conducted, through Wright Air Development Center, a significant number of radiation-effects contracts to develop components and materials suitable for the nuclear environment.

Contracts handled through the WADC Materials Laboratory with Shell Development Company, California Research Corporation, Esso Research and Engineering Company, and Midwest Research Institute have produced nuclear-radiation-resistant, high-temperature fluids together with solid and liquid lubricants of outstanding capabilities. Base fluids, particularly the meta-linked polyphenyl ethers, have been developed that offer multifunctional capabilities in numerous applications, such as lubricants, heat transfer, hydraulics, and power transmission. These base fluids have demonstrated definite promise of extending temperature use to 800-900°F or stability to exposures as high as 10^{11} ergs/gm carbon. Developments now under way are expected to produce an operational capability far in excess of that now available with conventional fluids and lubricants.

In the field of elastomers, B. F. Goodrich Company has been successful in developing greatly increased radiation-resistant tires, seals, and O-rings.

Work by the Bendix Aviation Corporation on communication, navigation, and identification (CNI) equipment indicates that we can build a satisfactory CNI subsystem for use in any of the development and test-bed types of manned nuclear aircraft proposed to date.

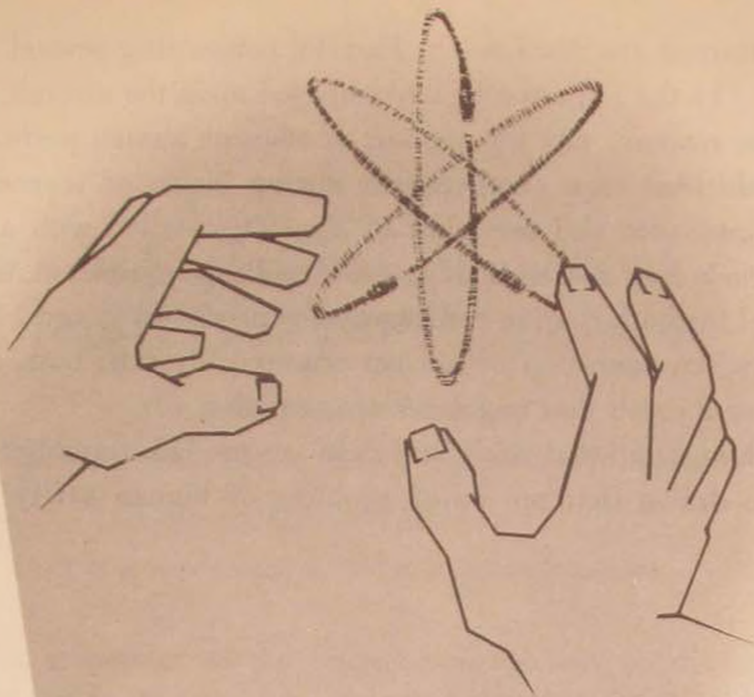
The Bell Telephone Laboratories, Incorporated, have been working on transistors and ferroelectric, magnetic, and silicon devices for use in the nuclear environment. Bell has conducted studies of a very fundamental nature that greatly increase understanding of nuclear effects on these devices. In addition to establishing probable maximum limits for utilization of these devices in the nuclear environment, Bell's work will be invaluable in the design and development of other systems utilizing such devices in a nuclear environment.

Numerous other studies and contracts have been and are being conducted by ARDC Centers, the Army, the Navy, the AEC, and industry for the development of nuclear-resistant components and materials. Because of the rapid progress, development, and wide-range interest in this area, the Air Force established the Radiation Effects Information Center at Battelle Memorial Institute, Columbus, Ohio, in May 1957. Over 125 separate projects or contracts currently in existence have been identified by REIC and are being monitored for contributions to the state of the art in radiation effects. Through its files, data-gathering service, and periodic reports available to both Government and industry on a classified and unclassified basis, REIC has been extremely useful in keeping management and technical personnel up to date on the latest developments and progress covering all types of radiation effects, from linear accelerators through aircraft nuclear propulsion, nuclear weapons, and space environments.

The general success of the radiation-effects work to date can be appreciated from the fact that both Camal development designs which resulted from the Convair-Lockheed airframe competition indicated that the current in-hand state of the art is more than adequate for a manned nuclear-powered development airplane.

The program that has been described is compiling significant data on materials, components, and systems under radiation and environmental conditions. The application of these data will advance any airborne nuclear program. No matter whether the vehicle is an aircraft, rocket, or missile, vital systems for guidance, navigation, flight control, and radar detection and warning are common to all three vehicles. The radiation-effects support program is working to determine a method for the accurate prediction of the performance of these vital systems under radiation and flight conditions.

Headquarters Air Research and Development Command



PART IV

The Human Element

DURING the immediate future the problems concerning the well-being of man in nuclear-powered flight appear to relate to the manned aircraft, although not far ahead the manned spacecraft impelled by the nuclear rocket may also be seen.

From the beginning of the nuclear propulsion programs the superposition of a nuclear environment on the crew compartment of a manned aircraft has been extensively studied. Equally important, the safety of the public in the vicinity of nuclear operations has been given continuing scrutiny. The concepts underlying these investigations and the conclusions attained are discussed in Part IV concerning several areas of research: (1) the radiation hazard imposed upon the aircraft crew by the airborne reactor; (2) the support of efficient human performance in a small, shielded crew compartment during flights of several days; (3) the maintenance and servicing of aircraft installed with a nuclear reactor, including the special ground-handling equipment and facilities essential for both routine and emergency procedures; and (4) the public safety in the operation of nuclear-powered aircraft, both during flight and after a crash that might release radiation.

While additional study and data are needed, the salient conclusion may be drawn that no major problem of human safety remains unsolved.

Radiobiological Aspects of Aircraft Nuclear Propulsion

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Director of Medical Research, School of Aviation Medicine

Colonel Gerrit L. Hekhuis

Chief of Radiobiology, School of Aviation Medicine

THE MAJOR advantage of the nuclear-powered aircraft over all other types of aircraft is its capability of very long-range flight nonstop and without aerial refueling. This potential of practically unlimited range can be fully exploited, mainly by extending the duration of current bomber and air-launched missile mission profiles. One type of application of this capability is to early-warning systems or computer platforms for missile detection. A second and perhaps equally unique advantage of nuclear power is the ability routinely to maintain appreciable percentages of aircraft in flight at all times as a security against surprise attack.

There are, however, factors that tend to limit the duration of any single mission and the frequency with which long missions can be performed. Prominent among these factors are the confined quarters in the crew compartment, with its minimum provisions regarding hygiene, rest and recreation, noise level, and environmental comfort.

In space-cabin simulator studies performed at the School of Aviation Medicine a number of seven-day flights have been conducted, using highly trained, carefully selected Air Force subjects. These pilot subjects were committed as an integral component of a man-machine system and have been systematically exposed as such to several relevant conditions of the closed environment of a nuclear crew compartment. These conditions include a simulated altitude of one half an atmosphere (18,000 feet equivalence) with a gaseous environment equivalent to that of ground level; an extreme degree of physical confinement, including restricted mobility; isolation and sensory deprivation; abnormal schedule of work and rest—four hours on, four hours off during the entire seven days; variation from customary nutritional support; high noise level; and limited facilities for personal hygiene. The period of seven days was selected because it allowed time for depletion of initial reserves and subsequent biologic adaptation to the above conditions. It is extremely interesting to note that these experienced pilots did adjust to their work schedule and that they maintained an extremely high level of proficiency for the entire period. In two instances they could have continued beyond the seven days of flight. These results strongly suggest that problems of work schedule, day-night cycling, boredom, isolation, nutrition, and limited hygiene can all be satisfactorily controlled.

Superimposed on these stresses will be the effect of exposure to ionizing radiation. Radiation begins with the elementary process of fission. Fission fragments thus formed are intensely radioactive. They decay by successions of particle emissions and conversions, accompanied by gamma radiation. The action of fission itself also releases high-energy gamma and neutron radiation.

These ionizing radiations, having a wide range of energy, can and do penetrate matter. They can penetrate the human body without being sensed. By a process of ionization they affect living cells and can produce changes that may result in serious illness and even death. Some of these changes can extend over periods of time varying from days to years after exposure. Many radiobiologists in the nuclear propulsion program feel that these levels of radiation exposure may be the prime limiting factor in the operation of an aircraft which otherwise meets the strategic requirements of several different mission profiles. This is true particularly if rigid adherence to current tolerance levels, as set forth by the National Committee on Radiation Protection for medical and industrial purposes, is a prerequisite to operation of nuclear-propelled aircraft.

It is important and imperative, therefore, that the biological hazard of dose-effect and the response to various radiation sources be well understood if realistic permissible levels of exposure—and thereby limits of operation—are to be determined. Since risk cannot be eliminated totally from man's life and work, there must be a careful balancing of potential radiation risk against the total advantages to be obtained.

In the design of a nuclear-powered aircraft the engineer, because of weight and cost considerations, desires a minimum of radiation shielding. The radiobiologist, on the other hand, desires to have the minimum radiation hazard, which means maximum shielding between the reactor and the crew. The question is: How much shielding is necessary for acceptable protection? Is this amount prohibitive in terms of the mission of the aircraft? Then, what is the amount of radiation that can escape the shield? Is this amount greater than the maximum permissible exposure which the human body can tolerate in complete safety? If not, how often can an individual be exposed to this amount of radiation without significant detrimental effects? A significant factor in this type of exposure is the ability of the human body to throw off some of the damage effects. In answering these questions it is extremely important to determine which biological endpoints are of most concern in this particular type of problem.

From data on the people of Hiroshima and Nagasaki, on the Marshallese, on accidental exposures at Argonne, Los Alamos, and Oak Ridge laboratories, as well as on the more recent exposures in Yugoslavia, on therapeutic radiation of selected patients in cancer therapy, and on a large number of animal experiments, we have learned the typical acute radiation response. We know much less about the latent or delayed effects from prolonged or repeated exposure to low levels of radiation. For the most part, however, sublethal, total-body radiation doses of less than 450 to 550 roentgens (r), but greater than 200 r, are required to produce acute effects.

So far, consideration has been focused on acute exposure approaching near-lethal levels, but attention must be given also to the smaller doses of radiation exposure received at varying intervals of time (days) over relatively long periods of time (months to years). Experimental data show a marked difference between acute and delayed responses to radiation exposure. Certainly in the low-dose repetitive schedule on small primates there is an absence of effect.

Even though the dose schedules discussed do not yet demonstrate irreversible biological change or damage, it is indeed true that these doses may have biologic consequences which are more subtle.

In an operational situation the radiobiology problem is not limited to the reactor itself. The neutrons released from the reactor in the fission process can induce activity in aircraft components, in the airframe, in the area where the aircraft is run up, and in the areas where preflight maintenance is performed. This induced activity can create secondary or activation-type radiation hazards. For example, concrete in a runup area can experience such a neutron flux that the iron and calcium in it will become radioactive. Similarly oil and grease spills in the maintenance areas can entrap radioactive particulates and retain them as radioactive contamination. However health-physics procedures currently in effect at facilities such as the Hanford Works clearly demonstrate that the established ground-handling techniques will enable personnel to remain within acceptable exposures as set by the National Committee on Radiation Protection. Techniques of remote handling and employment of shielded maintenance vehicles will further enhance this conclusion.

As in all other Air Force operations, emergency procedures and possible crashes of nuclear-powered aircraft must be considered. An ejection capsule similar to present-day space capsules will afford adequate crew protection during bailout. When a nuclear aircraft is involved in a crash, the possibility of loss of aftercooling and of an ensuing fire suggests a limited problem of fallout contamination over a rather narrow geographical area. This radiation pattern downwind, depending on the local meteorological conditions, is hazardous only at close proximity to the aircraft. Comparison of the hazard presumed under the worst possible conditions—loss of aftercooling, fire, and a strong climatological temperature inversion—with calculations of area hazards from potential reactor accidents in an AEC ground installation permits the conclusion that beyond the near vicinity of the crash the dose level will remain below that required to produce the acute radiation syndrome. Additional factors of safety to unprotected personnel obviously include flying over controlled air corridors, operating in areas of low population density, and restricting operations to favorable meteorological conditions—clear weather, light winds, and good air stability. The shielded crew compartment itself affords excellent protection against thermal and ionizing radiation during such accidents.

With all the above limiting points in mind, then, one must establish a practical dose-versus-effect schedule. In considering the application of nuclear propulsion in aircraft, as with all aircraft weapon systems, a period of training must precede operational readiness. The maximum exploitation of nuclear propulsion in manned flight vehicles—with minimum shield weight assumed—is dependent upon carefully planned training, integrated into an operational program that minimizes radiation exposures by alternation of aircrews and frequency of flight.

To do this and stay below the dosage that produces the so-called acute effects or syndrome, and to eliminate possible long-term latent effects from radiation, special emphasis must be placed on crew selection. Individuals must be chosen who can complete transition training from conventional aircraft and qualify in the nuclear aircraft in minimum flying time and thus undergo a minimum amount of radiation exposure during their training. Perhaps also to be considered is the selection of crews from an age bracket that will minimize the concern for and importance of genetic effect, temporary sterility, and possibly even the susceptibility to an increased incidence of leukemia. Thus older men may receive a higher average dose per year but over a relatively shorter period of time. Criteria have been developed to take these factors into consideration.

It is imperative that crew education be conducted and maintained to eliminate ignorance, fear, and misinterpretation and to provide an intelligent, healthy psychological approach to problems associated with radiation. Because of unwarranted adverse publicity, many prejudices now exist.

A program of mission duration and adequate rest intervals between missions must be clearly defined and established to permit maximum recovery from reparable injury. Mission profiles must be planned and selected so that all factors are carefully controlled in the over-all employment of the aircraft commensurate with an optimum maintenance of the crew. Long-range missions should be scheduled in such a way that maximum rest periods follow. Short-range missions, such as strategic profiles, probably can be flown more frequently with shorter intervening rest periods.

