THE UNIVERSITY OF MICHIGAN
INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

AUTOMOTIVE NUCLEAR HEAT ENGINES AND ASSOCIATED HIGH-TEMPERATURE MATERIALS

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1.0 INTRODUCTION

Five to ten years ago, few people would have predicted that in 1956 engineers would be building nuclear power plants of 100,000-200,000 kw, or that by 1970, 25% of all new public utility power plants will be nuclear power plants. In England, where the cost of fuel is high and the shortage of both domestic petroleum and coal is acute, the rate of growth of nuclear power plants may exceed that of the United States. Therefore, it may not be out of place to look at the question of nuclear powered vehicles at this time.

Nuclear heat engines can be considered as power plants for vehicles, locomotives, aircraft, and ships. Currently, about 25% of the total energy consumed in the United States is for operation of these types of automotive power plants (16).

Some interesting questions come to mind. How small would a nuclear power source be? How much shielding is necessary? Could one buy an automobile, with its supply of fuel adequate for the life of the car included in the purchase price of the car? How much will nuclear fuel cost? Will enough of it be available? How will it be produced? What is to be gained, in the way of car performance, by having a nuclear power plant?

It is conceivable that a nuclear power source could be very small if only the fissionable material needed to be considered. If the average life of a vehicle is 160,000 miles, the average speed 40 mph, the average horsepower 25, and the average hydrocarbon fuel cost 2.5 cents per mile, then the total cost of fuel for the life of the vehicle is $4,000, and the energy used is 100,000 HP-hours or 75,000 kw-hours. One gram of U-235 is capable of producing 1 megawatt day. In addition to requirements for critical mass for a given geometry and fissionable atoms necessary to overcome neutron losses to absorbing materials, about 300 gms. or 2/3 of a pound of nuclear fuel is required if used in an engine of 25% efficiency for the life of the vehicle. To compete with the cost of hydrocarbon fuel at 2 1/2 cents per mile for the conditions mentioned, the nuclear fuel's cost must approximate $13.00 per gram.

With our present knowledge of nuclear energy, fission fuel replaces fossil fuel in a nuclear power plant. The nuclear fuel is merely a substitute source of heat energy. As long as heat energy is used to produce mechanical power, one is confronted with the Second Law of Thermodynamics, which is at once discouraging. It tells us that, unless we can use the heat energy at higher temperatures than present experience allows, we can convert only a limited amount of heat energy to mechanical energy. The maximum temperature that is useful is that determined by the metallurgy of engineering materials; concomitant factors such as heat removal, conservation of neutrons, sizes of reactor vessels and attendant equipment coupled with neutron and radiation shields necessitate massive structures. Thus, achievement of a nuclear heat source for automotive purposes is dependent largely upon successful developments of materials of construction.

However, before looking at materials, a few observations on possible engine power plants are in order. One must accept the ambient temperatures of the atmosphere as the lowest practical temperature at which heat energy can be rejected in any kind of a heat power cycle. If 40°F is this heat rejection temperature, then the maximum efficiency for conversion of heat energy into work varies with the heat source temperature as shown in Figure 1. This is the efficiency of any reversible cycle. However, all practical cycles are not reversible cycles, and therefore, they have a lower efficiency than the solid curve of Figure 1. The dotted curve, for example, shows a comparable ideal Rankine cycle efficiency using steam without superheat. Actual cycles with component efficiencies less than 100% will have cycle efficiencies as low as one-half of the ideal efficiencies shown in Figure 1. The most efficient steam power plant built in the United States has an efficiency of 37%; highly developed diesel engines have efficiencies of about 40%.

Thus, one is faced with the problem that from 60 to 75% of the heat supplied to the power plant, whether it be from combustion or fission, must be rejected to the atmosphere. In present reciprocating engines and open-cycle gas turbines this is easily accomplished by using air as the working medium and discharging the exhaust to the atmosphere, thereby replenishing the oxygen for combustion and rejecting the unavailable heat to the atmosphere. In any closed-cycle plant, whether using gas or a vapor, the unavailable heat must be transferred from the working medium to the atmosphere. This necessity entails either large heat exchangers or large temperature differences. If large temperature differences are used, the heat rejection temperature is made higher and the cycle efficiency is lowered, or higher source temperature is required; the latter is affected by the ability of engineering materials to sustain higher temperatures. In any closed-cycle power plant, the heat rejection equipment is likely to require more bulk and weight than the prime mover. This is especially true if air is the immediate receiver rather than water. The desirability of using a condenser on steam locomotives was recognized for many years, yet even here, where the carrying of large heavy auxiliaries was possible, it was never done. This practical difficulty alone could prevent the development of nuclear power plants for many automotive applications. One solution is to use an open-cycle power plant and transfer the heat from the reactors to a working fluid which is unaffected by radioactivity. The second difficulty arises from the amount of shielding required for protection of people from radioactivity. Exposure to even minute amounts of gamma radiation over extended periods of time can have an eventual biological effect on personnel.

The U. S. Atomic Energy Commission reports that energy requirements for transportation can be expected to increase proportionally with the over-all growth of energy needs. The Commission has recognized, early in its programs, the possibilities for applying nuclear power to propulsion. This work, to date, has been limited to military applications.

