THE UNIVERSITY OF MICHIGAN
INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

NUCLEAR ENGINEERING REPORT

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TABLE OF CONTENTS

INTRODUCTION

The United States, being the greatest energy-consuming country in the world on the basis of per capita and total consumption, has a real interest in the infant of the energy field -- atomic energy. The atomic age for power development started in 1939 with the discovery of nuclear fission. Much research, development, and experience was gained in the new field under military pressure and with necessary government support. However, in late 1953, American private enterprise stated its interest in carrying forward a portion or all of the responsibilities for research and development of industrial applications of atomic energy. The turning point for industry was the Atomic Energy Act of 1954, which replaced government monopoly with private interests operating under a series of government regulations. In the last two years tremendous strides have been made in the application of atomic energy to diverse purposes by both industrial and government groups.

Cognizant of the importance of the new energy sources, the ASME established appropriate formal committees within the Society at an early date. Pasini has presented a brief summary of Society activities and achievements, including the official formation of the Nuclear Engineering Division.[1]

This new Professional Division has been responsible to a large degree for the many excellent articles appearing in Mechanical Engineering during the last year and a half. Added interest in the subject of atomic energy is demonstrated by the inclusion of one or more articles on the subject each month in the "Briefing the Record" department of Mechanical Engineering. Other engineering societies and organizations have developed nuclear engineering interests, and the ASME Nuclear Engineering Division has been active in cooperating with these responsible groups in the development of an optimum program for engineers and scientists associated with the atomic energy field. An example is the participation of the ASME in the EJC Nuclear Engineering and Science Congresses of December 12-16, 1955, and proposed for March 11-15, 1957.

Literature pertinent to atomic energy is so extensive and growing so rapidly that a complete independent survey of the field of interest to mechanical engineers does not appear practical.

This review was prepared on the basis of information from three principal sources[2,3,4] and a limited number of other publications as noted. It is well to note that the preparation of the McKinney Report alone involved fifteen seminar or discussion groups and approximately fifty special studies by over 300 authorities in their respective fields.

Engineering research and development in controlled nuclear fission and thermonuclear fusion, as well as the many associated fields making these possible, have been pursued intensively in the United States since 1943. The United Kingdom's Program started about 1945.[5] The entry of private industry into programs of atomic energy was originated early in 1950 by the United States Atomic

Energy Commission (AEC) with the assignment of studies for a power breeder reactor to the Knolls Atomic Power Laboratories.[6] Many reactor experiments are in operation now and include developments at Oak Ridge National Laboratories, Argonne National Laboratory, the Los Alamos Laboratories, The University of California at Berkeley, and the National Reactor Testing Station. The AEC announced in March, 1954, a five-year program for power reactor development; in January, 1955, the power demonstration reactor program; and in September, 1955, packaged nuclear power demonstration reactor program.

Concurrently with invitations for private enterprise to undertake energy production from nuclear fission, the AEC has permitted industrial ownership of ore-refining mills for conversion of uranium-bearing ores to uranium concentrates. Invitations were released to industry to build and operate feed materials plants to convert ore concentrates to gaseous diffusion feeds -- uranium hexafluoride, uranium trioxide, uranium dioxide, and uranium tetrafluoride.[7]

Communications from the AEC Division of Production and an announcement by Mr. W. Kenneth Davis, Director, Division of Reactor Development, indicated that proposals will be accepted up to October, 1957, for processing spent reactor fuels.[8]

The passage of the Atomic Energy Act of 1954, and subsequent amendments thereto, has granted relatively liberal policies for private proprietorship of novelties and inventions in this field. Through these avenues, coupled with aggressive viewpoints of many industrial leaders, the peaceful uses of atomic energy are moving forward rapidly to practicality. Power from nuclear fission by numerous methods is technically feasible now, but much engineering effort and time must be devoted to the development of competitive economic atomic power. With outlays of expenditures of great magnitude, progress in multiple and necessarily simultaneous programs becomes dependent on the training and skills of technical personnel as well as on the solutions to associated legal and management problems.

Many areas of nuclear engineering are of direct concern to the mechanical engineer. This brief review will be limited to those subjects more directly concerned with power production and its applications to the generation of electrical energy; propulsion systems for sea, air, and land; and the application of radiation sources for industrial purposes. Although the applications of nuclear engineering are vital to such areas as medicine, public health, agriculture, and the preservation of foods, no detailed consideration will be given here to these items.

There are many special problems associated with atomic energy that have a decisive influence on the application and development of reactors for power generation and radiation for industrial uses. Since basic nuclear science recognizes no national boundaries, and since the interests of our national security are paramount, a system of control of information on atomic energy becomes necessary. Recommendations are made that the AEC undertake the compilation of both classified and unclassified information on a continuing and current basis, and that it review the basic concepts of classification.