The final consideration, equally vital to the employment of the aircraft and the protection of its crew, is the concept of differing dose schedules. Minimum dose levels should be predicated on peacetime training and readiness requirements. Higher-dose-level schedules should provide guidance for commanders acting under national emergency requirements. Such dose schedules, based upon data as to both acute and chronic radiation-exposure level, should neither suggest nor demonstrate any unfavorable long-term prognosis for cataract production, leukemia induction, or shortening of the life span. Since there is no single biological-effectiveness number for all radiations and it is impossible to investigate all dose, dose-rate, energy, and radiation combinations for mixed neutron and gamma radiation for all possible biologic endpoints, salient limitations must be defined as best we can. Here both the nuclear-aircraft crew and the nuclear-radiation source must be considered, if we are to evolve a workable program.

RADIATION as we know it today can produce biologically detrimental responses. It is quite clear, however, that minimally effective doses do occur for every endpoint of concern, with the greatest question concerning possible genetic effect. In spite of this area of doubt, it is reasonable that a limited number of carefully selected individuals will be involved in nuclear operations. Dose schedules can be quite reasonably defined to achieve maximum aircraft utilization along with maximum personnel protection.

School of Aviation Medicine

Human Factors of Nuclear-Powered Aircraft

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THE DEVELOPMENT of a manned, nuclear-powered weapon system with sustained flight capability requires the evolution of a synthetic crew habitat. Within the vehicle an environment must be provided that will accommodate the normal capacities of man and permit him to live according to at least the essential facets of his individual habit pattern.

Habitability of an aircraft environment is intimately related to the duration of flight. Both the crew members and the equipment they operate must be selected and integrated to interact efficiently to accomplish required goals. They must function easily and quickly together within acceptable limits of accuracy and be able to withstand the kinds of stresses inherent in their own functional interactivity and in their intended operational environment.

The multiple factors that impinge on the human and tend to influence his effectiveness during sustained nuclear flight fall into three major problem areas: environment, consumption, and by-products. The environmental factors are described as conditions such as temperature, humidity, oxygen, and noise level that affect physiological welfare. They cannot change appreciably without deteriorating human performance. Consumption factors relate to things the man uses up while inhabiting the crew station—food, water, personal toiletries, clothing, charts, and other mission equipment. By-products are the results or waste factors of human usage that must be recycled, destroyed, ejected, or stored until mission completion: body waste, food residue, soiled clothing, and other used products. It is readily apparent from a listing of these problem areas that long-range flight is really contingent upon providing the occupant with the biologistic requirements for a normal habitat that will satisfy his essential needs. These provisions must be arranged in such a way within the living space that the man will be able to use them effectively without undue fatigue or loss of capability.

In the past several years a segment of the Air Force human-factors research effort has been organized to explore and define the parameters of human habitation and reliability in sustained air and space operations. The purposes of habitability research are manifold:

- to investigate the comprehensive factors of human habitation in sustained flight

- to define the parameters of crew accommodations, sustenance, sanitation, personal equipment, and the complex human response patterns in respect to time
- to identify problem areas through creative research and develop new concepts for investigation
- to devise imaginative new research equipment that will relieve the effect of time on human performance where normal relief measures unduly restrict the man's ability to do his job
- to provide scientific information on the complex human-factors problems of advanced weapon systems prior to contractor mockup.

Initial progress toward these objectives has been accomplished through analysis of past achievements in long-range sea and air operations and through the construction of fully instrumented crew-station simulators, programed to duplicate the anticipated mission profile of a highly mobile nuclear vehicle performing a five-day combat strike. In such broad research activity the piecing together of widely diverse segments of knowledge evolves a true picture of the problems in sustained air operations and their effect on the man and the weapon sytsem.

crew compartment space

A difficulty in the development of a nuclear vehicle from the human-factors viewpoint is in providing crew compartment space consistent with the aerodynamics of the total vehicle and still compatible with biologistic requirements. Based on known long-range flights and nuclear submarine trips, the volume of the inhabited compartment and the necessary number of men to operate the vehicle can be plotted against the total time of the mission. The resulting curve levels off after approximately a 700-hour flight, at which

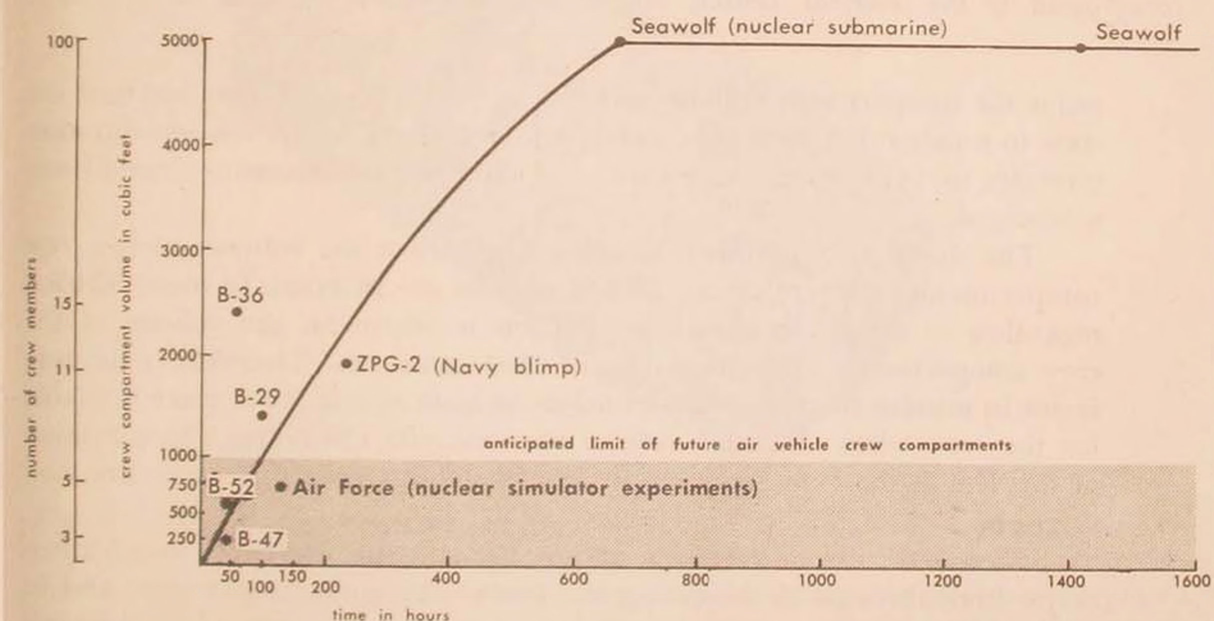


Figure 1. The ratio of man to volume in regard to time in flight.

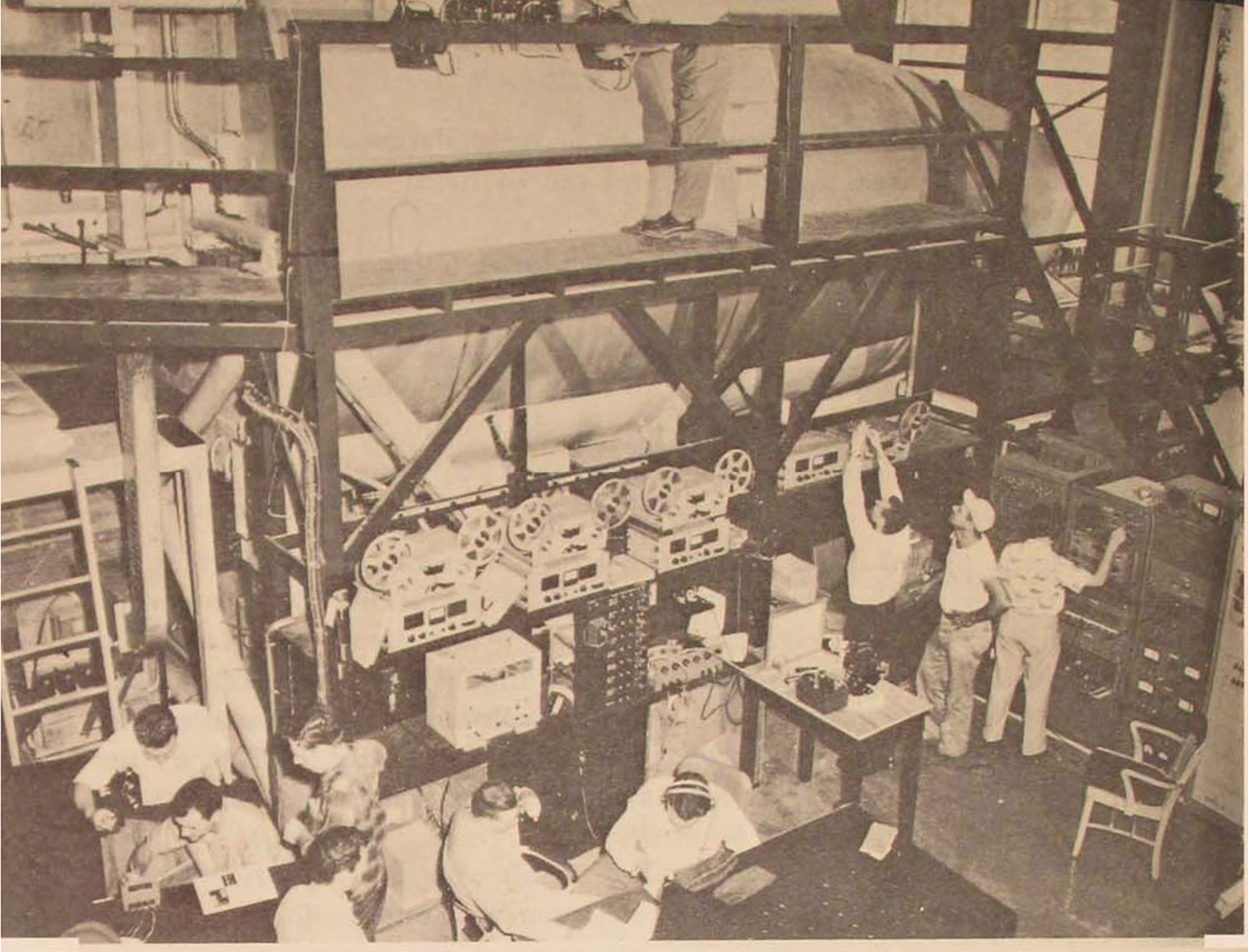


Figure 2. The pioneering Nuclear Aircraft Simulator Facility at the Aero Medical Laboratory, Wright Air Development Center, represents the first attempt to create a minimum-size crew compartment and to accumulate specific knowledge about an advanced weapon system before contractor mockup. At right, four metal cabinets house the electronic equipment used in gathering data on the physiological and psychological state of the crew members during their experimental "flights" in the simulator. At top, a technician adjusts one of the time-lapse cameras that automatically record the movements of the crew during the simulated flights. In the left foreground is the control center, where the multitude of data is recorded.

point the compartment volume is shown to be about 5000 cubic feet and the crew to number 100 men. The curve continues level as the mission duration increases to 1440 hours, the record time the nuclear submarine Seawolf was submerged.

The significance of this curve is realized when the volumes of the crew compartments of future strategic flight vehicles are analyzed. In these vehicles, regardless of their over-all size or mission requirement, the volume of the crew compartment will seldom exceed 1000 cubic feet. Therefore a limiting factor in mission duration with a nuclear weapon system is the space available for the crew when the total mission time exceeds 120 hours. For a mission of this length the experience graph indicates that a crew of four or five men is required.

These data demonstrate the urgent need in the Air Force to achieve a major breakthrough in increasing the size of the crew compartment and in reducing the number of men needed to operate the vehicle. Only then can the full potential of nuclear-powered flight be exploited to maximum military advantage, as on mobile airborne strategic alert.

Several possibilities offer themselves for the attainment of this breakthrough. One is the miniaturization of all equipment required in the crew compartment. Each saving of fifty cubic feet would permit one additional crew space in the compartment. A different possibility is the more complete automation of the vehicle functions so as to reduce the number of men required for both normal and emergency operation. Other approaches to the problem are also under investigation.

To establish basic standards for the many other human variables in long-mission nuclear flight, the first phase of a major research effort has recently been completed. Utilizing an instrumented nuclear-aircraft simulator, this study set out to determine for a typical mission the types of trained airmen and equipment required and the types, amounts, and storage space required for food and clothing. It was also necessary to explore the amount of water required for drinking and sanitation, the frequency and type of body relief, lighting conditions, and a host of other variables. In addition to these aspects of environmental design research, techniques were devised for measuring the psychological and physiological responses of the individual crew member as well as of the group.

In such a study it is necessary to create a complete environmental situation that parallels in every possible respect the airborne system under consideration. The crew compartment of the Aero Medical Laboratory simulator measures 210 inches long, 80 inches wide, and 72 inches high and provides a minimum-volume cockpit of approximately 710 cubic feet. The crew habitat is divided into two distinct areas: a work area containing all the controls

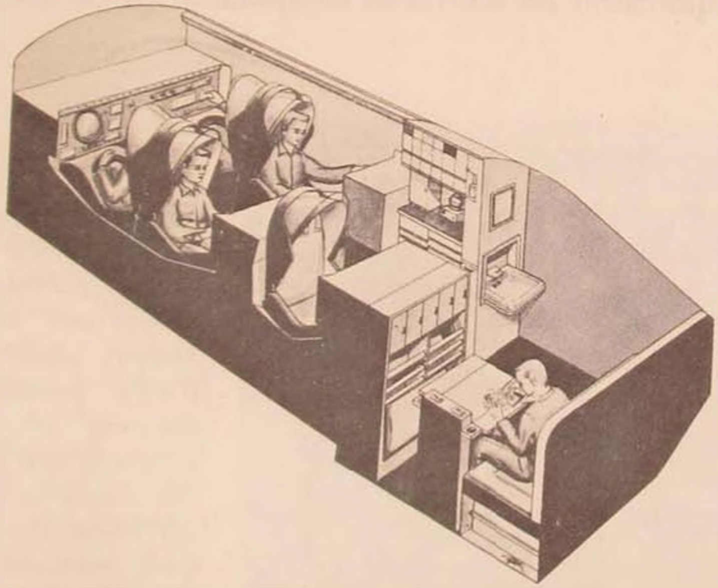
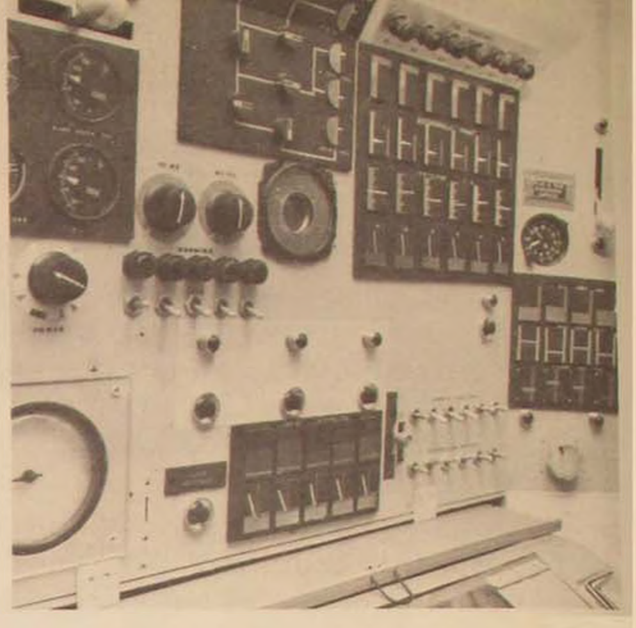


Figure 3. An artist's sketch of the crew compartment design and arrangement in the instrumented Nuclear Aircraft Simulator shows the aircraft commander in his capsule on the far side of the compartment and immediately aft the integrated feeding system. Across the aisle is the nuclear engineer, with the bombardier-navigator seated behind him. The defense director is seated back-to-back with the aircraft commander, and the copilot is off duty in the forward leisure section.