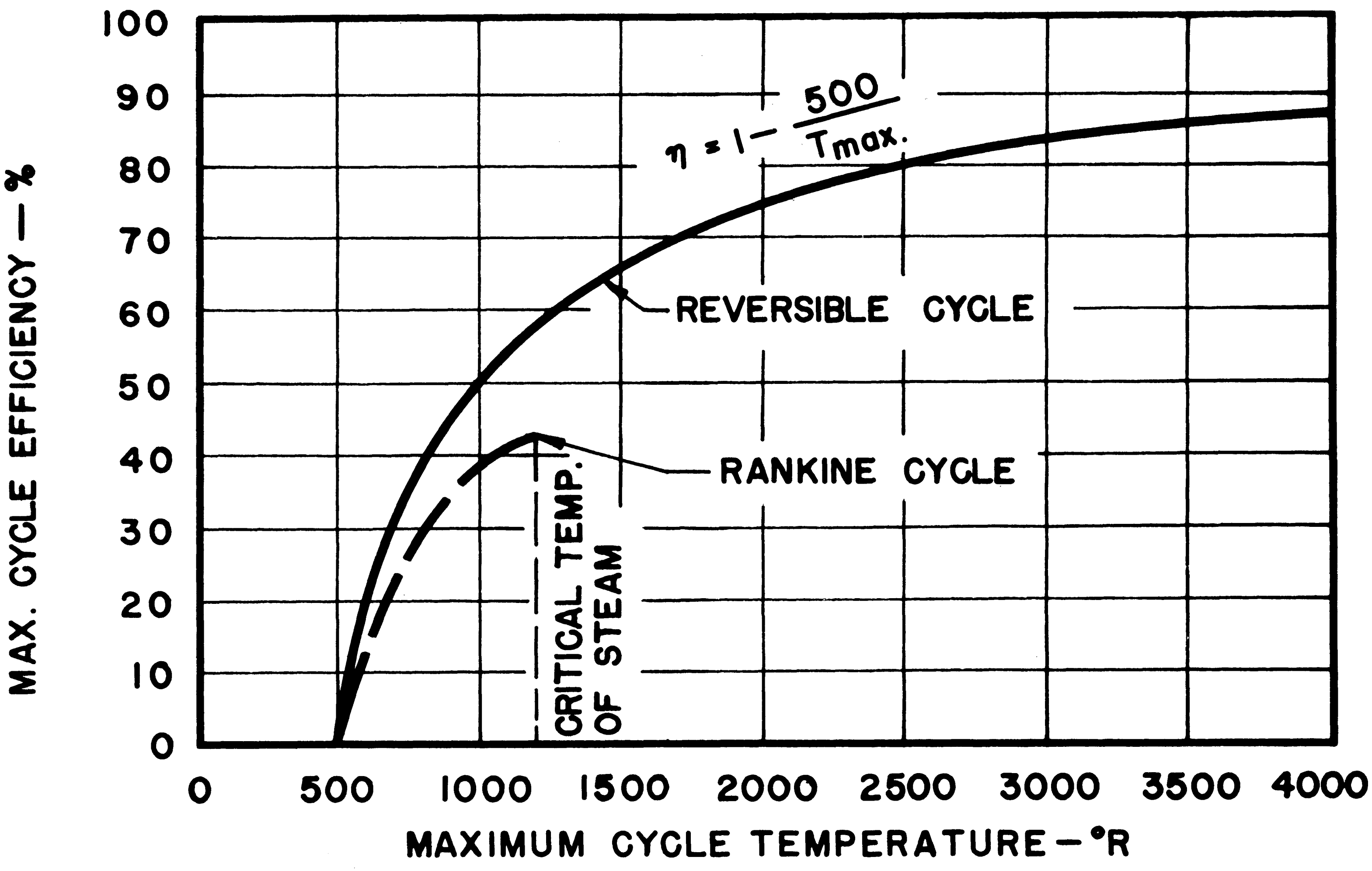

FIG. I HEAT POWER CYCLE EFFICIENCY

In its recent report to the Joint Committee on Atomic Energy, the following conclusions were presented:

1.1 Nuclear energy, as applied to merchant ships, can become a significant source of power within the next ten to fifteen years, depending upon the relative competitive position of nuclear power as well as upon necessities of atomic propulsion for the American merchant fleet.

1.2 The use of the nuclear power systems for aircraft appears to be technically feasible in terms of foreseeable technology; the impact of nuclear power upon commercial aviation does not appear to be likely for many years.

1.3 The use of nuclear energy for locomotives has apparent technical feasibility now, but economically competitive locomotives are not foreseeable.

1.4 Atomic-powered motor vehicles such as cars, buses, or trucks require major technological breakthroughs not now in sight.

A series of mobile power reactors are currently being developed. Two submarine reactors have been built, and several more are in design stages. Reactors for aircraft are being developed by the U. S. Atomic Energy Commission and the Department of Defense (9). The development of mobile nuclear heat power systems for aircraft, for merchant ships, for submarines, for locomotives, and for other vehicles faces a fundamental need for major breakthrough in new materials whose nuclear properties must be coordinated with the chemical and physical properties not now available to automotive engineering practices.

Those basic economic data which will determine the eventual competitive role of nuclear energy are some of the major parameters requiring definition and development. This paper is being presented as an evaluation of current reactor technology and associated high-temperature materials development in light of some requirements for automotive nuclear heat engine applications.

Although high-temperature materials have always been a problem in the design and construction of nuclear reactors, the problem has never been as critical as it now is in the development of automotive nuclear heat engines. In this case, weight of the nuclear-heat-power source associated with a heat engine is of paramount importance. In addition to requirements of materials of unprecedented purities for successful operation of nuclear fuels, the same problems of containment of high-temperature operations which the automotive industry has met for many year in chemically fueled engines are present in nuclear heat engines.

Progress in the development of automotive nuclear heat engines depends to a major extent on achieving new types of reactor fuels, new types of nuclear reactor containers, new types of coolants and working fluids for heat engines, and new types of materials for biological shields and other components.

It is hoped that this presentation will be helpful in outlining the current status in light of future needs and requirements so that research and developmental objectives become more apparent.

2.0 NUCLEAR FISSION

An atom is the smallest particle of matter which retains its chemical and physical properties. However, it is made up of many smaller particles. An atom may be thought of as a minute solar system with a nucleus taking the place of the sun, and surrounded by electrons which move about in orbits or shells much as planets move around the sun. The nucleus is made up of protons and neutrons. The neutrons differ from the protons in that they have no electrical charge, whereas the protons have a positive charge equal to the negative charge of an electron. The mass of a neutron or proton is roughly 1800 times the mass of an electron.

Several of the lightest and simplest atoms may thus be pictured as shown in Figure 2. The mass of the atom is nearly all in the nucleus, and the total positive charge of the protons in the nucleus offsets the total negative charge of electrons surrounding the nucleus.