The speed at which atomic energy applications will advance depends on the extent of public understanding, availability of qualified personnel, adequate facilities, and a maximum of unclassified information available for use. Nuclear engineering has much in common with other fields of engineering with respect to the present acute shortage of engineers and scientists. A knowledge of radiation hazards is important, and a sound atomic insurance program must be developed in order to provide proper conditions for the development of nuclear power.

In all our peace-time developments of atomic energy, we must bear in mind that it has a direct influence on international relationships. It has been recommended that the United States provide other nations with nuclear fuels, technical information, and financial assistance for the development of atomic power and industrial uses of atomic energy. In the spirit of the 1954 Act and of subsequent developments, it has been suggested that further attention be given to the ownership question of special nuclear materials which now rests in the Federal Government. Further clarification of patent provisions is necessary to insure maximum industrial participation in peace-time developments.

Economic nuclear power from fission is largely dependent on the cost and performance of the materials comprising various components of a reactor system. Improvements in the production of presently known materials have significant bearing upon capital investments. Developments of new materials, which permit operation of a nuclear reactor and its associated power-plant equipment at high temperatures, will improve efficiencies of heat cycles and have material influence on costs of power production.

Fuel Material

Fissionable materials contained in uranium ore consist of several isotopes. Two isotopes which are present in uranium in concentrations high enough to be of practical importance are uranium-238 and uranium-235. Uranium-235 is the only material known to man which exists in sufficient quantities in nature to be of practical importance in a self-sustaining fission process. It occurs in uranium ores to the extent of about 0.7 percent of the total uranium content. Other fissionable materials occur in nature in such small quantities that it becomes impractical to extract them for use. With our present-day technology, all nuclear reactors, with the exception of natural uranium reactors, require start-up with the fissionable isotope U-235. By proper arrangement of fuels which fission with materials which capture neutrons, such as uranium-238 and thorium-233, it becomes possible to produce in a reactor two other materials, plutonium-239 and uranium-233, which will fission in the ranges of energies considered presently practicable.

The ore deposits which contain uranium are usually of secondary sedimentary nature, lying between beds of sandstone. Large-scale mining techniques are being adapted to the production of uranium ores and present stockpiles indicate large reserves of uranium as a potential source of energy. The Office of Operations Analysis[9] had estimated the future uranium ore requirements that would result from an expanding nuclear power industry in this country. These estimates indicate that the average annual ore rate required for the period from 1960 to 1975 can vary from a few hundred tons to 19,000 short tons of U_3O_8 per year and that the 1975 procurement rate range varies from 6,000 to 90,000 short tons.

Palmer Putnam in his book[10] estimates that the total amount of uranium and thorium in the earth's crust to a depth of three miles is 10^{12} tons. It might be possible to develop methods for open mining and extraction so that about 10,000,000 tons of uranium and thorium may ultimately be competitive with fossil fuels. If this is the case and if a completely integrated fuels cycles program for nuclear power reactors is ultimately achieved, the energy requirements for a growing world can be satisfied from this source for about six centuries.

Thorium, by some estimates, is more plentiful in the earth's crust than uranium. Thorium is nearly always associated with uranium and the rare earths.[11] Production of thorium for nuclear energy has not yet reached significant proportions for the power reactor program.

Preparation of Nuclear Fuels

For technologies in the reasonable future, reactor fuel assemblages can be solids, liquids, and possibly gases. Most reactors undergoing present-day development utilize solid fuels in the shape of rods, tubes, or flat plates. The fuel elements are fabricated and arranged in such a manner that coolants can extract the fission energy in the form of heat energy. To prevent a given solid-fuel element from being corroded by the coolant and to confine highly radioactive fission products within the fuel elements, cladding materials are normally provided. Examples of cladding materials which have suitable nuclear, thermal, and structural properties for nuclear heat-power plants are aluminum, zirconium, and stainless steel. Stainless steels of various compositions are used as structural materials for heterogeneous fuels for reactors where neutron economies are relatively unimportant. The chemical and physical properties of these stainless steels make them suitable for use in power-producing reactors.

Several promising new types of compact reactor designs have their fuels in liquid form. For liquid fuels, it is possible to formulate homogeneous solutions by several methods. The liquid fuel can be an aqueous solution of a fissionable salt, and the homogeneous fuel can be either a fused salt (melting at high temperatures) in molten form or a molten metal of the fissionable material, or some alloy thereof.

Fertile Materials

Fertile materials may be defined as those materials which are capable of capturing neutrons and decaying radioactively to produce a fissionable material. Two such materials known today are uranium-238, which upon neutron capture produces plutonium-239, and thorium-232, which upon neutron capture produces uranium-233. These materials can be purified and fabricated into suitable form, so that when they are used in a reactor, an optimum utilization of neutrons for various energy ranges can produce additional fissionable fuels while consuming fuel to produce power.