Figure 4. The nuclear engineer's station in the Nuclear Aircraft Simulator shows the highly automated systems instrumentation required for the continual intensive monitoring of the power components. The panel also carries the clocklike device at lower left that gathers data on the engineer's vigilance at any moment during the entire simulated mission. The three small lights across the middle of the panel test the engineer's response to complex computations required of him over the period of the simulated flight.



and instruments necessary for the operation of the aircraft and a leisure area containing the fundamental provisions for relief of mental and physical fatigue.

The work area. The crew members are integrated into a highly coordinated arrangement in the work area. The aircraft commander and flight engineer are located side by side, as are the navigator and defense director. The copilot is forward of the flight engineer, across the aisle from the aircraft commander. The layout provides the aircraft commander direct visual and verbal communication with all other crew members. It also minimizes interruption of flight continuity when crew members shift duties.

The high performance anticipated in an advanced nuclear aircraft dictates the requirement for individual encapsulated escape systems. These cap-

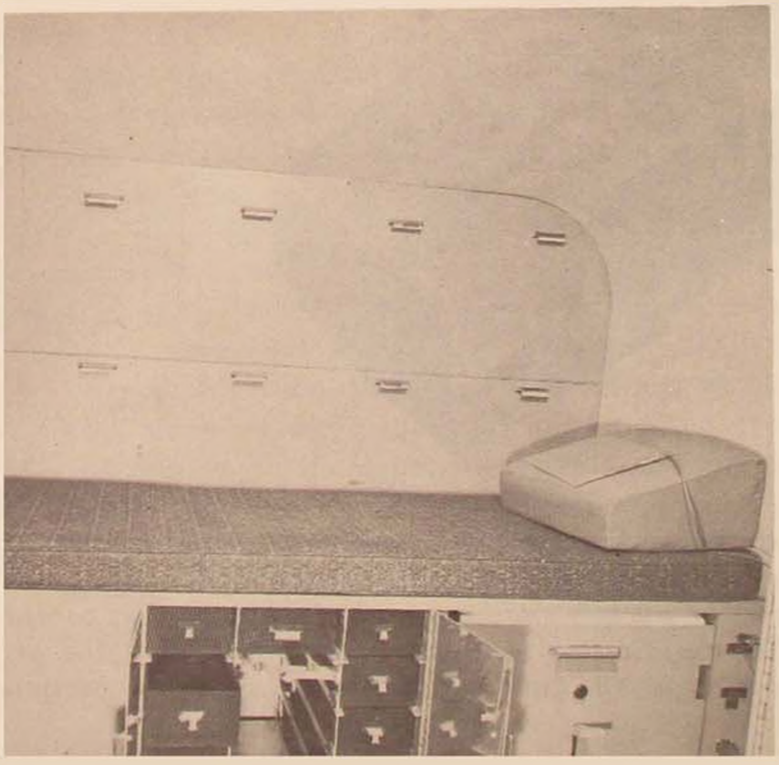


Figure 5. In the leisure area of the crew compartment, sleeping, storage, and relief facilities are integrated in a 36-sq-ft space. Two full-size beds permit simultaneous sleeping of two crewmen. Clothing and personal articles are stored in individual lockers above the bed. Below are wire containers for soiled clothing. The cabin air-conditioning system is vented through this cabinet to remove any garment odors. The pull-out electric incinerator toilet is at the lower right and the second bed, a pull-out berth, is at the lower left.

sules obviate the need for bulky protective garments and personal parachutes, since they are equipped for pressurization and parachute recovery. Once the ejection sequence is initiated, the entire escape system is fully automatic and delivers the airman to the ground without further action on his part. In each capsule 3200 cubic inches of storage space is provided for survival equipment. The low noise level anticipated in the crew compartment permits the elimination of headsets and protective helmets. In their place within the capsule are two small loud-speakers adjacent to the headrest that provide communication with the ground.

The leisure area. The leisure area is an airborne "bachelors apartment," equipped to satisfy every personal need and requiring very little effort to maintain. In approximately 36 square feet of floor space it provides clothing storage, relief facilities, and sleeping accommodations, as well as an integrated food-preparation facility and small mess table. A 2-cubic-foot freezer stores 35 precooked frozen meals. Nonfrozen foods such as canned juices, in-flight canned meals, and other similar rations are stored within the drawer spaces allocated for each crew member. Each crewman's food allotment provides approximately 5000 calories per day. Meal-preparation equipment consists of a warming oven, hotcups, sandwich grill, and fresh-water taps.

the duty schedule

Upon completion of the simulator it was necessary to select the test subjects and establish a duty schedule compatible with the proposed 120-hour mission. An analysis of previous sustained air operations suggested that future missions will require long cruise phases comprising 90 per cent of the total

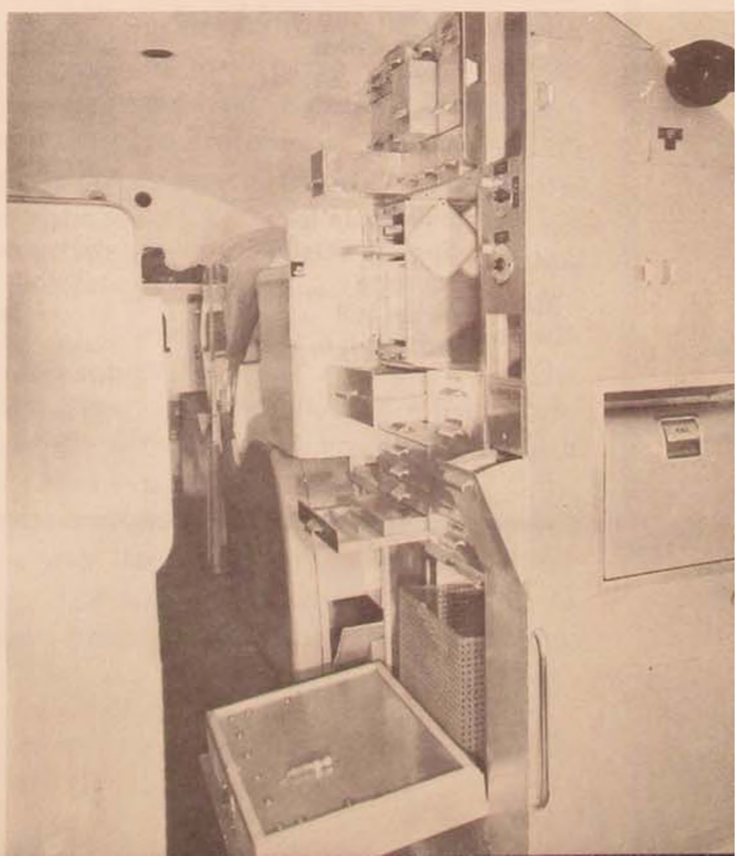


Figure 6. Compact storage of food products, cooking utensils, and lavatory facilities is achieved in the design of the simulator's integrated feeding system. Frozen meals are stored in the deep freezer shown at the lower front with open door, and prepared canned meals are kept in the drawer section immediately above. Warming oven, hotcups, and electric sandwich grill are located in the front center section above the drawers. On the right side of the feeding system is the pull-down wash basin, and above it, the two-door medicine chest.

Recommended Menu for 120-Hour Flight

	breakfast	*lunch*	*dinner*
1st day	eaten at home	apple juice pork steak bread and butter jam pineapple poundcake coffee, tea, cocoa	chicken soup beef pot roast potatoes mixed vegetables bread and butter jelly brownies milk, coffee, tea, cocoa
2nd day	orange juice grilled egg and bacon sandwich milk, coffee, tea, cocoa	tomato soup Swiss steak potatoes and peas bread and butter apple and cheese slice coffee, tea, cocoa	pineapple juice meat and spaghetti bread and butter jelly apricots fruit cake coffee, tea, cocoa
3rd day	tomato juice waffles applesauce sausage honey coffee, tea, milk	chicken soup grilled ham and cheese sandwich cookies nuts and candy milk, coffee, tea, cocoa	apple juice turkey sweet potatoes and Lima beans bread and butter cranberry sauce fruit cocktail cookies coffee, tea, cocoa
4th day	apricot juice grilled egg and bacon sandwich milk, coffee, tea, cocoa	orange juice chicken bread and butter cranberry sauce pears pecan roll coffee, tea, cocoa	tomato soup beefsteak bread and butter ketchup apple date pudding coffee, tea, cocoa
5th day	pineapple juice Spanish omelet sausage sweet roll coffee, tea, cocoa	apricot nectar chicken w/gravy potatoes and corn bread and butter honey brownies milk, coffee, tea, cocoa	tomato juice beef patty potatoes and green beans bread and butter peach pie caramels coffee, tea, cocoa

time airborne. Five per cent of mission time is estimated for the combat strike and the remaining five per cent for take-off, emergencies, and landing.

When interpreted in terms of crew duties, this mission analysis indicates that only the primary flight controls, engine functions, and navigational needs are necessary for the efficient operation of the vehicle during most of the mission. These duties can be easily accomplished by three men: pilot, navigator, and flight engineer. The critical periods of flight—combat, emergencies, take-off, and landing—require the minimum assistance of two crewmen. These two men also serve in relief for the duty stations which must be constantly manned during the long cruise period. Each relief man therefore spends one third to one half of every 24-hour period off duty and rotates his station to the positions of aircraft commander, flight engineer, and navigator. In the duty schedule tested in this experiment, the aircraft commander, flight engineer, and copilot were on duty for 16-hour periods followed by 8 hours off. The bombardier-navigator and defense director were on duty for 12-hour periods followed by 12 hours off. Careful selection of men by background experience minimizes the multiplicity of knowledge required for such a scheme of job assignment. For instance, three pilots with nuclear-engineering training can effectively rotate through the positions of aircraft commander and flight engineer. Two navigators cross-trained as bombardiers can guide the aircraft to its destination and still perform the important job of bombing the target. In sustained nuclear flight it is therefore desirable to have five men in the crew to accomplish the basic mission objectives within the requirements of effective mission performance.

crew selection

Mission requirements also dictate the selection criteria for a nuclear aircrew. The complexity of equipment on the aircraft, such as reactor, automated subsystems, and electronic offensive and defensive systems, makes it mandatory that each man have college training in addition to his Air Force operational flying training. Detailed review of the diverse aircraft systems indicated the college training of the crew should be interdisciplinary; that is, each man should be schooled in a different professional field, with preferred concentration of knowledge in engineering, electronics, nuclear physics, radiobiology, or chemistry.

The long-term cruise involved in nuclear flight and its concomitant problems of boredom and confined living require the selection of personnel who have considerable experience as team members. They must certainly possess both technical competence and respect for military discipline. The complexity of possible aircraft emergencies and the demands of mission continuation also necessitate the selection of well-seasoned personnel having a considerable amount of multiengine aircraft experience.

On the surface it appears from this analysis that the nuclear aircrew will be exceptional men who represent a very small minority in the Air Force personnel inventory. To the contrary. The college educational programs in the Air Force during the past ten years have provided the operational commands with people who easily meet these criteria. Furthermore the Strategic Air Command policy of maintaining combat operational stature has developed a level of airmanship that will provide easy transition from long-range chemical aircraft to sustained flight of nuclear aircraft. In physical description the nuclear aircrew is similar in many respects to the present Mercury Astronauts: age 30–40 years, married, college degree, senior pilot or navigator, ten years in the Air Force, combat experience, and additional background qualification in aviation research at some point in his career. This was the type of man who participated as a subject in the sustained flight experiments using the nuclear-aircraft simulator.

results of the experiments

The results in the series of 120-hour experiments indicated that present technical knowledge is adequate for the creation of an artificial life-space that is habitable by a five-man crew without serious stress. Psychological tests showed that the subjects effectively used their characteristic methods of adaptation to handle conflicts that arose at different times. The most common problem was arousal of hostile feelings toward fellow crew members. This was usually dealt with by the defense mechanism of suppression, denial, and undoing. Anger was seldom expressed directly, although it often appeared as sarcasm.

The test participants expressed satisfaction with the quantity, variety, and acceptability of the food. Of the 74 foods made available, none was considered unacceptable and none was recommended for deletion in future experiments. Each man consumed an average of 3650 calories per day. This exceeds the recommended 2900 calories for men ranging from 25 to 45 years of age and engaged in sedentary activity. The crew used 24.6 gallons of hot water and 2.2 gallons of cold water for washing purposes each day, amounting to 133.3 gallons for the 5-day test flight. Each day the crew used 4.2 gallons of drinking water, an average of 3180 cc per man, including quantities used in the preparation of coffee, tea, cocoa, and food. The data from the experiment show that only 1600 cc of liquid was consumed per individual in any 24-hour period. The difference between the quantity of water withdrawn from the system and the amount actually consumed proceeds from the quantity of beverages prepared but not entirely consumed. The crew members wasted almost one half of the drinking water withdrawn for internal usage. Weight fluctuations of the crewmen between the onset and the completion of the experiment were within normal variations except in one or two instances.