The chemical properties of materials depend on the electrons outside the nucleus. These contain relatively small amounts of energy, so that the energy of combustion when fuels burn is relatively small compared to the energy released when the nucleus is disrupted. In the early days of atomic studies, charged particles such as protons and alpha particles (helium nucleus) were accelerated to high velocities by passing them between enormous magnets. By such means, enough energy was given to such particles to penetrate and affect a physical change in the nucleus. Then, however, certain radioactive elements such as uranium were found to emit particles of their own volition with enough energy to disrupt the nucleus. One of these particles is the neutron.

Neutrons from a radioactive element may do one of several things. They may hit the nucleus of an atom and be absorbed, thereby creating a new isotope or element; they may cause the nucleus they hit to break into two fragments, thereby producing two new elements of lighter weight (this process is called fission); or the neutron may pass out into space and be lost.

Isotopes are atoms of the same element having same chemical properties but different masses in their nucleus. In Figure 2, two isotopes of hydrogen are shown. Each has one orbital electron; but heavy hydrogen has one proton and one neutron in the nucleus whereas ordinary hydrogen has only one proton in the nucleus. The subscript denotes the atomic number and identifies the element; it is equal to the number of orbital electrons outside the nucleus and the number of protons inside the nucleus. The superscript is the mass number and denotes the total number of protons plus neutrons in the nucleus; it is proportional to the mass of the atom.

A graphical representation of the fission process is shown in Figures 3 and 4. Figure 3 illustrates an incident neutron colliding with a nucleus of uranium-235, making the nucleus unstable as illustrated in