Other Materials Problems

In addition to fuels and fertile materials, nuclear reactors involve many additional materials usages. These include moderators for reducing neutron velocities, coolants for heat removal, neutron reflectors for control of nuclear balances, reactor structural materials for several services, neutron shields which slow down fast neutrons and absorb thermal neutrons, and biological shields for absorption of beta particles and beta rays.

NUCLEAR REACTORS AND POWER

The reactor development program in the United States consists basically of three main parts:

1. The development of basic technology.

2. The testing of concepts by integrated reactor experiments.

3. The power reactor development program.

Status of Reactor Construction (End of 1955)

Table I[12] provides information on civilian use reactor experiments and nuclear power demonstration plants, actual or proposed, as of the end of 1955. This list does not include the proposals for small civilian atomic powerplants (5,000 to 40,000 kw) invited by the AEC in the late fall of 1955.

Table II[13] (old Table V) is a listing by reactor type of all known reactor projects throughout the world. These projects are in various stages of completion, from late planning through construction and into actual operation.

Pressurized-Water Reactors

Most of the experience to date has been with reactors that utilize water as the means for extracting thermal energy from the fission reaction. In the AEC program for "Demonstration Plants" there are included three reactors which are cooled with either ordinary or heavy water.

Shippingport Reactor: The first of these is the pressurized-water reactor being built by Westinghouse Electric Corporation and Duquesne Light Company at Shippingport, Pennsylvania. The Babcock and Wilcox Company and Foster-Wheeler Limited are participating in providing the steam generator. The pressurized-water reactor was selected because it was the only type of reactor then ready for full-scale construction. The basic objective of the Shippingport Reactor is to demonstrate the reliable production of electrical energy. It is expected that valuable knowledge concerning costs for reactor fuels and operating procedures will result from this operation. The pressurized reactor for the Shippingport installation has a unit designed to produce 236,000 kw of thermal power with an electrical gross generating capacity of 100,000 kw. The reactor uses as fuel 12 tons of natural uranium and 52 kilograms of fuel enriched to about 90 percent of U-235. The moderator and coolant are light water; it is expected that the average coolant temperature will be 540°F and produce steam at 585 psig saturated. Present estimates indicate that the cost of the reactor, excluding research and development, fuel-element fabrication, and charges for nuclear materials, will approach 370 dollars per kilowatt of installed capacity. Many safety precautions have been taken to assure reliable operation in a concentrated population area.

TABLE I

Civilian Use Reactor Experiments and Nuclear Power Demonstration Plants
Actual or Proposed as of the End of 1955

Type	Sponsor	Power Level kilowatts	Estimated Cost[1] (Millions of dollars) Research and Development AEC	Research and Development Private	Fabrication and Construction AEC	Fabrication and Construction Private	Total
REACTOR EXPERIMENTS							
(a) Sodium reactor experiment	AEC-North American Aviation, Inc.	20,000[2]	8.4[3]		5.0[3]		13.4
(b) Experimental boiling water reactor	AEC (Argonne National Laboratory)	20,000[2]	16.1	-----	3.6	-----	19.7
(c) Homogeneous reactor experiment No. 2	AEC (Oak Ridge National Laboratory)	5,000[2]	37.0	-----	1.8	-----	38.8
(d) Experimental breeder reactor No. 2	--------do-------------	62,000[2]	24.3	-----	15.3	-----	39.6
(e) Organic moderated reactor experiment	--------do-------------	------	2.0	-----	----	-----	-----
(f) Liquid metal fueled reactor experiment	AEC (Brookhaven National Laboratory)	------	----	-----	----	-----	-----
"DEMONSTRATION" PLANTS							
(a) Pressurized water reactor (in operation 1957)	AEC-Duquesne Light and Power; Westinghouse Electric Co.	60-100,000[4]	59.6	-----	32.25	15.5	107.35
(b) Boiling water reactor (in operation 1960)	Commonwealth Edison, et al.	180,000[4]	----	-----	0	45.0[5]	45.0
(c) Fast breeder reactor (in operation 1959)	Detroit Edison et al.-AEC	100,000[4]	3.45	-----	0	55.0[5]	-----
(d) Pressurized water reactor (in operation 1959)	Consolidated Edison	140,000[4]	----	-----	0	55.0[5]	-----
(e) Aqueous homogeneous reactor (in operation 1962)	Pennsylvania Power and Light et al.-AEC	150,000[4]	(6)	(6)	(6)	(6)	(6)
(f) Sodium graphite reactor (in operation 1959)	Consumer's Public Power District of Nebraska et al.-AEC	75,000[4]	10.48	-----	0	16.72[5]	27.2
(g) Pressurized water reactor (in operation 1958)	Yankee Atomic Electric Co. et al.-AEC	134,000[4]	7.5	-----	0	33.0[5]	40.5

1 Cost estimate covers start as of July, 1953. Earlier costs for civilian application reactor experiments total 21.3 millions of dollars.