Each individual voided an average of 1200 cc of urine in a 24-hour period. This is a normal excretion value for the adult male population in the Air Force. The electric incinerator toilet was not used by any crew member during the first 26 hours of the simulated long-range flight. Each day thereafter the crew averaged slightly over 8 flushes for a total of 34 evacuations in the 5-day flight.

In the area of human performance, tests known to be sensitive in detecting fatigue did not reveal deterioration during the critical periods of take-off, strike, and landing. Mental efficiency was maintained at a constant level during the periods demanding alertness throughout the 120-hour mission. Link-trainer flights at the end of the simulator test showed that all subjects were capable of performing an instrument landing system approach and a ground-controlled approach within green-card instrument requirements.

THE RECENT advances in nuclear propulsion will provide weapon systems with performance capabilities approximating those required for space-equivalent conditions in almost all flight regimes. Within this advance in technology the future success of sustained, nuclear-powered, manned flight will be measured in terms of crew effectiveness as well as system performance. While current validated human-factors information is sufficient for the early nuclear flights, it is seriously in arrears for the length of flight time that would be involved in manned orbiting satellites or interplanetary flight. A nuclear aircraft capable of unlimited atmospheric flight would serve a highly desirable purpose as a space-flight trainer and a research vehicle to extend the exploration of human factors in space operations.

Wright Air Development Center

Ground Support for Nuclear Aircraft

HERVEY S. HUTCHINS

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THE GROUND maintenance and support of the nuclear aircraft and the current heavy bomber will be, in most respects, quite similar. Certain factors peculiar to the use of nuclear power for propulsion do, however, affect handling procedure and require new and unique equipment. The radiation environment restricts human approach. Heat continues to be produced in the reactor after shutdown. Emergencies may arise from the presence of nuclear fuel.

nuclear power and ground operations

The nuclear aircraft will carry a nuclear reactor as a primary source of heat. In producing heat, the fissioning nuclear fuel also produces radiation in the form of neutrons, gamma rays, and alpha and beta particles. Gamma radiation from the decay of the fission products in the fuel persists even after the reactor is shut down. This radiation is of such magnitude that unshielded approach to the reactor or to the aircraft with the reactor in place will be feasible only for very short periods of time. In a radiation environment of this kind much of the inspection, maintenance, and servicing would have to be done by remote means, with full shielding for personnel. These conditions make satisfactory ground support most difficult.

With full shielding around a reactor it is possible to contain entirely the primary radiation emerging from the reactor and eliminate the whole problem of radiation environment. But for military aircraft this would impose impractical shield weights and unacceptable performance. Most designs for military nuclear aircraft reflect a compromise between reactor-shield weight, flight performance, and other factors. The resulting limitations on the reactor shield bring about the radiation environment that must be contended with in ground maintenance procedures and equipment.

Aside from radiation the reactor brings another problem that must be accounted for in ground operations: the continuing production of heat in the fuel elements after shutdown. The extent of this afterheat is such that if the reactor is not cooled, critical temperatures will occur in the reactor structure. Even long after shutdown, when the rate of heat production has substantially decreased, the damage potential from afterheat remains high and cooling is required. Failure to sustain aftercooling not only results in reactor damage but also might cause the release of highly radioactive fission products to the atmosphere. Release could extend radiation contamination to the entire base and surrounding areas. Whenever the aircraft engines are stopped and the flow of air or other reactor coolant ceases, auxiliary cooling must be supplied and sustained in sufficient degree in order to hold the reactor temperature below critical levels. Reactor aftercooling must be provided for in all ground operations, including emergencies such as crashes and on-base operating incidents or accidents.

The airframe and systems components will also become radioactive because of irradiation by neutrons during reactor operation. The radiation from the activated airplane decays with time, quite rapidly at first, then progressively slower, finally reaching a low, essentially residual value. Even at its highest, this radiation is many orders of magnitude lower than that from the reactor and does not offer nearly as serious a problem. In the radiation environment from activation, direct maintenance, tempered with personnel-exposure control, is practicable and will permit the use of nearly normal procedures, schedules, and equipment.

But some ground support must always take place under the restrictive conditions of radiation that denies unshielded approach. Let us turn now to a discussion of these operations.

concepts of ground support

Extensive investigation has been made at Convair of the possible approaches to nuclear-aircraft ground support, and especially to the task of ground handling in a high-radiation field. Three methods have received the greatest attention. The first—to perform all operations from shielded vehicles or facilities, using remotely operated manipulators and special tools—has been rejected. Experiments have shown that the time penalties imposed are unacceptable in military operations, that operational flexibility is impaired, and that the complex equipment and facilities are inordinately costly.

The second method investigated was ground "safing" the reactor through shield augmentation—that is, the placing of additional shielding around the reactor on the ground to attenuate its after-shutdown gamma radiation. This method was rejected because of the size and weight penalties it imposed on airframe design; the still-remaining problem of reactor maintenance, inspection, and service; and the burdensome and time-consuming task of shield positioning.

The third and accepted method involves removal of the reactor as the initial step after each flight and its reinstallation as the final step before take-off. With the reactor removed, the high-level radiation environment about the aircraft is eliminated and the bulk of maintenance and support activities can be accomplished under favorable conditions. The practicability of reactor removal and replacement between flights was demonstrated many times in the successful flight program carried out at Convair with the nuclear test airplane described later.

Because of the high level of radiation from the core, inspection and repair of the reactor must be done remotely in a special shielded facility. Following removal, the reactor must be transported to a special maintenance and storage facility for service or to await the next flight. Fixed facilities for reactor removal and replacement are costly, and the special features and equipment required are usually best suited to only one type of aircraft. Mobile equipment may be used as readily and is, because of its versatility, far more satisfactory from an operational viewpoint. Shielded manned vehicles and equipment place the operator in the most favorable position for observation as he accomplishes the desired tasks and largely eliminate the need for extensive shielded structures. In addition operations may be carried out at any point on the nuclear base for operational flexibility and capability.

In the scheme for ground support with mobile equipment, the events follow this sequence: Upon landing, the time of maximum reactor and airframe radioactivity, the aircraft proceeds to a designated area for reactor removal. There auxiliary reactor-aftercooling equipment is set in operation, and the reactor is immediately taken from the aircraft and transported to its maintenance facility for servicing and storage awaiting the next flight. After removal of the reactor the airframe and systems components are prepared for the next flight under nearly normal maintenance and inspection routines. In the final preparations for flight the aircraft is fully serviced, systems are checked out, armament and weapons are installed, and the flight crew makes its inspection before the reactor is installed. After the reactor is installed, a ground check with the reactor at low power is made, and the aircraft is ready for take-off.

mobile ground-support equipment

Only a few basic types of special ground-support equipment are required under the mobile ground-support concept. Normal operations require a shielded reactor-handling vehicle, a shielded towing vehicle, a shielded jeep-type maintenance vehicle, and special aftercooling equipment. Also necessary for emergency operations, regardless of what support concept is followed, are remotely operable armament-handling equipment and shielded fire-fighting, crash-removal, and crew-rescue vehicles. The term "shielded" here applies to the shielding placed around the cabs. The mechanisms of the vehicles do not require shielding, as they are essentially unaffected by the radiation field in which they operate.

Equipment for normal operations. The insertion and removal of the reactor is the most demanding of the remote-handling tasks. The reactor, together with its shielding and accessories, is a large and very heavy object that must be installed or removed with precision. Controls, piping, and other connections should be provided with centralized, quick-disconnect couplings that mate and unmate all connections simultaneously with the reactor. The heart of the vehicle to be used for reactor handling is the mechanism for carrying the reactor and controlling the insertion or removal actions. To align the reactor mountings with those in the aircraft, the mechanism must provide six degrees of controlled motion: vertical, longitudinal, lateral, roll, pitch, and yaw. A pneumatic-tired, self-propelled vehicle with a shielded operator-cab will serve as a carrier for the mechanism.

The shielded towing vehicle is conceived as essentially a standard tow tractor equipped with a shielded operator-cab and a remotely controlled tow bar. It will tow the aircraft whenever the reactor is aboard and also serve as an emergency means for retrieving other shielded vehicles or equipments if disabled in a high-radiation field.

Even though the reactor may be checked out and prepared for flight prior to insertion in the aircraft, there will always be some last-minute service and minor adjustment tasks to accomplish after it is installed. In addition there is the usual array of connections for checkout equipment, ground power, air conditioning, and aftercooling that must be made or disengaged when the reactor is in place. In these jobs, and in emergencies, the shielded jeep-type maintenance vehicle will find use. It features a small, shielded cab equipped with manipulatorlike devices that accommodate various adapters for handling lines, air hoses, or simple tools. The cab is flexibly mounted on a self-propelled base, and all operations are controlled from within the cab.

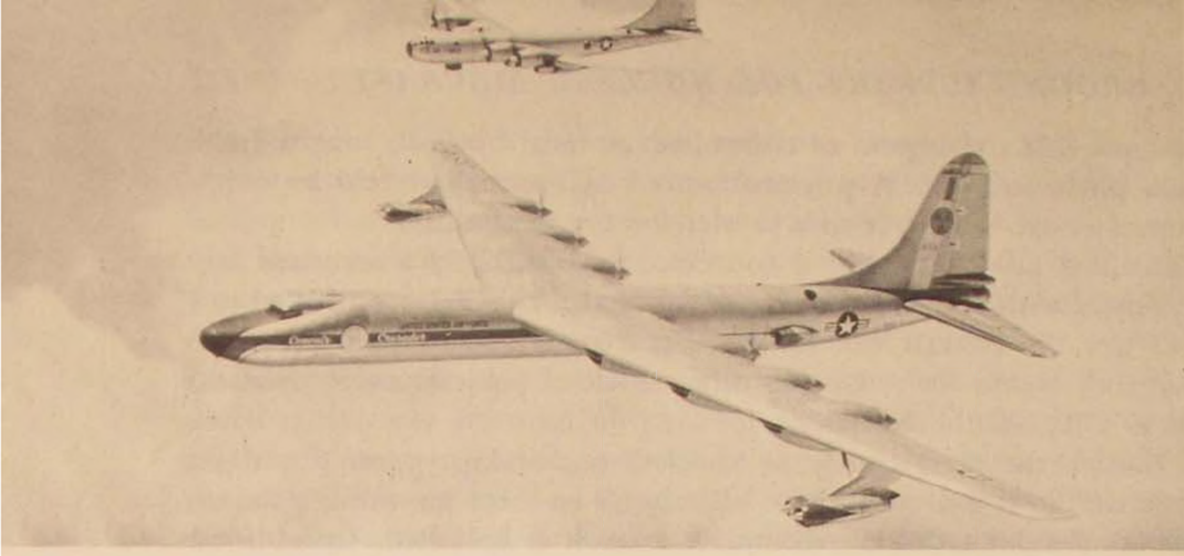
The special aftercooling equipment may be trailer-mounted and unmanned. The type of equipment provided will depend on the type of reactor being supported. Air-cooled reactors require large, powered blowers; liquid-cooled reactors require coolant, pumps, and heat exchangers. This equipment will be handled by the shielded maintenance vehicle and, once attached to the reactor, will remain in continuous, automatic operation.

The descriptions of this special equipment for nuclear-aircraft ground support have been much simplified, but they do delineate the major pieces of equipment required to support normal ground operations in the high-level radiation environment.

Equipment for emergency operations. Shielded equipment for emergency operations—fire, crash, or other accidents—presents a more complex problem. There are two basic categories of emergency conditions associated with the operation of nuclear aircraft: (1) aircraft accidents or disabling incidents in which no reactor damage is sustained; and (2) the far more serious accidents in which reactor damage occurs or is likely to occur through an inability to initiate or sustain aftercooling. Typical of the first category are such disabling operational incidents as flat tires, landing-gear damage, and mistakes in landing or taxiing. In these cases aftercooling is provided through operation of the engines until suitable ground-support equipment can be employed. With any of the engines operable, aftercooling may be sustained until auxiliary cooling equipment can be engaged.

In the second category are the more damaging accidents such as crash landings, runway undershoot or overshoot, collapsed landing gear, and fire. A major consideration in this category is the prevention of an extraordinary increase in reactor heat.

In the case of aircraft fire the radiation environment and problem of reactor-damage control place added burden on fire-fighting personnel, equipment, and procedures. Remotely operated extinguisher nozzles, such as are



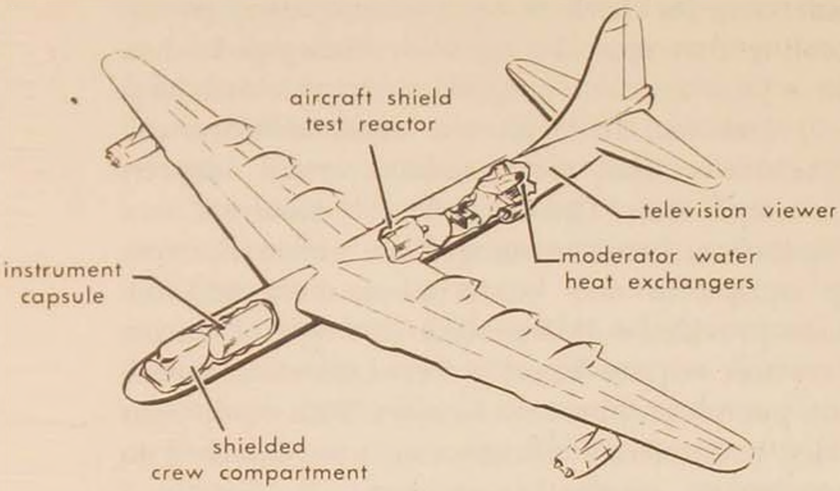
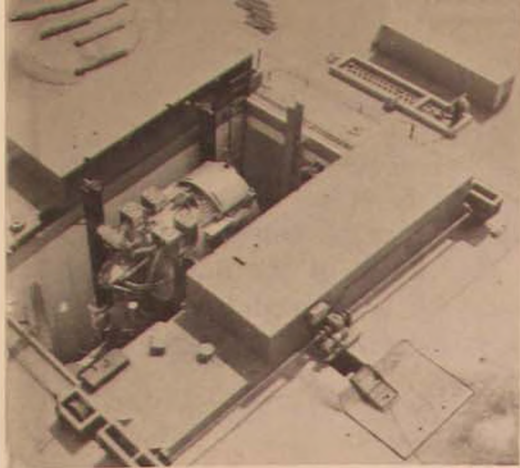


Figure 1. Nuclear Test Aircraft flights permitted study of shielding, radiation effects on the aircraft, and methods of flight and ground operations. Diagram identifies special equipment of the NTA.

found on existing trucks, and a shielded operator-cab are necessary. Most chemicals and extinguishing equipment in use today are believed to be satisfactory for nuclear-aircraft operations.