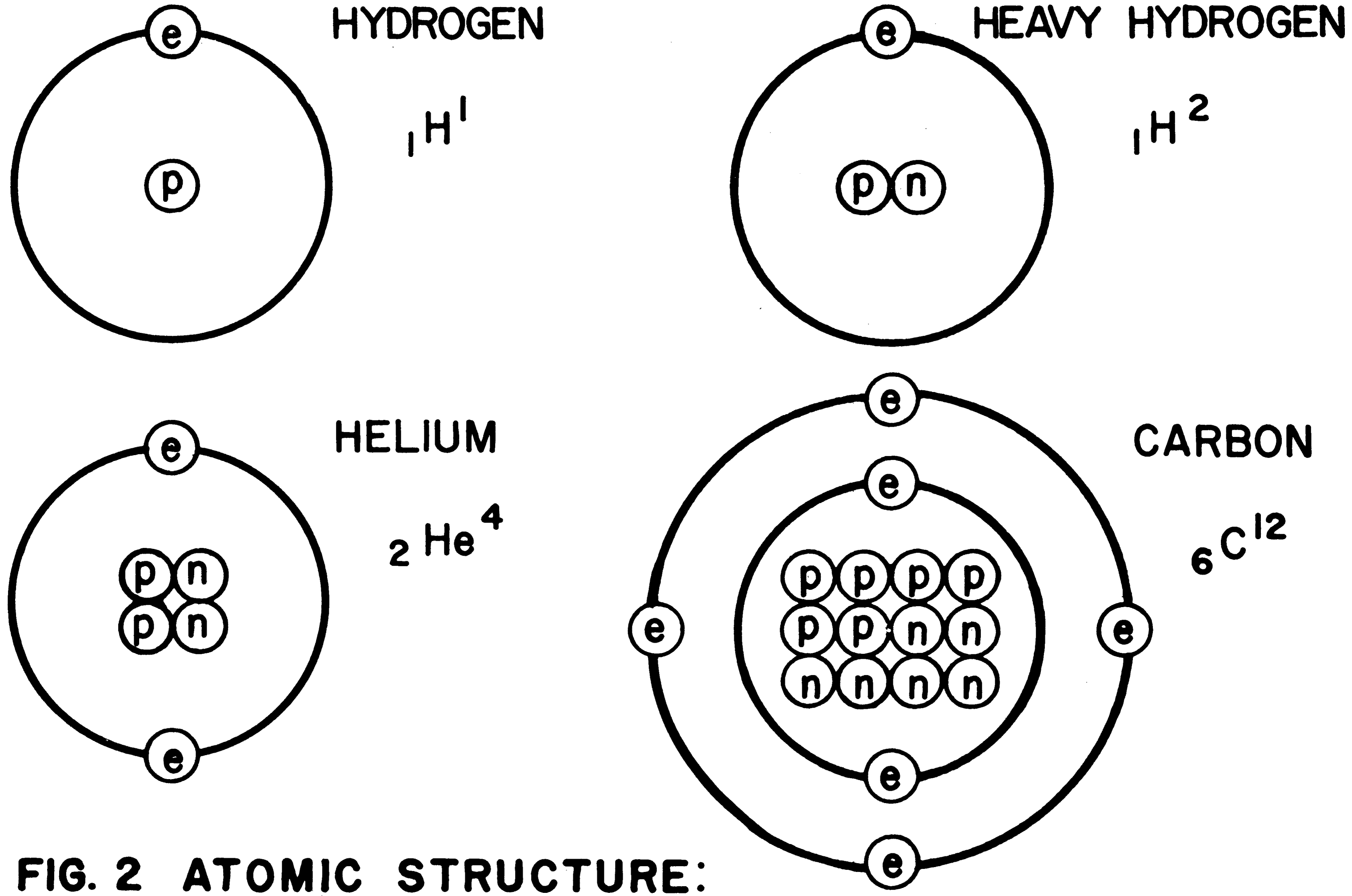

FIG. 2 ATOMIC STRUCTURE:
HYDROGEN, HEAVY HYDROGEN, HELIUM, CARBON

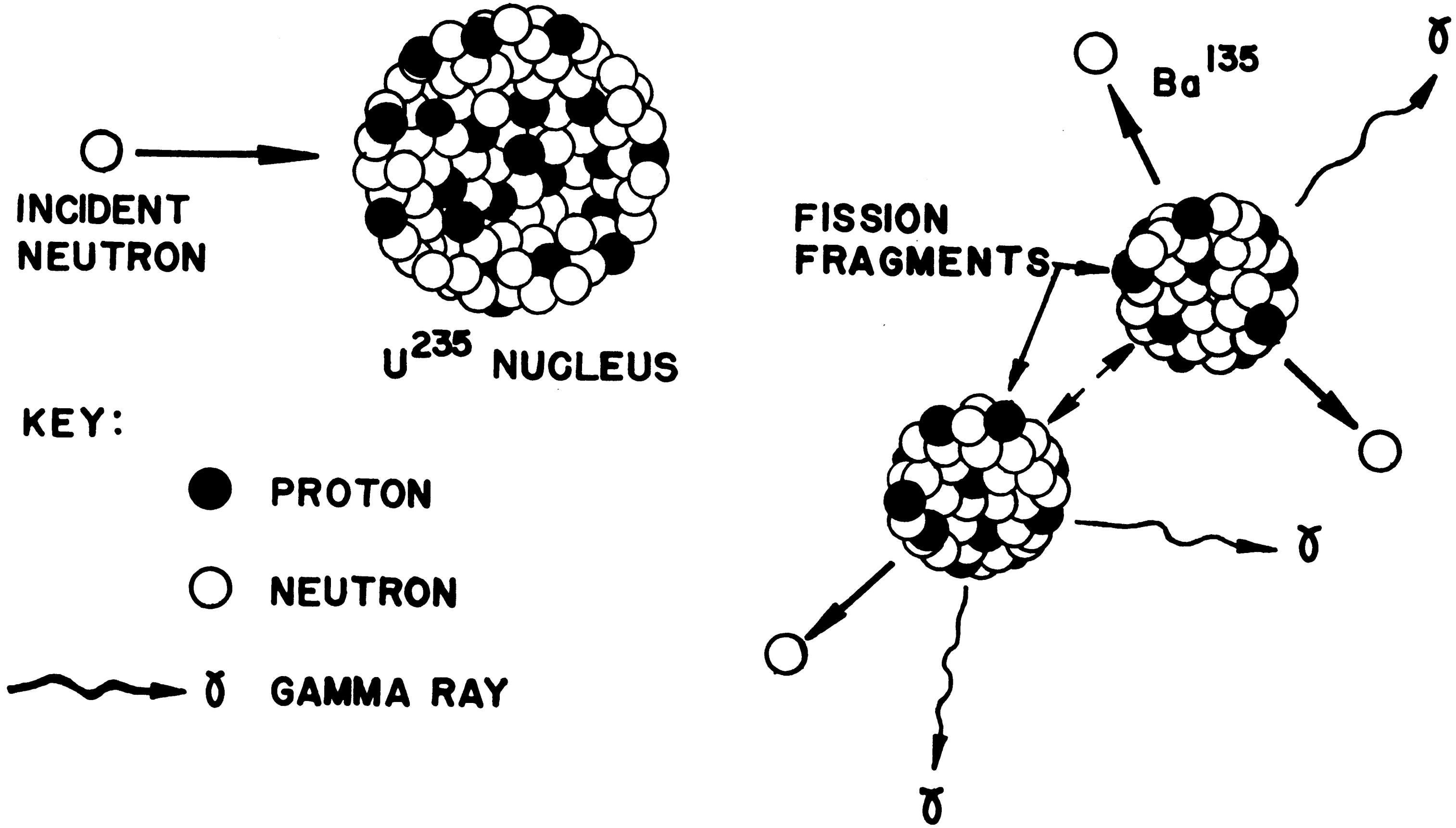

FIG. 3 FISSION OF U^{235} NUCLEUS *

* REF. 13

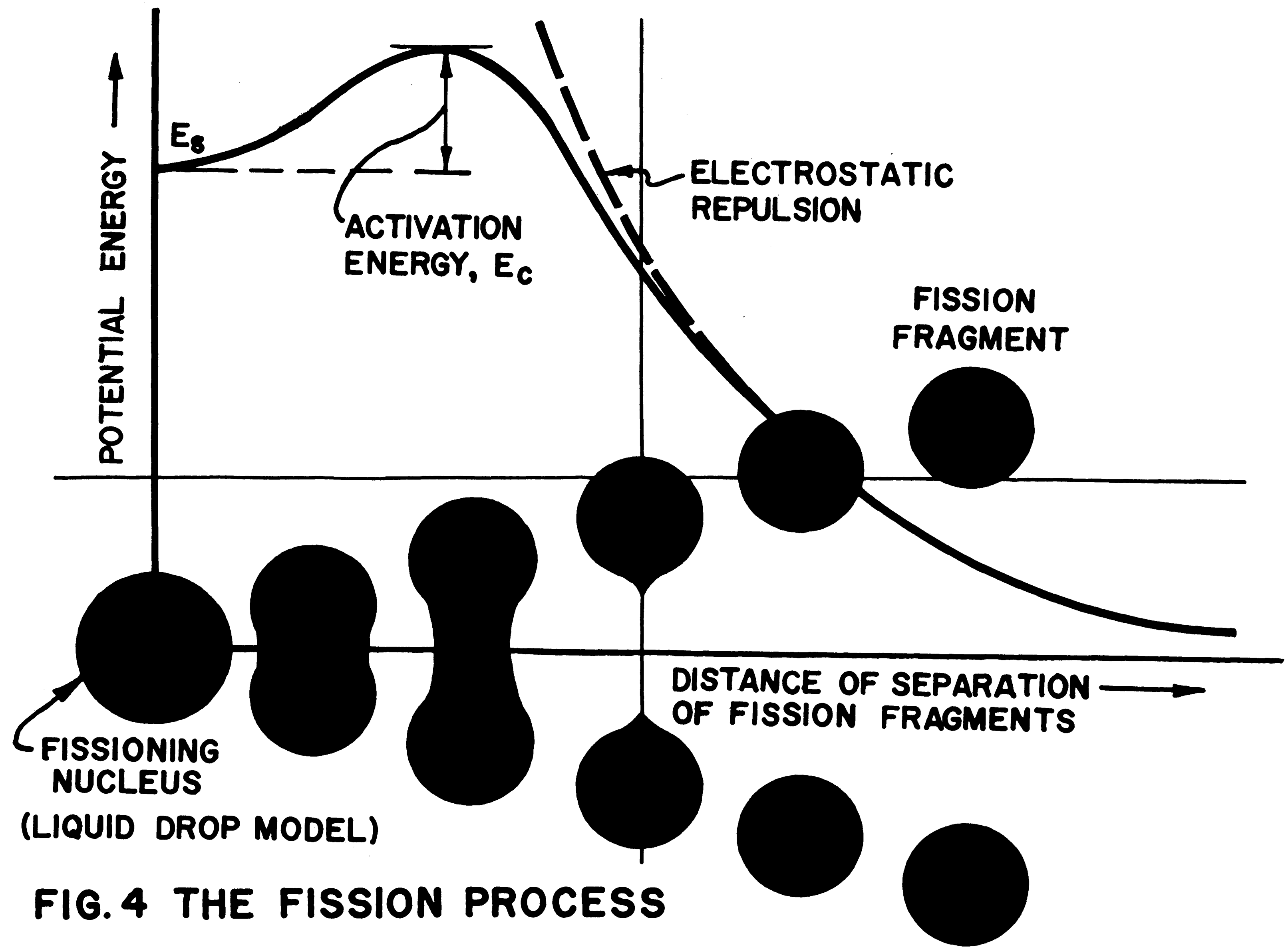

FIG. 4 THE FISSION PROCESS

Figure 4. The products formed by the fission process are:

2.1 Energy equal to 192 Mev per atom, about 3×10^{10} Btu per pound.

2.2 Neutrons equal to between 2 and 3 per fission (on average, 2.5 for U-235).

2.3 Fission products--about 60 primary products which, through decay, produce about 300 different isotopes which range from mass number 80 to mass number 60.

2.4 Beta particles which are high-speed electrons.

2.5 Gamma rays, which are extremely hard x-rays, have high penetrating power, and are hazardous to health.

As an example, consider the fission of the nucleus uranium-235. This nucleus can be regarded as a cluster of 92 protons and 143 neutrons. If this cluster absorbs or captures a neutron, it becomes unstable. The energy which was available to hold the original cluster together is insufficient, and the unstable cluster breaks up into two or more new clusters. These new smaller clusters become the nuclei of lighter elements.

The production of two to three neutrons for each neutron captured by a nucleus means that, if additional atoms of uranium-235 are in proximity to the neutrons released by the original fissioning nucleus, they will capture such neutrons and also undergo fission. These atoms also release two to three neutrons per atom fissioned so that a chain reaction becomes possible.

A chain reaction of this type in which neutron production can be controlled can produce useful energy.

Control of a chain reaction is possible by controlling the number of neutrons which can be captured by fissionable atoms at any given instant. The number of neutrons can be controlled by insertion of suitable neutron absorbers into proper locations in a fissioning mass of fuel. The control of the amount or number of neutrons which are absorbed by materials that do not fission is a means of setting a predetermined power level of operation.

The probability that neutrons will be captured by nuclei depends on the speed of the neutrons. The velocity of neutrons emitted in fission is very high, too high to be useful in producing additional fissions in some elements. They may be slowed down by impact with lightweight atoms such as hydrogen, helium or carbon. At lower speeds they readily penetrate the nucleus of atoms and cause fission. So called thermal neutrons are relatively slow speed neutrons having velocities about the same as hydrogen molecules at room temperature. Thermal neutrons have the highest probability of producing fission in U-235.