2 Thermal.

3 Allocation not given. AEC participation in total, 10.55 millions of dollars; NAA participation, 2.85 millions of dollars.

4 Electrical.

5 Represents total private participation, portion allocated to research and development not given.

6 Estimate not available.

TABLE II. LIST OF REACTORS OF VARIOUS TYPES*

Pressurized Water -	LITR (Low Intensity Test Reactor, MTR Mock-Up)
	MTR (Materials Testing Reactor)
	STR Mark I, II (Submarine Thermal Reactor)
	RFT (Russian)
	PWR (Pressurized Water Reactor)
	SFR (Submarine Fleet Reactor)
	LSR (Large Ship Reactor)
	WTR (Westinghouse Test Reactor)
	ETR (Engineering Test Reactor)
	TRR (Thermal Research Reactor, Russian)
	Yankee Atomic Electric
	APPR (Army Package Power Reactor)
	Consolidated Edison (+96 Mw C. F. Sup. Ht.)
	SAR (Submarine Advanced Reactor)
	University of Florida
Boiling Water -	BER I (Boiling Experimental Reactor, Borax I, Destroyed)
	BER II (Boiling Experimental Reactor, Borax II, Rebuilt as III)
	BER III (Boiling Experimental Reactor, Borax III)
	EBWR (Experimental Boiling Water Reactor)
	Rural Cooperative Power Assoc., Minn. (+4 Mw C. F. Sup. Ht.)
	Nuclear Power Group (Dual-Cycle)
Swimming Pool -	BSR (Bulk Shielding Reactor)
	Convair Research Reactor
	TSR (Tower Shielding Reactor)
	Pennsylvania State University
	Geneva Conference Reactor (Swiss Research)
	University of Michigan
	Naval Research Laboratory
	American Machine and Foundry
	Battelle Memorial Institute
	Livermore Laboratory (LPTR)
	ORR (Oak Ridge Research Reactor)
	Omega West
	Watertown Arsenal
	Washington State
	Trombay (Indian)
Homogeneous -	LOPO (Low Power Water Boiler)
	HYPO (High Power Water Boiler
	SUPO (Super Power Water Boiler)
	HRE (Homogeneous Reactor Experiment, Dismantled)

* Courtesy of Raytheon Manufacturing Company, Waltham, Massachusetts, Nuclear Reactor Data, November 15, 1955.

Homogeneous Cont'd.	- NAA (North American Aviation) NCSR (North Carolina State Reactor) LAPR (Los Alamos Power Reactor) HRT-1 (Homogeneous Reactor Test 1) (HRE No. 2) Armour Research Foundation Gamma Corporation UCLA Medical PAR (Pennsylvania Advanced Reactor)
Heavy Water	- CP-3 (Chicago Pile 3, Modified to CP-3') ZEEP (Zero Energy Experimental Pile, Canadian) NRX (National Research Experimental Reactor, Canadian) ZOE (French) Russian Research CP-3' (Chicago Pile 3') JEEP (Norwegian-Netherlands) SACLAY (French P-2) CP-5 (Chicago Pile 5) Savannah River (5 Reactors) Swedish DIMPLE (Deuterium Moderated Pile, Low Energy, British) Harwell Research (British) CISE (Italian) NRU (Canadian) Australian Research NPD (Nuclear Power Demonstration, Canadian) Brookhaven Medical Swiss Research Reactor Norwegian Power (Boiling) Massachusetts Institute of Technology
Graphite	- CP-1 (Chicago Pile 1, Rebuilt as CP-2) CP-2 (Chicago Pile 2) X-10 (Oak Ridge X-10 Area Reactor) Hanford 305 Test Reactor Hanford (8 Reactors) GLEEP (Graphite Low Energy Experimental Pile, British) BEPO (British Experimental Pile O) BNL (Brookhaven National Laboratory) TTR (Thermal Test Reactor) RPT (Reactor for Physical and Tech. Investigations, Russian) Sellafield (British Production, 2 Reactors) APS-1 (Atomic Power Station 1, Russian) RBI (Belgian) G-1 (French Production) Russian Power (Two APS-1 Type Reactors)

TABLE II. (CONT'D)

Graphite Cont'd.	- G-2 (French Production) British Power (2 Reactors, 25 Elec. Mw each) West German
Sodium Graphite	- SRE (Sodium Reactor Experiment) CPPDC (Consumers Public Power District of Columbia)
Liquid-Metal Cooled	- Los Alamos Fast (Clementine, Dismantled) Sir Mark A, B (Sodium Intermediate Reactor) ARE (Aircraft Reactor Experiment)
Liquid Fuel	- LMFR (Liquid-Metal-Fuel Reactor)
Fast Breeder	- EBR-1 (Experimental Breeder Reactor 1, CP-4) Zephyr (British Fast Breeder Prototype) British Fast Power Breeder EBR-2 (Experimental Breeder Reactor 2) APDA (Atomic Power Development Associates)