Flight-crew removal under high-level radiation conditions may also be necessary in emergencies. For this task a shielded crew-removal vehicle is necessary, having a van body and an extendible hatch for mating with the aircraft escape hatches.

To clear the runway for resumption of normal operations there must be a capability for removing damaged aircraft and crash debris under high-level radiation conditions. For lightly damaged, intact aircraft the regular shielded ground-support vehicles may be used. In severe accidents when the aircraft has sustained major damage, the remains must be cleared away by a vehicle equipped with lifting and pushing devices remotely controlled from the shielded operator-cab.



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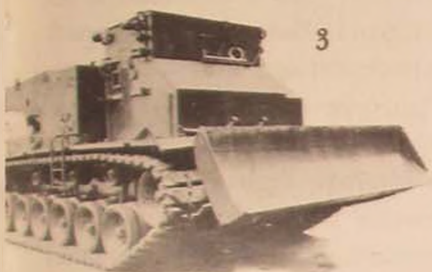

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Figure 2. Mobile and fixed ground support equipment for the Nuclear Test Aircraft. (1) Aircraft Shield Test Reactor in its loading pit with "turtle decks" open. (2) Shielded-cab towing tractor for positioning NTA over reactor-loading pit. (3) Shielded-cab crash-rescue vehicle. (4) The Nuclear Test Aircraft over the closed reactor-loading pit.

equipment reliability

One of the principal keys to successful nuclear-aircraft operations is a high degree of performance reliability in special ground-support equipment. Reactor handling especially requires an ensured continuity of operations under all circumstances. Equipment must have high reliability and be augmented by suitable backup provisions to meet these exacting requirements. Unreliable ground-support equipment for the radioactive environment could imperil personnel, impair operational flexibility, and, at the extreme, cripple base operations to the point where satisfactory military operations could not be achieved.

Nuclear-aircraft support equipment with the required reliability can be achieved within present design and production capabilities. Mechanical reliability may be achieved through design of simple, rugged mechanisms and apparatus. Functional reliability may also be gained through design simplicity and may be further ensured by providing redundant or fail-safe circuitry and mechanisms in critical areas. Human reliability may be enhanced by close attention to human-engineering factors in the design of the shielded cabs and operator controls. Two operators should be accommodated whenever possible, and features should be provided for safe operator replacement under critical radiation conditions.

the NTA–ASTR program

For several years Convair successfully conducted flight operations with an airborne reactor. The Nuclear Test Aircraft (NTA) was a modified B-36 bomber that flew on its own conventional engines but was equipped with a shielded crew compartment, nuclear instrumentation, and a reactor, the Aircraft Shield Test Reactor (ASTR). The purpose of the NTA flights was to study radiation-shield methods and effectiveness, radiation effects on aircraft materials and components, and nuclear-aircraft flight and ground operations. The concept of reactor removal between flights was employed. The reactor was designed for easy and rapid insertion and removal. A fixed mating station having many of the characteristics previously described for the reactor-handling vehicle was designed, fabricated, and successfully utilized throughout the program. Between flights the reactor was serviced and maintained outside the aircraft in a special facility by remote means. The aircraft, although radioactive, was maintained in a conventional manner.

In practice the NTA was positioned over the reactor-handling mechanism with a shielded tow tractor. The mechanism, mounted on a hydraulic ram, telescoped in and out of a pit. Sensing probes mounted on the reactor carriage controlled the movement of the reactor, ensuring proper alignment.

Two pieces of shielded equipment were developed for support of the NTA—a shielded-cab towing tractor and a shielded crash-rescue vehicle. The tow vehicle was a modified USAF Coleman tractor. A T-51 tank retriever was equipped with a shielded cab for crash-handling purposes. Because of the special shield design and low power of the reactor a conventional, thermally shielded USAF fire truck served as a fire-protection vehicle.

The success of the Nuclear Test Aircraft flight program has shown that ground handling by mobile equipment and maintenance under nearly normal conditions is not only possible but entirely practicable.

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Public Hazards from Nuclear Aircraft

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FROM THE inception of the nuclear-aircraft program the Air Force has recognized the potential hazard of operating nuclear power plants and has continually maintained an attendant program of hazards evaluation to ensure public safety.

This concern stems from the fact that derivation of power from a fission reactor carries with it the possibility of the release of radioactive fission products. In the event of damage to the reactor, fission products may be released to the atmosphere, spreading downwind and affecting persons miles from the release point.

The release problem has plagued all programs for the useful application of atomic energy, but the amount of fission products that might be released has been reduced to acceptable levels by the application of many safeguarding restrictions on major and detailed design features, on operating techniques, and through extensive health-safety procedures. Finally emergency plans have been prepared for positive action to warn and protect the public in the event an accident actually occurs.

An aircraft nuclear propulsion system presents a risk to the public and requires safeguarding restrictions on design, techniques, and procedures. These restrictions will have to be modified to account for the mobility of the system. This "difference" has always been recognized, and active study of the resulting safety-of-operation problem was initiated by the Air Force during 1955. Operational analysis techniques have been used to investigate the various aspects of the operation of nuclear-powered aircraft. All operational phases, such as developmental flight testing, production flight testing, training, and peacetime operation, that lead to the "fighting" capability have been studied. Operational restrictions have been established, and their effectiveness in providing protection has been determined. The designs of the propulsion system have been examined for characteristics that would act as sources of hazard. Unacceptable features have been eliminated. Experiments have been performed to confirm the results of the studies. Safety criteria have been established on the basis of these studies and experiments, so that basing selections can be made which will not present an unacceptable risk to the public. It is from this body of research and study material that the following discussion of the hazards of nuclear aircraft has been drawn.

In discussing the hazards of nuclear-powered flight, we can say at the outset that the aircraft poses no threat under normal operating conditions. It will fly at altitudes high enough to keep radiation from reaching persons on the ground, but even should it fly low, the radiation received below will be negligible because of the shielding surrounding the reactor. The dosage from exposure to leakage radiation would be very small because the time of exposure would be very brief. We may therefore confine our attention to accidents that could cause the release of fission products from the reactor.

Predictions of the hazards in this event are somewhat controversial because surprisingly little is known about the release, dispersal, and biological effects of fission products freed by a reactor accident. This lack of data is due mainly to the amazing safety record achieved in the atomic energy program to date. Only one major release of fission products from a reactor has occurred, the instance of the Windscale reactor in England. In that case, as would likely be in any other release, the radioactive fission products were widely dispersed over a very large area, and the exposure of a person from the radioactive cloud was so small as to be negligible. For some distance downwind from the Windscale reactor the ground contamination over relatively small areas reached such concentrations that unacceptable internal exposures from ingestion of contaminated food or liquid might have occurred had not appropriate countermeasures been taken. In these areas the hazard was controlled, and no one received an overexposure.

If a nuclear-powered aircraft crashes, it is likely that some fission products will be released. Even with the power plant not operating, the fission products in the reactor core emit sufficient energy to melt the core if the coolant is shut off. A more serious but much less probable accident could occur if all the reactor safety controls failed in a particular sequential way, causing the reactor power to "run away." This event might vaporize the core, releasing more fission products than in melting it.

The hazards from release of fission products are determined to a large extent by the weather condition at the time of the accident. On a typical sunny day, good atmospheric diffusion will prevail. This is the so-called "lapse" condition. Under these circumstances the released fission products will spread rapidly, with a concurrent rapid reduction in concentration. At night or in conditions of "inversion," such as occur when smoke drifts in layers, diffusion is poorer, and higher radioactivity concentrations will extend to greater distances. The flight testing of nuclear aircraft will be carried out only in daylight hours under good diffusion conditions. It is expected that, by the time the aircraft become operational, enough will be known about nuclear flight safety to reduce test restrictions appreciably.

The Aircraft Nuclear Propulsion group at Convair has made a detailed study of the hazards of nuclear flight testing. Four typical nuclear accidents spanning combinations of hazard situations over the entire range of severity were defined: runaway-inversion, meltdown-inversion, runaway-lapse, and meltdown-lapse. The radiation doses shown in the table are the maximum doses which a person downwind from one of these accidents would receive as the "cloud" of released fission products blew past. The maximum permissible exposure (MPE) is a measure of the biological importance of a given radiation dose. Generally, this is a radiation dose which is thought to cause no appreciable biological damage in humans.

	1 MPE (injury unlikely)	*4 MPE (possible illness)*	*lethal exposure*
runaway-inversion	35 mi	0 mi	0 mi
meltdown-inversion	16	0	0
runaway-lapse	2	.9	0
meltdown-lapse	.8	.4	0

No serious exposures are expected outside the immediate confines of the crash (2000 or 3000 feet at most). Levels which could cause temporary radiation sickness should not extend beyond one mile from the release point. Figure 1 shows that the 1-MPE condition will exist in a narrow strip downwind from each of the selected typical accidents. These results are for idealized weather conditions.

In actual practice, shifts in wind direction, if greater than 3°, at either the release point or downwind during passage of the cloud will cause the areas shown in Figure 1 to be further broadened and foreshortened with a corresponding decrease in the total area covered by the 1-MPE condition. It is most uncommon for a wind direction to hold generally steady, on an average value, during much longer than 10 to 15 minutes. For this reason the distances and areas shown are probably two or more times greater than would actually occur. Recent experimental measurements of the spread of fission products released from melted fuel elements tend to verify this estimate.

The hazard from the radioactive release is short term, occurring over a period of a few hours as the cloud blows downwind. A longer-term hazard may occur from the radioactivity that falls from the cloud onto the soil or that may be "scrubbed" from it by contact with vegetation and the ground. In this event the radiation levels from an aircraft accident would be low, and the problem would generally be confined to contamination of ground vegetation. Experience in the Windscale accident indicates that proper controls can prevent persons from receiving an unacceptable radiation dose in consuming contaminated food. The remaining discussion will, therefore, be confined to the immediate hazard from the radioactive cloud itself.

The single most important point in the hazard prediction is the fact that the nuclear power plant is completely mobile. With unrestricted flight, an accident might occur anywhere. The obvious conclusion is that flights of a nuclear-powered aircraft will be ordinarily restricted to over the ocean or over low-population-density land areas. Sufficient land areas have been located wherein the average population density is less than one person per square mile and which in general are not used for the production of food. The protection of the public's interests in these areas will be relatively easy, requiring only a simple emergency plan that provides for taking two actions

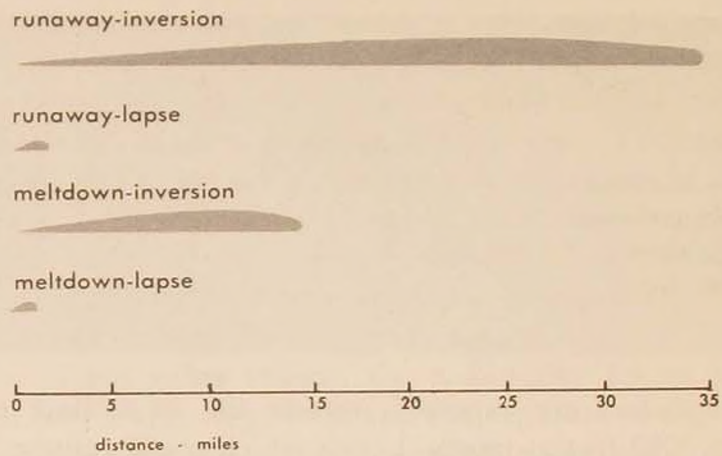

Figure 1. Extent of 1-MPE hazard after selected types of accidents.

after any accident. First, it will be necessary to warn the few people (probably about 20) that might be in a ten-mile downwind area that an accident has occurred and that they should follow the prearranged instructions given them. Secondly, it will be necessary to evacuate anyone discovered within one mile of the location of the accident and to establish this area as an exclusion zone.

Military and civilian accident records show that a high percentage of flight accidents occur during take-off or landing and that in these accidents the airplane will almost certainly come to rest inside an area 2 miles wide by 9 miles long, centered on the runway. In view of this we further confine this analysis to possible accidents on or near the flight base and to estimating their chances of occurrence.

First, let us impose certain flight restrictions: (1) flying will be restricted to daylight hours; (2) take-off will be permitted if good diffusion (lapse) conditions exist at time of take-off and if good diffusion conditions can be predicted for the time of landing (2 hours before sundown). Within these flight restrictions Air Force meteorologists have stated that the chances of landing under inversion conditions are negligibly small. We will be pessimistic and assume that 1 flight in 100 will lead to a landing under poor diffusion (inversion) conditions. A study of the propulsion system has led to the conclusion that not more than 1 accident in 100 would involve a reactor runaway.

On the basis of the probabilities given above, estimates can be made of the relative chances of occurrence for each type of accident defined previously. Assuming that an accident seriously affecting the reactor has occurred, the chances are 99 in 100 that the accident will occur under the more favorable lapse weather conditions, only 1 in 100 that it will occur in inversion conditions. As to the type of fission-product release that the accident would cause, the chances are 99 in 100 in favor of reactor meltdown as against 1 in 100 for a runaway reactor. Combining weather and reactor-accident probabilities, the chances are 98 in 100 that the reactor accident would be a meltdown occurring under lapse conditions, 1 in 100 of meltdown in inversion conditions, 1 in 100 of runaway in lapse conditions, and 1 in 10,000 of runaway in inversion conditions. So the chances are only about 1 in 10,000 that an accident would be of the most severe kind.