The chance of collision between a neutron and a nucleus is defined by the nuclear cross-section. The nuclear cross-section is not the actual dimension of the nucleus but an area of influence around the nucleus, such that if a neutron comes within that area, capture or fission will take place. The effect of radioactivity on materials is therefore closely related to the nuclear cross-section. It becomes a nuclear property similar to physical properties of density, stress, etc.

Before a self-sustaining fission process is possible, a certain minimum quantity known as critical mass must be present. The amount required is determined by the probability that neutrons will be captured by fissioning atoms as compared to the probability that neutrons will escape and be absorbed elsewhere. Thus, a critical mass is interdependent upon a critical geometry. The energy released per atom fissioning is large. Table I indicates the amount and distribution of energy due to fission.

TABLE I. ENERGY OF FISSION

	Mev per Fission	Kilowatt hours per Fission
Energy available immediately after the fission process:		
Kinetic energy of fission fragments	162	
Kinetic energy of prompt neutrons produced in the fission process	6	
Energy of instantaneous gamma rays	6	
Energy from absorption of excess neutrons produced in the fission process which are captured in non-fission processes by reactor materials	8	
Total	182 Mev	8.08×10^{-18}
Energy which appears as the fission products decay:		
Energy from fission product gamma rays	5	
Energy from fission product beta particles	5	
Total energy available	192 Mev	8.52×10^{-18}
Unavailable energy:		
Energy carried away by neutrinos accompanying the fission product beta decays	11 Mev	0.488×10^{-19}

3.0 CONSTRUCTION MATERIALS FOR NUCLEAR-HEAT-POWER REACTOR SYSTEMS

Materials used for construction of nuclear-heat-power reactor systems require unique nuclear properties in addition to conventional engineering properties such as corrosion resistance, strength, ductility, stress and thermal properties.

The engineer involved in development engineering and operation of power reactors might be classified under the following general headings: (1) nuclear fuels; (2) moderators and coolants; (3) reflectors; (4) control rods; (5) vessels, mechanical equipment, piping, etc.; (6) shielding.

Materials in these classifications are subject to interactions with radiation and nuclear particles. Alpha particles, beta particles, gamma rays and neutrons produce chemical and physical changes in materials (2, 4, 19). Such interactions are referred to, oftentimes, as radiation damage.