Yankee Atomic Electric Company: Another type of pressurized-water reactor is the one being developed by the Yankee Atomic Electric Company for installation in western Massachusetts. This reactor has a thermal capacity of 480,000 kw, producing 134,000 kw of electrical generating capacity. This is a partially enriched reactor, containing about 2.7 percent U-235, and having a fuel loading of 28,800 kilograms of fuel. The unit is moderated and cooled with light water. Expected average coolant temperature is 535°F. The reactor pressure is 2,000 psig and will produce saturated steam at 600 psig. Estimates for the plant indicate the installed cost per kilowatt is about 246 dollars.

Consolidated Edison Company: A third type of pressurized-water reactor is being developed by the Consolidated Edison Company for installation at Indian Point, New York. This reactor is a combination of a fossil-fuel-fired superheater and a pressurized-water reactor. Thermal generating power is 500,000 kw with an electrical generating capacity of 250,000 total. The reactor employs 275 kilograms of 90 percent enriched U-235 fuel and 8,100 kilograms of thorium. It is expected to produce considerable quantities of U-233. The moderator and coolant are light water; the operating temperature of the reactor is 500°F; the reactor pressure is 1,500 psig; the saturated steam produced is at about 405 psig. Estimates of installed cost per kilowatt are about 230 dollars.

Boiling-Water Reactor

The Commonwealth Edison Company, associated with the General Electric Company, is planning the installation of a power-producing, boiling-water reactor near Chicago. This reactor will have a thermal power output of 682,000 kw with a gross electrical generating capacity of 180,000. The fuel to be employed is 1.1 percent enriched U-235 natural uranium, containing about 68,000 kilograms of fuel per loading. Cooling and moderation will be by light water. The reactor conditions are 488°F for cooling and a reactor pressure of 600 psig. Steam production is at 485 psig with a steam temperature of 467°F. Estimates for the reactor and associated turbo-electrical generating plant are 250 dollars per installed kilowatt.

Sodium-Graphite Reactor

The Consumers Public Power District of Nebraska is planning the installation of a sodium-graphite type of reactor, which has been developed largely by North American Aviation, Inc. The proposed installation has a thermal generating capacity of 250,000 kw, producing about 75,000 kw of gross electrical generating capacity. The fuel is partially enriched U-235 (1.8 percent) with a fuel loading of 24,600 kilograms. The reactor is moderated with graphite and cooled by liquid sodium metal. The reactor operating temperature in the sodium is estimated to be 925°F at an operating pressure of 300 psig. Under these conditions, an 800 psig, 825°F steam is produced. Estimates for the reactor indicate costs of 320 dollars per kilowatt.

Fast Breeder Reactor

The Power Reactor Development Company, Inc., is developing a fast breeder reactor for installation and construction in the Detroit Edison service area. Dedication ceremonies were conducted on August 8, 1956, and approvals with reservations were given by the Reactor Safeguards Committee of the Atomic Energy Commission. This fast breeder reactor has a thermal heat output of 300,000 kw, with 100,000 kw gross electrical generating capacity. It is a core-blanket type of reactor, using a core of 2,100 kilograms of fuel which is enriched with 20 percent U-235. The blanket is natural uranium. Since this is a fast reactor, no moderator is provided. The coolant is sodium. The expected reactor temperature is 800°F, operating at pressures from 100 to 200 psig. The steam produced has conditions of 585 psig at 730°F. Estimates indicate that the total installed cost might approach 450 dollars per kilowatt.

Aqueous Homogeneous Reactor

The Westinghouse Electric Corporation and the Pennsylvania Power and Light Corporation are planning an aqueous homogeneous reactor with a gross electrical generating capacity of 150,000 kw, utilizing a uranium salt solution in water for the production of 585-psig saturated steam.

Liquid-Metal-Fueled Reactor

A liquid-metal-fueled reactor, termed LMFR, is one in which the uranium is dissolved in liquid bismuth metal. Basic research and development for this reactor type has been done at the Brookhaven National Laboratory. The Atomic Energy Commission has recently awarded to the Babcock and Wilcox Company a contract to install a liquid-metal-fueled reactor experiment.

Projected Power Demonstration Reactor Projects

In September, 1955, the Atomic Energy Commission invited proposals from industry for small power demonstration reactor projects with electrical generating capacities from 5,000 to 40,000 kw. The seven proposals received by the Atomic Energy Commission are indicated in Table III.