To complete the probability picture, an estimate of the chances that these accidents will affect people must be made. Figure 2 shows the surroundings of a typical flight-test base (several actual sites, chosen for the small number of surrounding towns, were plotted and analyzed). The 1-MPE radiation patterns of the two worst accidents under inversion conditions

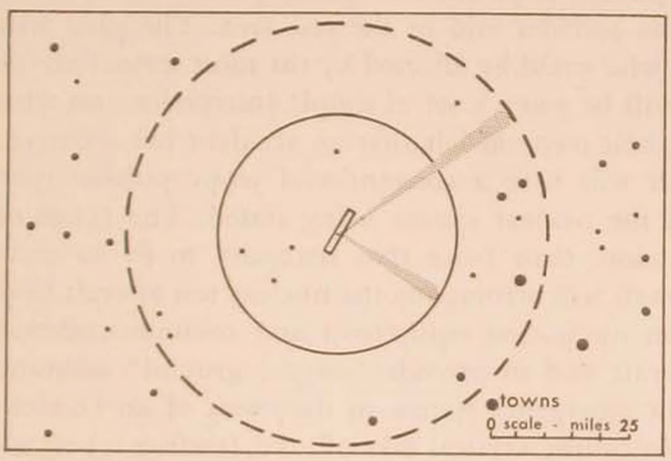

Figure 2. One-MPE radiation patterns hypothesized for the two worst accidents (meltdown-inversion, runaway-inversion) occurring at a typical flight-test site.

have been superimposed in the diagram, with their release points at the center of the runway. The radioactive release from the most probable accident which occurs during good diffusion conditions is too small to be shown on this scale. Detailed analysis of all jet test-aircraft accidents shows that near or on-base accidents all occurred within a narrow rectangle with the runway at the center. Therefore in general only the most severe accident could possibly affect towns surrounding the site. Since the rural area is so much larger than the town areas, there is only about 1 chance in 100 that the released products will intersect a town. Applying this to the probability that the most severe accident will occur (1 chance in 10,000) and even assuming that the aircraft crashes, there is only about 1 chance in 1,000,000 that a town will be affected. Or putting it another way, assuming a crash occurs, the chances are 1,000,000 to 1 that only the nuclear base and a rural area will be affected.

Study of aircraft accidents indicates no more than 1 chance in 10 that an accident will happen during the first two years of the initial flight program. Therefore, the predicted chance of people being affected in a nearby town is about 1 in 10,000,000. It should be remembered that being "affected" means receiving a maximum permissible exposure but not a dose large enough to cause mild radiation sickness.

Judging by the results of the studies and experiments accomplished since 1955, the nuclear-powered aircraft can be designed, tested, and operated without undue risk to the public. It is expected that the aircraft used to flight-test the propulsion system will be based somewhere west of the Mississippi River. The site will be located in sparsely populated territory, surrounded by a large unpopulated exclusion area (12 by 19 miles) and joined to a sparsely populated test area by a low-population flight corridor. Special areas about 100 miles apart in the corridor and test area will be set aside for emergency landings under controlled conditions without increasing the risk to the public. A public emergency plan will be arranged with local officials along the corridor and in the test area. The plan will be explained to every person who could be affected by the most serious accident conditions. These persons will be given a set of simple instructions on what to do if they are notified by their own officials that an accident has occurred.

The aircraft will have a conventional jet-propulsion system completely independent of the nuclear system being tested. The range of the chemical system will be more than twice that necessary to fly to and from the test area. Escort aircraft will accompany the nuclear test aircraft to provide backup for the precision navigation equipment and communications system carried by the test aircraft and to provide "on the ground" assistance to the crew or to initiate the emergency system in the event of an accident. Other emergency aircraft, including vertical take-off and landing types, will be available to provide quick-reaction assistance as required.

As noted, the tests will be conducted during daylight hours only. The test aircraft will use its conventional propulsion system for take-off, landing, and flight to and from the test area. A take-off for a nuclear test will not be made unless the existing weather provides safe diffusion conditions and unless it is predicted that the landing will not be made under a temperature inversion (poor diffusion). The test aircraft will be recalled at any time that weather conditions are predicted to become unfavorable. Nuclear flight tests will be conducted about two weeks apart, with complete flexibility as to weather. The aircraft will be flown at such altitudes that no person on the ground will receive a significant exposure, even if the airplane were to pass directly overhead with the nuclear propulsion system operating at full power.

Similar basing and operating conditions will be established for the production-phase testing, for the operational-training program, and for the peacetime operationally ready deterrent force. The studies to date indicate that the procedures planned for these phases can provide adequate protection to all persons and that the risk to the public will not increase.

Fort Worth, Texas
and
Aircraft Nuclear Propulsion Office

APPENDIX

A Glossary of Terms Relating to Aerospace Nuclear Propulsion

compiled by

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Aircraft Nuclear Propulsion Office

aerospace. The earth's envelope of atmosphere together with deep space, the two considered as a single realm for air and space weapons, vehicles, satellites, etc.

aftercooling. The necessary cooling of a reactor core after its shutdown by pumping a liquid or gas through it to carry off the excess heat generated by continuing radioactive decay of fission products within the core.

afterheat. The heat generated in a reactor core after shutdown by continuing radioactive decay of fission products.

air scattering. The dispersion of radiation particles which results from collisions between primary radiation particles and atoms within the air.

ALOO. AEC's Albuquerque Operations Office. It provides technical direction of the work being done under AEC contract by the Los Alamos Scientific Laboratory for the Rover (nuclear-powered rocket) project.

alpha emitter. A radioactive nuclide that decays by alpha-particle emission.

alpha-neutron reaction. A transmutation reaction in which alpha particles entering a target atom create a new species of atom and cause the release of a neutron in the process. This reaction is common to neutron source materials such as polonium-beryllium.

alpha particle. One of the particles emitted from radioactive decay (see **radioactivity**). The alpha particle, which emanates from a nucleus, bears a positive charge, and is composed of two protons and two neutrons, is identical with the nucleus of the helium atom. The natural range of alpha radiation is limited to a few centimeters in air.

ambient temperature. The temperature of the medium, such as gas or liquid, that surrounds and comes in contact with an object.

annealing. As applied to radiation damage, a recovery process through application of either heat or electrical current wherein atomic dislocations and vacancies are eliminated and a material returns to an undistorted structure.

ANPO. Aircraft Nuclear Propulsion Office, the joint AEC-Air Force office located at the Atomic Energy Commission, Germantown, Maryland.

ANP program. Aircraft nuclear propulsion program or project, a joint Air Force-Atomic Energy Commission effort begun in 1950.

ASTR. Aircraft Shield Test Reactor, a part of the facilities for development of the manned nuclear aircraft, located at Convair, Ft. Worth, Texas. This reactor was installed in the conventionally powered B-36 Nuclear Test Aircraft and utilized in extensive in-flight shielding research over a two-year period.

atomic number. The number of Z protons in an atomic nucleus and thus the number of positive charges on the nucleus. Also the number of orbital electrons surrounding the nucleus of a neutral atom. An element of atomic number Z occupies the Zth place in the periodic table of the elements. Its atom has a nucleus with a charge $+Ze$, which is normally surrounded by Z electrons, each of charge $-e$.

atomic percentage. Of given mixture of two or more elements, the percentage of atoms of one of the specific elements.

atomic weight. The weight of an atom according to a scale of *atomic weight units*, awu, valued as 1/16 the mass of the oxygen atom ($_8O^{16} = 16.00000$). Thus expressed, the atomic weight to the nearest integer is identical with the **mass number** (see). One awu = 1.661×10^{-24} grams.

attenuation. The reduction in intensity of radiation by passage through matter and consequent absorption and scattering.

average core flux. The average value of the neutron flux across a reactor core.

background. Effect in apparatus above which a phenomenon of interest must manifest itself, e.g., interference from foreign radioactivity.

bare core. A reactor core without a reflector.

barn. A unit of area for measuring a nuclear cross section. One barn equals 10^{-24} cm^2.

beta energy. The energy of a beta particle in electron volts (ev).

beta particle. One of the particles that may be emitted by a radioactive nucleus. Beta radiation is composed of high-speed electrons, negative or positive (positrons), created at the moment of their emission from the nucleus. The emission of the β^- particle entails the change of a neutron into a proton inside the nucleus, the emission of $\beta+$ the change of a proton into a neutron.

bev. Billion electron volts. See **electron volt.**

bimetal. A material or system composed of two different metals, as plutonium-molybdenum.

biologistics. The transport, quartering, and supply of persons.

biosphere. That portion of the atmosphere surrounding the earth which can sustain biological life.

"bola" concept. Concept of a manned nuclear vehicle in which a long cable separates the manned platform from the reactor power system, with consequent reduction of biological hazard and the need for heavy shielding.

Brayton cycle. A propulsion cycle in which a gas is subjected to a sequence of thermodynamic processes: isentropic compression, constant-pressure heat addition, isentropic expansion, and constant-pressure heat rejection. The cycle in a ramjet.

bremsstrahlung. Electromagnetic radiation produced by the rapid change in the velocity of an electron or another fast, charged particle as it approaches an atomic nucleus and is deflected by it.

burnup. In a reactor, the percentage of fissionable atoms that have been fissioned. Depletion of fuel by fission.

buzz. In ramjet aerodynamics, an oscillating motion induced by an airflow instability in which the normal shock of a ramjet inlet cone has moved upstream on the cone until the shock front is in advance of the inlet and supersonic air spills out and around the inlet. The accompanying instability and pulsation can tear the engine apart.

Camal. Abbreviation for continuously airborne alert missile launcher and low-level penetration airplane.

CANEL. Connecticut Aircraft Nuclear Engine Laboratory built in 1955 near Middletown, Connecticut, at which Pratt & Whitney Aircraft conducts its program to advance the high-temperature, indirect-cycle technology and materials for ultimate application to high-performance nuclear-powered aircraft systems.

capture. Acquisition or absorption of an additional particle by a nucleus.

Carnot efficiency. The efficiency of an idealized heat cycle (the Carnot cycle), expressed as the ratio of the work delivered to the heat received from the source.

cermet. Material that is a fused combination of a ceramic and a metal, such as silicon silicon-carbide (silicon being the metal, silicon-carbide the ceramic). Used for high-temperature applications.

chemical fuel. Any fuel from which energy is released by chemical reaction, normally combustion, e.g., hydrocarbons, fluorines, etc.

cladding. A coating, usually bonded, placed on the surface of a material. Cladding on nuclear fuel material protects the fuel from corrosion and erosion and prevents the loss of fission products. In some cases the cladding can be a closed pipe into which the fuel, as pellets or

The Glossary reflects accepted usage in the field of nuclear propulsion technology, but in a number of terms comprehensive, technically precise statement has yielded to general and less-technical definition.

cylinders, is inserted. Before sealing the fuel "can," a gas or liquid metal is poured in under pressure to provide good thermal bonding between the fuel and the clad.

collision. An encounter between two subatomic particles that changes their existing momentum and energy conditions. The products of the collision may or may not be the same as the precollision particles. The "collision" may be actual collision or the close approach and deflection of the particles.

elastic collision. A collision between two particles in which no change occurs in the internal energy of the particles, or in the sum of their kinetic energies. Commonly referred to as a billiard-ball collision.

inelastic collision. A collision between two particles in which changes occur both in the internal energy of one or both of the particles and in the sums, before and after collision, of their kinetic energies.

control swing. The amount or span of control-rod movement, from start-up to operating point of a reactor, that is necessary to prevent reactor shutdown at high temperatures. As high-temperature reactors reach design operating temperature, the negative reactivity effect caused by increased temperature requires that control rods be withdrawn more and more to counter the tendency of the reactor to shut down at higher temperatures.

creep. The slow but continuous deformation of a material under constant load or prolonged stress.

critical. Capable of sustaining a chain reaction.

criticality factor. As applied to a reactor, the numerical value of the effective multiplication factor (k_e), denoting the degree to which the reactor has achieved a self-sustaining chain reaction.

critical mass. The amount of concentrated fissionable material that can just support a self-sustaining fission reaction.

critical reactor. The steady-state condition of a reactor in which the neutron fission process is self-sustaining without the aid of external neutron sources.

critical temperature. As applied to reactor overheat or afterheat, the temperature at which the least resistant component of the reactor core begins to melt down.

cross section. In nuclear physics, the probability of occurrence of an interaction between a nucleus and an incident particle or photon. The cross-section quantity may be considered as the effective target area that the nucleus presents for the reaction. It is measured in area units expressed as barns (1 barn $= 10^{-24}$ cm^2).

cryogenic temperature. In general, pertains to physical phenomena in very low temperature range—below about —50°C—and more particularly at temperatures within a few degrees of absolute zero. Concerns temperatures down in the range of those of liquified gases.

curie. A unit of radioactivity defined as the amount of radioactivity which undergoes 3.7 $\times 10^{10}$ disintegrations per second.

daughter element. The decay product of a specific radioactive element that decays by other than gamma emission.

day-night cycling. The cycle that people customarily follow in allocating their activity between work and sleep.

decay. Decrease of a radioactive substance because of nuclear emission of alpha or beta particles, positrons, or gamma rays. See **radioactivity.** In *beta decay*, for example, the emission of a β^- particle, i.e., an electron, causes radioactive change into a daughter element of the same atomic weight as the parent element but of atomic number higher by 1.

delayed neutrons. See **prompt neutrons.**

depleted uranium. Uranium containing a lower percentage of the U^{235} isotope than is naturally found in mined uranium (0.07 per cent).

diffusion. A relatively high percentage of scattering of particles during passage through a substance.

dimensional stability. The degree to which a material resists change in any of its dimensions impelled by mechanical or thermal stress.

direct air cycle. A thermodynamic propulsion cycle (in this instance, involving a nuclear reactor and turbojet engine) in which air is the working fluid. It is successively compressed in the compressor section, heated in the nuclear reactor, and expelled through the turbine-tailpipe section to obtain thrust. Also called *direct cycle.*

dissociation. The process of ionizing a molecule of matter into two ions, one positively charged and one negatively charged.

doping. The introduction of a material in a semiconductor to increase the numbers of free electrons or holes that can be produced in the semiconductor when an electric potential is created across it; e.g., lead telluride is doped with bismuth.

effective neutron cycle time. The lifetime of an average neutron within a reactor from the time it is produced to the time it is fission-captured. This average takes into account delayed as well as prompt neutrons.

elastomers. Rubber-type compounds with additives. They are used as pliable components, as in tires, seals, or gaskets.

electrical kw-year. A unit for electrical power rating: one kilowatt of electrical energy produced continuously for one year.

electromagnetic radiation. In nuclear physics, radiation resulting from fission or radioactive decay that is of wave form rather than particle form.

electron. The first elementary particle recognized. The electron bears a unit negative electric charge ($-e$). All atoms consist of one nucleus and one or more electrons.

electron-positron pair. Pair production resulting from a gamma ray interacting with a charged field. The pair consists of two electrons—one with the normal negative charge, and the other with a positive charge, hence a positron.

electron volt (ev). The energy necessary to raise one electron through a potential difference of one volt. Nuclear energy is usually expressed in million electron volts (mev) or billion electron volts (bev).

electrostatic unit of charge. A unit for the measurement of a quantity of electric charge, established by choosing a unit of such size that, placed one cm from an equal charge in a vacuum, the mutual force between the charges is equal to one dyne.

ev. See **electron volt.**

exponential. Pertaining to an increase or decrease in a numerical value by a change in exponent or power.

fast neutron. Usually a neutron of 100 kev or greater energy.

fast reactor. A reactor containing no moderator, so that all the fissions take place at higher energies—on the order of 100 kev or greater.

fast reactor period. A reactor period in which the rate of power increase is large enough to make the control of the reactor extremely difficult. For example, if the period is five seconds, then, if unchecked, the power of the reactor would increase approximately 700 times in thirty seconds.