3.1 Nuclear Fuels

For technologies in the reasonable future, it can be expected that any mobile nuclear-heat-power sources will depend upon one of the following materials as the fuel to sustain the fission process: (1) uranium-235 (found in nature); (2) uranium-233 (artificially made by neutron capture in thorium-232); (3) plutonium-239 (artificially made by neutron capture in uranium-238).

Reactor fuel assemblages can be solids, liquids, and possibly gases. Most reactors undergoing present-day development have their fuels in solid form. Several promising new types of compact design have their fuels in liquid form. If the fuel is in solid form, the elements may assume shapes as rods, tubes, and flat plates. The fuel elements are arranged so that coolants can extract the fission energy in the form of heat energy.

A diagrammatic arrangement of solid fuel element configuration which indicates passages for coolant, moderator, and space for control rods is shown in Figure 5.

To prevent the fuel element in Figure 5 from being corroded by the coolant and to contain highly radioactive fission products in the fuel element, the fissionable fuel is clad or jacketed. Examples of cladding materials which have suitable nuclear, thermal, and structural properties for nuclear-heat-power units are aluminum, zirconium, and stainless steel.

A liquid homogeneous fuel can be formulated in one of three ways, as follows: (1) an aqueous solution of a fissionable salt; (2) a fused salt in molten form; (3) a molten metal of the fissionable material or some alloy thereof.

Certain reactor concepts employing high-temperature liquid

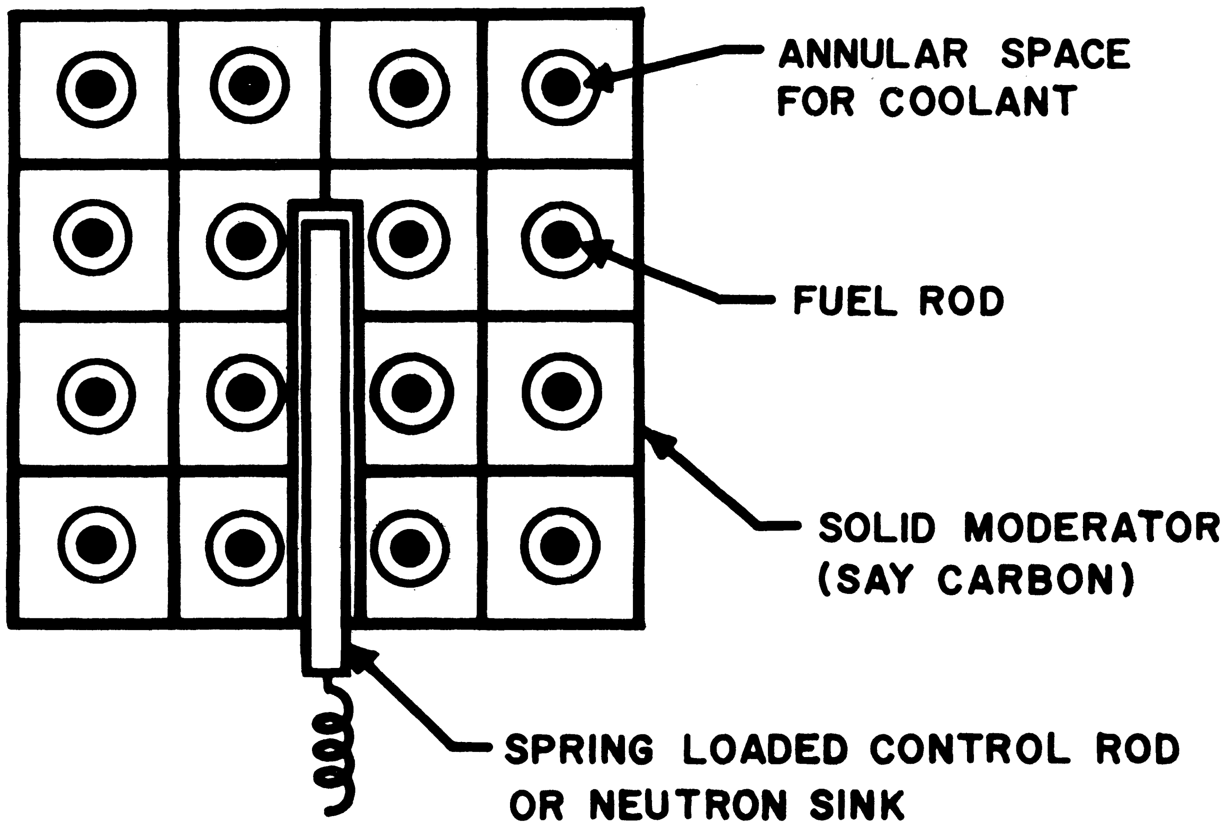

FIG. 5 REACTOR CORE – SOLID FUEL ELEMENTS

fuels with suitable heat transfer means may offer considerable promise for several applications of automotive nuclear heat engine systems.

3.2 Structural Materials for Heterogeneous Fuels

Reactor fuel elements are units which, when assembled in suitable mass and geometry in a nucleus, have contained fuel materials undergoing fission. Fast neutrons, beta particles, gamma rays, and fission fragments are generated in a fuel element during fission (19). Materials used for fabrication of fuel elements must have certain nuclear, chemical and physical properties (9).

Requisite nuclear properties are low neutron absorption cross-sections and minimum changes due to radiation.

Desirable chemical properties are resistance to oxidation and corrosion.

Desirable physical properties are high mechanical strength, high heat capacity and low thermal shock.

3.2.1 Zirconium

Zirconium can serve as a material to clad fissionable fuels. In water cooled power producing reactors, zirconium has desirable properties up to temperatures of 800°F (7).

Zirconium has chemical properties similar to hafnium, titanium, and thorium. Table II gives a summary of properties for these materials.

As a fuel cladding material, it is not attacked severely by water or oxygen at high temperatures. The mechanical properties of zirconium metals and its alloys permit it to meet requirements for reactor fuels.

3.2.2 Stainless Steels

Stainless steels have higher neutron absorption cross-sections than zirconium.

The chemical and physical properties of the stainless steels are suitable for power producing reactors. Minor impurities influence these properties.