Nuclear Power Reactors for Propulsion

Over the last five years much has been published on the use of nuclear reactors for propulsion. Possibilities for applying nuclear energy to propulsion were recognized early in the atomic energy program. To date, actual work in the field has been limited to military applications. The Navy and Air Force are engaged in extensive research and development programs directed toward atomic-powered submarines, surface vessels, and aircraft.[14] The Joint Committee on Atomic Energy reports that nuclear energy can become a significant source of power for commercial shipping within the next ten to fifteen years. The actual rate of development is dependent on (1) the relative competitive position of nuclear power as it is determined through experience and (2) the basic governmental decisions concerning the requirements for atomic propulsion in the

TABLE III

Organization	Type of Reactor	KW Electrical Capacity	Scheduled for Operation
University of Florida	Pressurized light water	2,000	1959
Wolverine Elec. Corp. Foster-Wheeler and Worthington Corp.	Aqueous homogeneous	10,000	--
Chugach Electric Alaska, and Nuclear Dev. Corp., White Plains, N. Y.	Sodium-cooled heavy-water-moderated	10,000	1961
City of Pique, Ohio	Organic moderated	12,500	1960
City of Holyoke, Mass. and Ford Instrument	Gas-cooled (Closed-cycle gas turbine)	15,000	--
Rural Coop Power Assoc. and AMF	Boiling light-water	22,000	1960
City of Orlando, Florida	Liquid-metal-fueled	40,000	1960

American merchant fleet to further the program for application of nuclear reactors to commercial maritime vessels with atomic engines.

One of the first applications to prove the technical feasibility of atomic energy for propulsion was the successful operation of the U. S. S. Nautilus. The pressurized-water type nuclear reactor and propulsion plant for this submarine have been described in several places.[15,16,17]

Atomic propulsion of aircraft appears to be technically feasible. Major problems have yet to be solved before nuclear-powered aircraft will become economically feasible for commercial aviation. According to the McKinney Report commercial aviation with nuclear-heat engines is likely in the next 15 to 20 years.

The significantly unique advantage for the application of nuclear energy to the propulsion of commerical-type aircraft is a flight range unlimited by fuel tankage and the resulting freedom from a system of overseas refueling airfields and a reduction of supply problems associated with the need for fuel stops. Some of the disadvantages for nuclear aircraft lie in the problem of protective shielding. A very substantial amount of shielding would be required to limit radiation dosages to acceptable tolerances for passenger traffic. The shield weight is highly concentrated and necessitates a conventional aircraft structure to be redesigned to accommodate such high specific loads.

The relative economics of conventional chemically fueled aircraft and nuclear-powered aircraft depend on the range of travel, as illustrated in Figure 1 (p. 246, Figure 1, McKinney Report, Vol. II). In nuclear aircraft operation consideration must be given to (1) dual runways on flight take-offs and landings in the event of an accident releasing radiation, (2) the location of engine stations in remotely operated shielded areas for removal of fuel and decontamination, (3) the installation of remotely operated maintenance and nuclear fuel handling operations in properly designed buildings, (4) provisions for the disposal of radioactive decontaminated materials, and (5) special types of vehicles and ground support equipment for proper attention to craft and crew.

Nuclear propulsion for locomotives is technically feasible on the basis of present-day technologies. Future nuclear locomotives would require the same general dimensional and weight characteristics of present day locomotives. The probable shaft-horsepower output for a nuclear locomotive lies between 2,000 and 5,000 hp with an efficiency of 25 percent for conversion of heat to mechanical energy. This means that the reactor's heat-generating capacity will be between 8 and 20 megawatts. Much of the nuclear engineering and technology required for nuclear locomotive engineering can be supplied from the basic information required to prove the feasibility and economics of naval and commercial shipping, as well as aircraft.

A major concern in advancing nuclear engineering technology for locomotive applications lies in safety and hazards. Such hazards might be minimized by engineering design wherein the nuclear heat engine can withstand the shock of locomotive collision. Drastic reductions from present-day cost figures are