FETF. Flight Engine Test Facility, located at the National Reactor Test Station, Idaho. Basically the flight-engine propulsion test stand of the facility. It will house a prototype nuclear-powered aircraft and provide for reactor installation and removal.

fission products. The particles which result from a fissioned nucleus. The fissioned nucleus splits into two lesser nuclei that are usually radioactive and highly energetic.

fission wastes. The irradiated materials, usually fuel elements, that after removal from a reactor must be contained and disposed of while they are still radioactively "hot."

flux. In nuclear physics generally, the number of radioactive particles per unit volume times their mean velocity.

gamma flux. The total gamma energy emitted per square centimeter per second.

neutron flux. The sum of the distances traveled by all the neutrons in one cubic centimeter in one second. Normally the figure must be energy qualified, e.g., thermal, intermediate, or fast neutron flux.

free-stream capture area. The cross-sectional area of a column of air swallowed by a ramjet engine.

gamma energy. The energy of a gamma ray, ranging from 10^4 to 10^7 electron volts.

gamma-neutron ratio. For a given reactor, the number of gammas emitted per neutron emitted. For any given irradiation, the ratio must be qualified by energy of the gammas and neutrons and the reactor operating history.

gamma photon. Synonymous with gamma ray or gamma radiation. See **photon.**

gamma radiation. An electromagnetic radiation of wave form emitted by a radioactive nucleus and similar to X rays but of higher energy and shorter wave length.

GE-ANPD. General Electric Aircraft Nuclear Propulsion Department. Formed in 1951, it is presently engaged in research and development work to produce a nuclear-powered, direct-cycle, turbojet propulsion system capable of flying manned aircraft. Research and development work is carried on at the Air Force-owned-and-GE-operated plant at Evendale, Ohio. The GE-ANPD testing site is located at AEC's NRTS in Idaho.

g loading. The multiple of normal gravity force that is exerted on a body.

GNAL. Georgia Nuclear Aircraft Laboratory, an Air Force-owned radiation-effects facility built in 1956 at Dawsonville, Georgia, and operated by Lockheed Aircraft Corporation. It is designed to irradiate and test large aircraft components and major subsystems anticipated for use in nuclear-powered airborne vehicles.

habitability. The capability of an enclosure (e.g., crew compartment) to serve for human occupancy.

halflife. The average time required for one half the atoms in a sample of radioactive element to decay.

HARAO. The Hartford Aircraft Reactors Area Office, a field extension of LAROO and located near Middletown, Connecticut, at the Connecticut Aircraft Nuclear Engine Laboratory (CANEL) of Pratt & Whitney Aircraft. Provides technical and administrative day-to-day program management for the indirect-cycle development.

hard gamma. A high-energy gamma (i.e., a quantum greater than one mev) capable of deep penetration in even the most dense material.

heat sink. In nuclear propulsion, any thermodynamic device, such as a radiator or condenser, that is designed to absorb the excess heat energy of the working fluid. Also called *heat dump.*

heat-transfer analogs. Analog-computer codes used to predict heat-generation spectra across reactor cores.

high-intensity gamma. A level of gamma-radiation flux usually on the order of 10^4 roentgens or higher.

hot and cold junctions. The extreme ends of a thermocouple, one being heated and one not heated. The difference in temperature at the ends creates an electric-potential difference along the thermocouple, allowing electrons to flow from one end to the other.

hot "crits." Critical-reactor experiments to prove out theoretical reactor designs. A small prototype reactor is operated at very low power. Since the particular study is with high-temperature reactors, these prototypes are placed in ovens in which the ambient temperature can be raised to levels that simulate rocket or ramjet application, hence the term hot "crits."

hot-junction ring. A cylindrical ring in which the hot junctions of the thermocouples are seated. The ring itself ensures good thermal bonding between the heat source and the thermocouples.

hot shop. A building in which the components of a nuclear reactor or other irradiated device can be disassembled and reassembled. Since all the components are highly radioactive, or "hot," the work is done remotely from behind shielded walls, usually thick concrete.

HTRE. Heat transfer reactor experiments, a joint Air Force-AEC development and test program since 1951 to determine the characteristics and feasibility of the reactor core, shielding, and control designs for the direct-cycle nuclear turbojet. Program consists of ground test of the direct-cycle nuclear reactor coupled to turbojet engines at the GE-ANPD-operated facility at NRTS in Idaho. The first experiment (see HTRE-1) was conducted in January 1956.

HTRE-1. Heat Transfer Reactor Experiment No. 1. Designates the first ground testing at the Idaho Test Station, NRTS, of turbojet engines driven by heat from a nuclear reactor. Begun in January 1956, the tests culminated in 1957 with approximately 150 hours of successful operation by GE-ANPD.

inert atmosphere. A gaseous medium that because of its lack of chemical reaction is used to enclose tests or equipment.

in house. A capability or result produced within the immediately available internal resources of an agency without recourse to another agency or firm.

integrated flux (nvt). The total number of neutrons per unit area that interact with particles constituting the sample. It can be stated as the product of nv (the flux, or neutrons per square centimeter per second) multiplied by t (the duration of the neutron dose); n is the number of particles per unit of volume and v their mean velocity.

intermetallic compound. An alloy of two metals in a solid phase which is characterized by hardness, brittleness, and limited solubility with the other phases present. It is a distinct phase of certain alloy systems where the constituent atoms are in fixed integral ratios. The compound, which is held together by metallic bonding, may form a very complicated crystal structure.

inversion. A meteorological condition in which the air temperature increases with altitude. Normally the air temperature decreases with altitude (see **lapse**).

ion. An atom or group of atoms not electrically neutral, i.e., bearing a positive or negative electrical charge. Positive ions result when neutral atoms or molecules lose an electron; negative ions when an electron is gained.

ionization. The process in which a neutral atom loses or gains one or more of its electrons and thus bears electrical charge. Ionization of a gas is the breaking of its molecules into positively and negatively charged fragments, (see **ion**), giving the gas ability to conduct electricity. The phenomenon of ionization is fundamental to many processes for detecting radiation.

ionizing radiation. Incident radiation that ionizes the atoms in the material through which it passes.

iron-aggregate concrete. Concrete in which pieces of iron ore are embedded to increase density.

irradiation. The process of subjecting a material, component, or system to a radiation flux.

isentropic. Pertaining to thermodynamic process that occurs without change in the amount of the unavailable energy in the system.

isothermal. Pertaining to thermodynamic process in which the temperature remains constant.

isotopes. Atoms of the same element and hence of the same atomic number (nuclear charge) but of different atomic mass. In other words, atoms of an element in which the nuclei contain the same number of protons but different numbers of neutrons, for example, the carbon isotopes ${}_6C^{12}$ and ${}_6C^{13}$ with 6 protons in each nucleus but 6 neutrons in one isotope and 7 in the other. Similarly the uranium isotopes ${}_{92}U^{235}$ and ${}_{92}U^{238}$ each have 92 protons in their nuclei but 143 and 146 neutrons respectively. See **mass number**.

ITS. Idaho Test Station, a section of AEC's National Reactor Test Station provided to GE-ANPD for the heat-transfer reactor experiments. Reactors and propulsion-system assemblies are tested here under supervision of the Idaho Test Division of LAROO.

kev. Thousand electron volts. See **electron volt**.

Kiwi-A. The first reactor developed under the Rover (nuclear-powered rocket) project. It operates on an open cycle where the propellant (hydrogen gas) heated in the reactor core is expanded through a nozzle to the atmosphere. This reactor was not intended for flight application but to explore the feasibility of nuclear propulsion for rockets. Kiwi-A tests at the AEC's Nevada Test Site were completed in July 1959.

kwe. Kilowatts of electrical energy.

lapse. Meteorological condition of a decreasing air temperature with increase in altitude.

LAROO. AEC's Lockland Aircraft Reactors Operations Office at Evendale, Ohio. A field extension of the ANPO which exercises day-to-day technical management of the Air Force and AEC contracts for the direct- and indirect-cycle programs, and through its Idaho Test Division supervises testing of reactors and propulsion-systems assemblies at the AEC's Idaho Test Station.

LASL. Los Alamos Scientific Laboratory, owned by AEC, located at Los Alamos, New Mexico, and operated under contract by the University of California. Rover (nuclear-powered rocket) reactor work is under its direction.

lattice. In nuclear physics, a geometric pattern, as, the pattern in which fuel and moderator are interspersed in a heterogeneous reactor. The pattern of negative and positive ions held together by electrostatic forces. The normal arrangement of atoms in a molecule.

lead-and-borated-water slab shield. A shield built up of a series of slabs of lead interspersed with a water solution of a boron compound.

leakage. Loss of neutrons by outward diffusion from a reactor core. Especially net loss from unreflected neutrons or escaped neutrons or by radiation through an imperfect shield.

LRL. Lawrence Radiation Laboratory, owned by AEC, located at Livermore, California, and operated under contract by the University of California. Pluto (nuclear-powered ramjet) reactor work is under its direction.

macroscopic. Large enough to be visible to the naked eye or under low order of magnification.

mass number. The whole number *A* nearest the value of the atomic mass of an element as expressed in atomic mass units (see **atomic weight**). The mass number is assumed to represent the total number of protons and neutrons in the atomic nucleus of the element and is therefore equal to the **atomic number** (see) plus the number of the neutrons. The mass number of an atom is usually written as a superscript to the element symbol, as in O^{18}, an isotope of oxygen with mass number 18.

mass ratio. The ratio between the initial mass of a rocket or full vehicle (take-off mass) and the final mass of the vehicle or payload (burnout weight) after power is exhausted or cut off.

Mercury Astronauts. The select group of seven military test pilots who have been chosen to make the first manned orbital flights undertaken by the U.S. under Project Mercury.

meta-linked polyphenyl ethers. Base fluids under development for use in a nuclear environment and having multifunctional capabilities in such applications as lubricants, heat transfer, hydraulics, and power transmission.

metallic fuels. Fuels which are a mixture, a pressed powder, or an alloy of a fissionable material, e.g., uranium-235, plutonium-239, and a metal, such as aluminum, nichrome, or stainless steel.

mev. Million electron volts. See **electron volt.**

milli-g. An exerted force equal to one one-thousandth of normal gravity.

mission profile. A graphic display of a flight mission, including the integral components such as flight duration, altitudes, airspeeds, etc.

moderator. A material that has a high cross section for slowing down fast neutrons, with a minimum of absorption, e.g., heavy water, beryllium.

MPE (maximum permissible exposure). A measure of the biological importance of a given radiation dose. Generally, a radiation dose which is thought to cause no appreciable biological damage in humans, usually accepted as 25 rem. Sometimes referred to as *maximum permissible dose (MPD)*.

NARF. Nuclear Aircraft Research Facility, funded by the Air Force and operated by Convair at Ft. Worth, Texas. The outstanding device is the ground-test reactor, which is capable of dynamically testing small aircraft components in a nuclear radiation field and in any one of three environments: pressure, temperature, or humidity. Also available is the Aircraft Shield Test Reactor as well as a number of other sources of radiation. These devices are used for radiation testing and shielding experiments.

negative temperature coefficient. The decrease in reactivity of a reactor with increase in temperature. Increasing temperature within the reactor increases the average neutron energy. Since the cross section of the fissionable material decreases with increased neutron energy, the net effect is to decrease the number of fissions. Hence, a steady-state reactor will tend to go subcritical.

NEPA. Nuclear Energy for the Propulsion of Aircraft, the first study project initiated to explore feasibility of nuclear-powered aircraft. It was undertaken for the Air Force by the Fairchild Engine and Airplane Corporation at Oak Ridge National Laboratory in May 1946 and was completed in 1951 with general feasibility indicated. This project was the forerunner of the aircraft nuclear propulsion program.

NETF. Nuclear Engineering Test Facility, a new nuclear radiation facility being built by the Air Force at Wright Air Development Center, Dayton, Ohio. It consists of a 10-megawatt research reactor, two 330-cubic-foot environmental-radiation test cells, and a remotely operated handling system for irradiated materials.

NRTS. National Reactor Test Station, an AEC nuclear testing facility near Arco, Idaho.

NTA. Nuclear Test Aircraft, a modified B-36 bomber that flew on its own conventional engines but which was equipped with a shielded crew compartment, nuclear instrumentation, and a reactor (the Aircraft Shield Test Reactor). The purpose of these flights, conducted by Convair of Ft. Worth, Texas, was to study radiation-shield methods and effectiveness, radiation effects on aircraft materials and components, and nuclear-aircraft flight and ground operations.