Irradiation effects in uranium and its alloys (15) produce dimensional changes due to thermal cycling and structural variables. Irradiation damage is minimized by proper fabrication techniques.

TABLE II. PROPERTIES OF IV-A SUBGROUP ELEMENTS

Element	Ti	Zr	Hf	Th
Molecular Weight	47.90	91.22	178.6	232.12
Principal Valance	4	4	4	4
Other Valences	3,2	3,2	3,2	3,2
Metal-Density, gm/cc.	4.50	6.4	12.1	11.4
M. Pt., °C	1725	1857	2227	1730
Sol'y of oxygen in metal	$>1\%$	$\sim 1\%$	$\sim 1\%$	$<0.1\%$
Melting Point of Oxides, °C	1825	2677	2774	3050
Tetrafluoride				
M. Pt., °C		~ 900	~ 900	~ 1000
B. Pt., °C	284	~ 900	~ 900	~ 1700
Tetrachloride				
M. Pt., °C	-23	437	432	765
B. Pt., °C	136	331	317	922

TABLE III. EFFECT OF IRRADIATION ON THE STRENGTH PROPERTIES OF STANDARD 0.250" DIAMETER URANIUM TENSILE BARS*

Description of Specimen	Ultimate Strength		Yield Strength		% Elongation		Young's Modulus
	(1000 psi)	% Change	(1000 psi)	% Change	(1" Gauge)	% Change	(10^6 psi)
Control Specimen	104	-	33	-	17	-	25
Irradiated at 120°C to 0.035% atom burnup	76	-27	71.5	117	0.36	-97.9	28
Irradiated, annealed 15 hours at 400°C in vacuo	65	-38	52	58	0.54	-96.8	-
Irradiated, hot tensile at 285°C	71	-32	70	112	0.7	-95.9	12

*Reference 15

Table III presents some effects of irradiation on the strength properties of standard 0.250 diameter uranium tensile specimens.

3.3 Moderators

A large amount of the energy released during fission is in the form of velocity. In "thermal" power reactors, it is necessary to provide means for reducing the velocity of neutrons to such speeds that increase the probability that they will be captured by other fissioning nuclei.

Moderators are materials which slow down velocities of neutrons. Slowing down is accomplished by collisions between neutrons and the moderating material. The best types of moderators are those which have nuclei of masses which most closely approach the masses of neutrons. Thus, hydrogen is a good moderator.

In Table IV, relative moderating ratios are given for water, heavy water, beryllium, graphite, sodium and a sodium-potassium eutectic. For illustration, the moderating ratio for light water is 1.0. Thus, heavy water, beryllium and carbon are all relatively better moderators from a nuclear viewpoint than light water, whereas sodium, and sodium-potassium liquid metals are very poor moderators. Some general properties of materials found to be good moderators are given in Table V (11, p. 60).

TABLE IV. MODERATORS*

	Relative Moderating Ratio
H_2O	1.0
D_2O	87.0
Be	2.4
C (graphite)	2.5
Na	0.006 (poor)
NaK	0.002 (poor)

*Reference 12

TABLE V. PROPERTIES OF MODERATORS

	Material				
	H_2O	D_2O	Be	C	BeO
Density	1.00	1.10	1.84	1.60	2.80
Atomic or Molecular weight	18	20	9	12	25
Atoms/cm^3 or molecules/cm^3	3.3×10^{22}	3.32×10^{22}	1.23×10^{23}	8.05×10^{22}	6.75×10^{22}
σ_a at 0.025 ev, barns	0.66	0.92 mb	9 mb	4.5 mb	9.2 mb
σ_s at 0.025 ev, barns	110	15	6.9	4.8	11.1
Epithermal σ_s, barns	46	10.5	6	4.8	9.8
Moderating ratio	67	5820	160	169	180
Slowing down length, cm	5.7	11.0	9.9	18.7	12.0
Slowing down time, sec.	10^{-5}	4.6×10^{-5}	6.7×10^{-5}	1.5×10^{-4}	7.8×10^{-5}
Albedo (infinite)	0.82	0.97	0.89	0.93	0.93

3.4 Coolants

Heat removal from a nuclear-heat-power source is one of the controlling engineering parameters for automotive nuclear heat engine systems. In reactor development programs underway, the media used for coolants would be water, air, and liquid metals.

The heat produced per unit volume in a nuclear-heat-power unit can be made as high as permitted by maximum working temperatures for construction materials and reactor fuels. Heat transfer surfaces can control the size of a nuclear heat source. Thus, a coolant which has low probabilities for neutron capture must have the ability for good heat transfer and the withstanding of high temperatures.

Some properties of coolants are given in Table VI (11, page 66). Table VII (11, page 66) gives some heat transfer data for reactor

TABLE VI. PROPERTIES OF COOLANTS*

	Thermal Neutron Cross Section				
	Microscopic (barns)		Macroscopic Absorption Cross Section		
Coolant	Absorption	Scattering	at 650 F(cm^{-1})	Melting Point ^{o}F	Boiling Point ^{o}F
H_2O	0.602	164	0.0079	32	212
D_2O	0.92 mb	15.3	0.000037	38.87	214.7
Na	0.45	4	0.0074	208	1621
Na-K alloy (44% K)	1.1	3.2	0.0113	66.2	1518
K	2.5	1.5	0.0166	147	1400
Bi	0.015	9.0	0.00059	520	2691
Bi-Pb alloy (44.5% Pb)	0.17	9.9	0.0021	257	3038

*Reference 11

TABLE VI. PROPERTIES OF COOLANTS
(Continued)

Coolant	Operating Pressure psia	Density (lb/ft^3)			Specific Heat ($Btu/lb-^{o}F$)		
		$100^{o}F$	$500^{o}F$	$1000^{o}F$	$100^{o}F$	$500^{o}F$	$1000^{o}F$
H_2O	14.7	62.0			0.9976		
D_2O	1500		48.6			1.165	
Na	14.7		55.3	51.1		0.3150	0.3005
Na-K alloy (44% K)	14.7	56.1	52.9	48.7	0.2733	0.2583	0.2486
K	14.7		48.7	44.6		0.19	0.18
Bi	14.7			608			0.0369
Bi-Pb alloy (44.5% Pb)	14.7		646	624		0.035	0.035

coolants as a function of flow velocity.