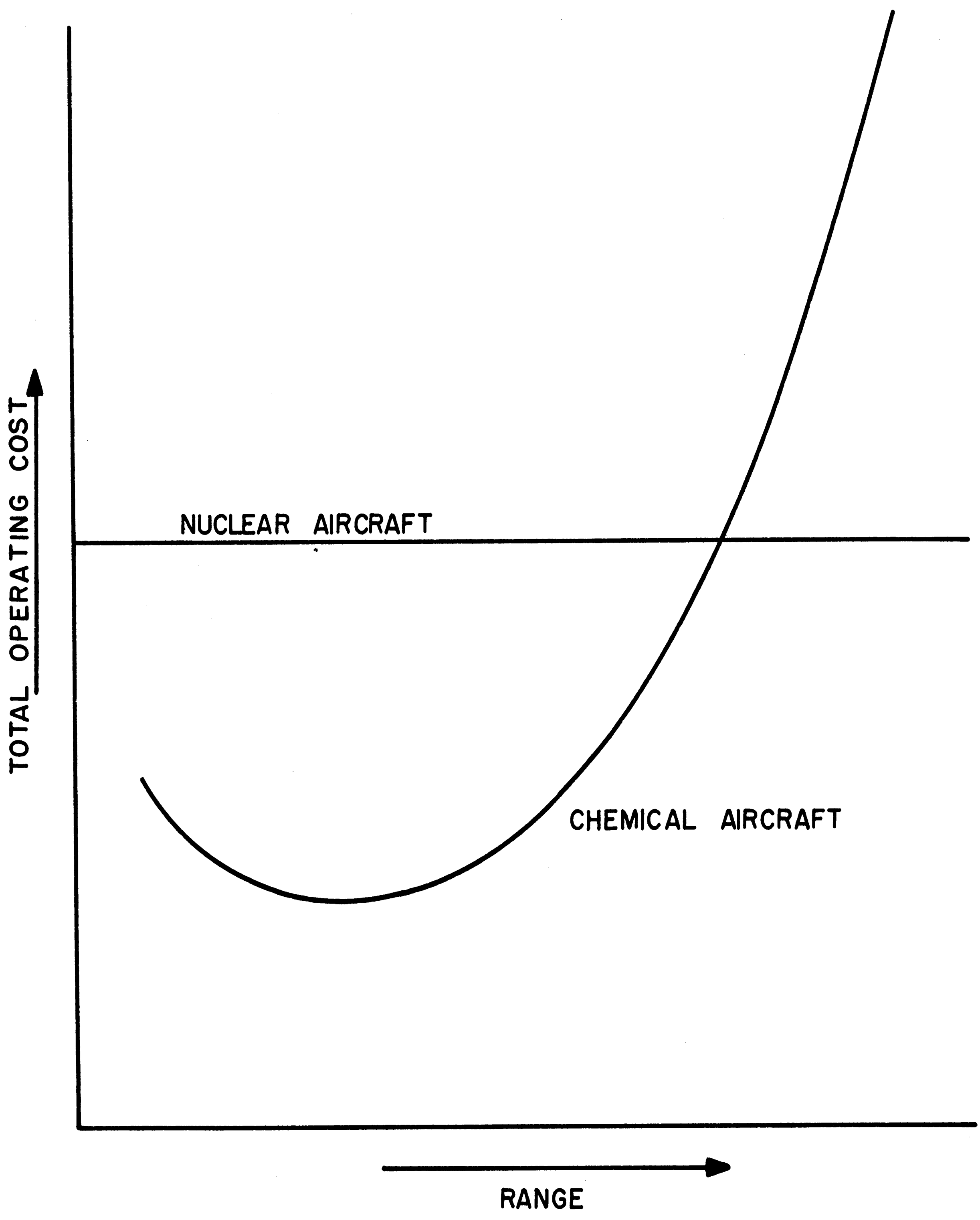
TOTAL OPERATING COST
NUCLEAR AIRCRAFT
CHEMICAL AIRCRAFT
RANGE

FIGURE 1.

required in order to compete with capital costs of approximately 100 dollars per horsepower or 134 dollars per kilowatt for diesel electric locomotives.

At the present time, there is no AEC program directed toward the development of nuclear-powered locomotives. Governmental activity in this field has been limited to a preliminary study initiated by the Army Transportation Corps to determine if any military requirement exists in this field. Decisions as to economic practicality for application of nuclear energy to locomotives would be dependent for some time on the information which evolves from existing military programs for nuclear propulsion of ships and aircraft.

It can be concluded that the practicality of utilizing nuclear energy for the production of electricity for general use and the propulsion energy for naval vessels and merchant vessels has been established. The desirability of applying nuclear power to aircraft propulsion will be determined from results of extensive development toward this goal. Possible advantages that might accrue from the use of nuclear propulsion for land vehicles are still a subject of much speculation. At the present time there are no advantages favoring nuclear power in terms of available range for most civilian land transportation purposes.

CONTROLLED THERMONUCLEAR POWER

Controlled thermonuclear power has potentialities of foremost significance as a usable energy source. The McKinney Report recommends: "1. That the Commission, within the limitations which national security conditions impose, permit the maximum interplay of scientific and engineering ideas, and develop procedures by which more people can contribute to the controlled thermonuclear program in the United States; and 2. that the Commission, in encouraging investments in nuclear fission power, see to it that investors have sufficient information about the feasibility of nuclear fusion power upon which to base determinations for themselves as to the propriety of their investments and actions."[18]

The Reactions

Thermonuclear reactions whose aim is the controlled energy release from fusion of light nuclei has been pursued by the AEC under the Sherwood program. Actively engaged are groups at Los Alamos, Princeton University, Livermore, Oak Ridge, New York University, and others.