NTS. Nevada Test Site, an AEC facility near Las Vegas for testing weapons and propulsion reactors.

nucleus. The core of the atom in which most of the mass and the total positive charge are concentrated. A nucleus is composed fundamentally of one or more protons, as indicated by the atomic number of the element, and an approximately equal number of neutrons. The mass number of the element is the sum of the protons and neutrons in the nucleus.

nuclide. An individual atom of given atomic number *Z* and mass number *A*, for example, $_{92}U^{235}$. It is any species of atom that exists for a measurable length of time and has a nuclear structure distinct from that of any other species of atom.

pair production. The creation or "materialization" of a positron and an electron, usually called an *electron pair,* from the annihilation of a gamma-ray photon, as in the strong electric field near an atomic nucleus. See **electron-positron pair.** The "opposite" process, annihilation of positrons by conjunction with an electron, also occurs, producing one or more but usually two gamma rays. The phenomenon of pair production is due to the conversion of the incident photon into mass. The photon disappears, and the electron and positron are hurled in divergent directions from the point of formation.

particles. The problem of breaking down the atom into its components has led to an entangled multiplicity of at least 20 known and probable mass or energy particles that are "elementary" to the atom or are the observed products of subatomic reaction. All known particles have been discovered to undergo various of several types of reactions, either with other particles, with other radiation, or by decay. Mass particles regarded as constituents of the atom include the neutron n, the electron e, and the proton p. Among the particles emitted from reaction are the positron e^+, the photon γ as a quantum of radiated energy, and the alpha (α) and beta (β) nuclear "fragments." In symbolic notation the charge of a particle and its mass to the nearest whole number may be indicated by inferior and superior numerals accompanying the symbol for the particle. Thus the neutron $_0n^1$ is a particle of zero charge and mass number 1 (see **atomic weight**). The electron with zero mass and charge —1 is shown as $_{-1}e^0$. For example, the alpha particle $_2He^4$ has a charge of +2 and mass of 4.

particulate. Radiations which are of particle form, such as alpha, beta, and neutron, as opposed to wave-form radiations, such as gamma rays.

period. The time interval during which the power level (flux) of a reactor changes by e (= 2.718, the base of natural logarithms).

period scrams. Electronic safety circuits that automatically insert safety rods in a reactor when the reactor period decreases below the safe minimum limit.

photon. The physical unit of electromagnetic waves, which are propagated through space in definite bundles of energy, or quanta, and that exhibit characteristics of both wave and particle, i.e., frequency and wavelength, yet also obey many of the laws that govern accelerated particles. Photons are generated in collisions between nuclei or electrons or in other incidents in which an electrically charged particle changes its momentum. They may be absorbed by any charged particle. The photon moves at the speed of light.

pile radiation. Radiation of mixed neutron-gamma ratios emanating from and characteristic of a given reactor.

plasma. A neutrally charged gas in which the ionization potential of the gas atoms has been exceeded, thus allowing each atom to separate into a positively charged ion and an electron. The charged gas contains all the ions and separated electrons.

plasma diode. A thermionic device consisting of a hot cathode and a cold anode between which an easily ionized gas has been introduced.

Pluto project. An AEC experimental program established in 1956 to develop technology and to design, build, and test experimental reactors that will demonstrate scientific and technical feasibility of applying nuclear energy to a ramjet engine for missile propulsion. AEC has responsibility for reactor design and development, and the Air Force has development responsibility for the nonnuclear components of the ramjet engine. Technical work is centered at the Lawrence Radiation Laboratory.

poison. In a nuclear reactor, those atoms (of such elements as boron) other than fuel that have large capture cross sections for thermal neutrons. In capturing thermal neutrons unproductively, these atoms decrease the number available to cause fission.

positron. A particle equal in mass to an electron and bearing an equal but positive electrical charge. The positron is created by radioactive decay of an unstable nucleus or in collision between an energetic photon (exceeding one mev) and a charged particle or another photon.

power density. The rated power of a reactor or isotopic power source per unit weight of the fuel-bearing material, e.g., kilowatt-hours per pound or gram. In reactors, power density is often stated in kilowatts per cubic centimeter of core volume.

Project Orion. An ARPA-sponsored space program to launch a space station, with booster propulsion coming from a series of controlled atomic explosions. Feasibility studies are now under way.

prompt critical. Describes a reactor condition in which criticality is being sustained on prompt neutrons alone. This is an accident condition, since the reactor period will be dangerously short. In this condition the excess multiplication of prompt neutrons (or reactivity) is of such a large value that the delayed neutrons have no opportunity to slow the rate of increase in neutron density.

prompt neutrons. The neutrons released by the fission process, as contrasted with the *delayed neutrons* not produced immediately by the fission but emitted by the fission products.

proton. An elementary particle of positive charge (e) equal to the negative charge of the electron but of 1837 times the mass. A constituent of all atomic nuclei. The number of protons in the nucleus of an atom is indicated by the atomic number of the element.

radiation. The emission and propagation of energy quanta in the form of waves through space or a material medium. By extension the term includes not only *electromagnetic radiation* but also streams of subatomic particles (alpha rays, beta rays) and the emitted subatomic particles themselves.

radiation dose. The amount of radiation absorbed by a material, system, or tissue in a given amount of time; usually measured in one of the commonly accepted terms—roentgen, rem, rep, etc.

radiation spectrum. The quantitative energy distribution of radiation being emitted from a source.

radiation syndrome. Those symptoms which occur in man as a result of radiation. Acute radiation syndromes are distinguished by the rapidity with which these symptoms appear.

radioactive particulates. Minute radioactive particles.

radioactivity. The process in which nuclei of certain elements undergo spontaneous disintegration, accompanied by corpuscular or electromagnetic emanations (radiation). In natural radioactivity the emissions may be alpha rays (alpha particles), beta rays (beta particles), or gamma rays (wave form). "Artificial radioactivity" produced by bombardment in atomic transmutations may be further characterized by positron emission or orbital-electron capture.

radioisotope. A radioactive isotope that decays in a predictable decay scheme at a definite rate under normal conditions.

radionuclide. A radioactive nuclide. See **nuclide.**

ram air. Air entering an air scoop or air inlet as a result of the high-speed forward movement of a vehicle.

Rankine cycle. An idealized thermodynamic cycle consisting of two constant-pressure processes and two isentropic processes. The principle appears in boiling a cycle fluid with isotope heat and driving a turbine generator by the expansion of the resulting vapor through a nozzle.

rare earths. The 15 metallic elements of atomic numbers 57 through 71 having such similar chemical properties that they are considered to occupy the position of a single element in Group III of the chemical periodic table.

reactivity. In a nuclear reactor the ratio of the change in the effective multiplication factor to the effective multiplication factor ($\delta k_e/k_e$). This change can be positive or negative; in the positive sense, the power level of the reactor is increasing exponentially; in the negative sense, the power level is decreasing exponentially. The reactivity factor provides a quantitative measure of the change in the power level of a given reactor.

reactor core. The central portion of a nuclear reactor, exclusive of the reflector and shields, containing the fissionable material and the moderator, if any. Normally coolant channels pass through the core.

reflected core. A reactor core surrounded by a reflector that throws back into the core a percentage of the escaping neutrons.

reflector. A material of high scattering cross section that surrounds a reactor core to reduce the escape of neutrons, many of which are reflected back into the core. The "savings" from escaping neutrons allow a more economical use of fissionable materials.

refractory. A material, usually ceramic, that resists the action of heat, does not fuse at high temperatures, and is very difficult to break down.

REIC. Radiation Effects Information Center established by the Air Force in May 1957 at the Battelle Memorial Institute, Columbus, Ohio. Compiles data and reports on all types of radiation effects from research contracts, projects, and other sources.

rem. Roentgen-equivalent-man. A dose rate equal to that quantity of radiation which, when absorbed by a human being, produces the same effect as the absorption of one roentgen of high-voltage X rays.

rep. Roentgen-equivalent-physical, a proposed unit of an ionizing radiation dosage that is not included in the definition of the roentgen. Generally defined as a dose that induces energy absorption of 93 ergs per gram of tissue. Used extensively for the specification of permissible doses of ionizing radiations other than X rays or gamma rays.

r/hr. Roentgen per hour.

roentgen. A unit of radiation of X rays or gamma rays, being the amount of such radiation that produces one electrostatic unit in a cubic centimeter of dry air under standard conditions of temperature and pressure. Symbol: r.

Rover project. A joint AEC-NASA effort established in AEC in 1955 to demonstrate the feasibility of applying nuclear energy to rocket propulsion applications by developing a nuclear-rocket engine. The project is oriented primarily toward filling advanced space-propulsion requirements. Technical work is centered at the Los Alamos Scientific Laboratory.

scattering. Change in direction of a particle because of a collision with another particle or nuclear system.

Seebeck effect. The establishment of an electric potential within a given material as a result of a difference in temperature between any two points within the material.

semiconductor. An electrical conductor having comparatively high resistance to electron flow. Its electrical conductivity is in the range between those of metals and insulators.

shadow shield. A shield, other than the reactor shield, that is interposed between the radiation source and a specific area to be protected. Useful in space, it is less effective in the earth's atmosphere because air scattering deflects radiation around it.

shield, or **shielding.** Any material, such as concrete, lead, or water, used to reduce the intensity of radiation.

Slam. Abbreviation for supersonic low-altitude missile. An ARDC project on which three aircraft contractors (Chance Vought, North American Aviation, Inc., and Convair) are working on conceptual designs to make preliminary determination of basic requirements of the nuclear-ramjet missile system.

Snap. Abbreviation for systems for nuclear auxiliary power.

Snap-3. A proof-of-principle, thermoelectric generator weighing four pounds and using a radioisotope power source (polonium-210), produced by the Martin Company. Radioactive decay of the fuel serves as the source of heat. Snap-3 produces about three electrical watts, with an over-all conversion efficiency of about seven per cent.

Snap program. A program established to develop *systems for nuclear auxiliary power,* low-power devices of light weight and long life that produce from a few watts to several kilowatts of electricity to operate as reliable, long-enduring power sources for instrument packages in satellites and space probes. The Snap effort, which serves both Air Force and NASA needs, follows two heat-source avenues: the development of small, compact-core reactor-powered systems and the harnessing of the energy from decay of radioisotopes. The Atomic Energy Commission is responsible for developing both nuclear-heat sources and the conversion equipment into an integrated, electricity-producing power package.

solar batteries. Batteries which utilize large areas of photoelectric cells that are activated by the sun to produce electricity.

specific heat. The ratio between the amount of heat that it takes to raise the temperature of a given substance one degree and that required to raise an equal mass of water one degree.

specific impulse. A performance parameter of a rocket power plant or rocket propellant equal to the pounds of thrust developed per pound per second of propellant flow. Also the thrust in pounds divided by the propellant consumption rate per second.

specific power. The energy delivered per pound of fuel in a reactor or in a radioisotopic power source.

stagnation temperature. The "ram" temperature created on the leading edges of an aerodynamic vehicle traveling through the atmosphere. Refers to the complete standstill of air molecules on the leading edges of the craft.

static conversion. Energy conversion in which no moving parts of equipment are utilized.

steady state. The stable operating condition of a reactor in which the neutron inventory remains constant; that is, the effective multiplication factor (k_e) is equal to one.

Stefan-Boltzmann law. A law of heat transfer by direct radiation in which the amount of heat rejected from a given surface is proportional to the area of the surface and to the absolute temperature of the surface raised to the fourth power.

Stirling cycle. A thermodynamic cycle in which heat is added at constant volume, followed by isothermal expansion with heat addition. The heat is then rejected at constant volume, followed by isothermal compression with heat rejection. If a regenerator is used so that heat rejected during the constant-volume process is recovered during heat addition at constant volume, the thermal efficiency of the Stirling cycle is the same as for the Carnot cycle, with less compressive work needed.

stoichiometric ratio. The law of chemical composition whereby elements will only combine with each other in definite, established ratios which are whole numbers of each constituent element.

strategic mission profile. A profile of a specific mission. See **mission profile.**

structure activation. Radioactivity induced in the structure of the aircraft, ground vehicle, building, etc., in which the reactor is operated.

subcritical. The status of a reactor that has slipped below just critical, the number of new fissions being less than the previous generation. If not regulated with control rods, the reactor will shut itself down on an exponential decrease.

substrate. Of a coated material, the material which is protected by the coating.

supercritical. The status of a reactor that has proceeded past the just-critical point, generating one new fission per previous fission. The added fissions increase exponentially, power going up in the same proportion. If not contained with control rods, the reactor will run away.

target materials. Materials selected for irradiation by neutrons or gamma rays or both within a reactor or gamma-radiation test facility.

thermal mw-year. A power of one megawatt of thermal energy produced continuously for one year.

thermal shock. The stress developed by rapid heating or uneven distribution of temperature in a material.

thermionic conversion. The process whereby electrons released by thermionic emission are collected and utilized as electric current. The simple example of this is provided by a vacuum tube, in which the electrons released from a heated anode are collected at the cathode or plate.

thermionic emission. Direct ejection of electrons as result of heating the material, which raises electron energy beyond the binding energy that holds the electron in the material. Thus the work function of an electron.

thermocouple. A connection or junction of two pieces of dissimilar metals which produces a current when heated.

Tory-2. A Lawrence Radiation Laboratory reactor experiment to demonstrate the feasibility of nuclear-ramjet propulsion and to verify materials, neutronics, and other design information.

TSF. Tower Shield Facility, constructed at Oak Ridge, Tennessee, to simulate aircraft-reactor radiation patterns during flight. During tests, different crew shields and shield materials are lifted to equal level with a nuclear reactor suspended aloft from four 324-foot towers.

turbofan. A turbojet engine in which additional propulsive thrust is gained by extending a portion of the compressor or turbine blades outside the inner engine case. The extended blades propel bypass air which flows along the engine axis but between the inner and outer engine casing. This air is not combusted but does provide additional thrust caused by the propulsive effect imparted to it by the extended compressor blading.

undoing. The process whereby, according to psychiatry, the unconscious mind seeks to wipe out painful thoughts and memories.

Van Allen radiation belts. Two concentric, doughnut-shaped layers of radioactive particles surrounding the earth that were discovered and measured by the Explorer satellites and Pioneer space probes. The first belt is 2000 miles thick and begins at 1400 miles altitude; the second is 4000 miles thick and begins at 8000 miles altitude.

void fraction. The fraction of the frontal area of a reactor that is open to air flow. Also called *free-flow area*.

watt-hr/lb. A unit of power density, being equal to one watt-hour of electrical energy produced per pound of energy source material.

working fluid. A fluid, such as air or a liquid metal, which is heated by the reactor and from which heat is removed by a device which converts the heat into some other form of energy.

zerogravity field. An environment in which zero net gravity force is exerted upon mass.

The Quarterly Review Contributors

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