Fusion may be defined as the interaction of two light nuclei to form one heavy nuclei with corresponding releases of energy. These reactions require temperatures in the order of hundreds of millions of degrees and must be contained. Certain proposals suggest containing the reaction in electromagnetic fields which may provide insulation effects by proper arrangement. It is conceivable that a fusion reaction could occur without neutron production. Such a reaction could essentially eliminate requirements for shielding.

Russian Thermonuclear Experiments

At Harwell, England, the Russian scientist Kurchatov delivered a dramatic address on April 26, 1956, during his visit to England.[19] He told of the thermonuclear investigations being conducted by academician Artsimovich, and discussed conditions for fusion, control of thermonuclear reactors, theory of the "Pinch" effect, gas discharge experiments, behavior of high-temperature discharges, and neutron production.

NUCLEAR FUELS CYCLES

The fuels cycles for nuclear reactors depend on the type of reactor which is selected and the uses for which it is intended. The three isotopes which will fission in neutron energy ranges presently considered practicable are uranium-235, uranium-233, and plutonium-239. Other materials will fission, but technology has not been developed whereby their use is practicable. Manson Benedict in his paper of November, 1953, discussed in detail the relative merits of various fuels cycles.[20]

Reactors for power might be classified as follows:

1. Power-Only Reactors

The fuel for such a reactor would likely have high enrichments of one of the three isotopes. Unless systems of dynamic nature permitting continuous addition of nuclear fuel and removal only of fission products are developed, reactors for power only must depend on fuel cycles of specified times. The time cycle for a fuel in a reactor depends mainly on the structural stability of fuel and the accumulations of fission products poisons which capture neutrons.

2. Single-Region Power-Convertor Reactors

A power-convertor may be considered as a dual-purpose reactor to produce power and convert fertile materials to fissionable materials. U-238 captures neutrons and through decay converts to Pu-239. Thorium-232 captures neutrons and through decay converts to U-233. When the desired conversion and fissionable isotope specifications are reached, the fuel and fertile materials must be removed and reprocessed for recovery of the converted fissionable materials.

3. Two-Region Convertor Reactor

This type of power reactor is a core-blanket type. The core would be enriched with fissionable materials such as U-235. The reactor can produce power and the fertile materials would convert partially to Pu-239 when the blanket is U-238 or to U-233 when the blanket is thorium-232. Two fuel cycles are involved: (1) for the recovery of materials from the core and (2) for the recovery and separation of fissionable materials from fertile materials and fission products in the blanket.

4. Power Breeder Reactors

A breeder reactor is of the core-blanket type and produces more fissionable material than it consumes. Breeding in the thermal range is probably possible when the fissionable material is U-235 and the fertile material is thorium. Breeding in a reactor which employs plutonium as fuel and U-238 as fertile material is possible only in the "fast" neutron energy ranges. Two fuels cycles are required; one for recovery of fissionable materials from the core and one for the separation of fissionable materials produced in the blanket.

Since fuels for nuclear power reactors are considered as one of the prime economic parameters, major technological advances are requisite to balance costs of fuels preparation, fuels cycles, and values of products produced. For high-cost fuel preparation, long "burn-ups" are desirable provided specification for marketable products can be maintained for specific reactors.

If a sufficient differential of value is sustained between fuels charged to a reactor versus fissionable material produced, the fuels cycle is measured then in terms of such differentials.

General Industrial Uses

Radiation and radioisotopes are being used in many industrial manufacturing processes as well as for special applications in research and development. Radioisotopes provide an important extension to the established techniques in radiographic inspection and non-destructive testing of materials and products. Practical and economically feasible applications of radioactive isotopes have been made for lubrication and wear studies, tracer techniques for the purpose of marking, instruments like the thickness gage for gaging and control, and ionization. Irradiation of materials before, during, or after chemical processing appears to have important possibilities.

Although the nuclear reactor is a source of heat, there appears to be "no immediately foreseeable economic advantage in the use of nuclear fuels for either space heating or process heating in applications where conventional fuels are now satisfactory."[21]

SUMMARY

The feasibility of atomic power has been demonstrated. Much money and effort is still necessary to develop economically feasible and practical atomic power. Atomic power should "be exploited as a source of electric power at a rate consistent with sound technological, economic, and public policy considerations."[22]

Many industrial applications are now practical and it is to be expected that the list will continue to grow rapidly.

Rapid advancement in nuclear technologies is also to be expected, making necessary a frequent re-evaluation of cost parameters and reserves of fossil fuels and of nuclear fuels. Although ownership of all special nuclear materials by the federal government is now desirable and useful, technical achievement and other developements may change at some time in the future the factors motivating federal ownership.

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