TABLE VII. COOLANT PROPERTIES**

Coolant	Relative Absorption Cross Section	Heat Transfer Coefficient	Pumping Power for Equiv. Heat Removal/°F*	Cost per lb.
H_2O	215	1000	1	$.10/1000 gallons
D_2O	1	1000	1	$28
Na	200	5000	3	$0.16
NaK	305	4000	5	$2.00

*Same temperature difference assumed. **Reference 12

Some of the coolant properties which require consideration for a specific reactor are given in Table VII. For the four possible coolants listed, the first column lists the relative absorption cross-section for neutrons assuming heavy water = 1.0. The heat transfer coefficient (film coefficients) which can be achieved for practical fluid velocities with suitable allowance for fueling are given in the second column. Considering differences in densities for comparable hydraulic heads, the relative pumping powers for each of the four coolants are given in the third column.

Since economics are important considerations in industrial reactor design, engineers must consider the relative costs of the various materials.

3.5 Neutron Reflectors

Neutrons produced in the fission process are used in a nuclear-heat-power system for sustaining the nuclear chain reaction and for control. As the size of the nuclear heat source is reduced, the ratio of surface to volume of the critical geometry increases. Thus, the probability of neutrons escaping from the system increases.

A reflector material is one which permits the neutrons, tending to escape from critical volume, to collide without absorption in such a manner that the neutrons return to the critical volume at the energies required to prompt fission.

3.6 Reactor Control

Control of a chain reaction at desired power level is accomplished by controlling neutron absorptions at rates which do minimize power surges, but do not shut down the reactor.

Control of neutron absorption can be achieved by controlling amounts of fission products at any given time in the reactor by the insertion of control rods, "shim" and scram rods, and by controlling the amount of neutron reflection.

Safety and assurance of reactor control are enhanced for thermal reactors since delayed neutrons are produced in sufficient quantities and over long enough periods of time to permit operation of control mechanisms.

3.7 Structural Materials

Choice of reactor structural materials depends upon size and type of reactor, the intended service and operating temperature. Reactors which operate with thermal neutron energies can use only material with low absorption cross-sections.

Reactors which operate with fast neutron energies permit selection of a wide variety. The economic design of power reactors to operate at high temperatures limits the selection of structural materials.

In regions of the reactor where neutron intensities are high, expensive materials such as zirconium are required. The vessel containing fuel, moderator, coolant, and reflector materials can be of more ordinary materials, such as stainless clad carbon steels, etc.

Materials as known to engineers today require compromises for reactor size, operating temperatures, fuel inventories, and economic parameters.

Table VIII presents some properties of structural materials. These properties include thermal neutron absorption cross-sections.

3.8 Neutron Shields

For safe operation of a nuclear-heat-power unit, provisions are needed to absorb all neutrons that tend to escape from the nuclear heat source. Such absorption of escaping neutrons is accomplished by neutron shields.

Neutron shielding materials must have nuclear properties which "slow down" fast neutrons and absorb slow neutrons. The neutron absorption process generally results in release of gamma rays. Thus, neutron shield materials are located and contained within materials provided for gamma shielding. Table IX (11, page 77) indicates some satisfactory neutron shielding materials and the thicknesses of shields needed to reduce neutron intensities to 1/10 the value of incident neutrons (1).

TABLE VIII. PROPERTIES OF STRUCTURAL MATERIALS*

ELEMENT	THERMAL NEUTRON ABSORPTION CROSS SECTION (Barns)	DENSITY (Grams/ cm^3)	MELTING POINT (°C)	SPECIFIC HEAT (Cal./gm -°C)	THERMAL EXPANSION COEFFICIENT (Per °Cx10^6)	MODULUS OF ELASTIC-ITY (10^6psi)	HARD-NESS (BHN)	TENSILE STRENGTH (10^3 psi) Annealed	Cold Worked
Aluminum	0.22	2.70	660.2	0.22	24	10	20-25	13	24
Beryllium	0.010	1.85	1,300	0.5	12	42	110	45	--
Magnesium	0.059	1.74	651	0.25	--	6.5	50	32-46	32-50
Molybdenum	2.4	10.2	2,620	0.065	5.5	40-50	147	100	250
Nickel	4.5	8.9	1,455	0.11	13	30	75	47	125
Tantalum	21	16.6	2,996	0.036	6.5	27	75-125	50	125
Titanium	5.8	4.5	1,725	0.129	8.5	16.8	200	80	122
Vanadium	4.8	6.02	1,735	0.12	--	20-22	260	--	---
Tungsten	19	19.3	3,410	0.034	4.0	50-60	260	50	300
Zirconium	0.18	6.5	1,830	--	5.0-5.8	12	---	35	85
18-8 Stainless Steel (Fe, Cr, Ni, Mn, Nb)	2.9	7.92	1,400-1,420	0.12	16.7	29	160	90	---
Inconel "X" (Ni, Cr, Fe, Ti, Nb)	4.1	8.3	1,400-1,420	0.11	13.9	31	200-400	160-180	--

*Reference

TABLE IX. NEUTRON SHIELDING DATA

Neutron Energy	Shielding Material	Σ cm.$^{-1}$	Thickness to Reduce Intensity by 1/10, cm
1 Mev	Hydrogen (in water)	0.281	8.2
	Oxygen (in water)	0.268	8.6
	Lead	0.178	13
10 Mev	Hydrogen (in water)	0.064	36
	Oxygen (in water)	0.050	46
	Lead	0.165	14

3.9 Gamma and Beta Shielding

The fission products and "capture" products resulting from fission are highly radioactive. The radioactivity is released in the form of gamma rays and beta particles. Reactors, therefore, must be shielded (biological shields) to protect life.

The absorption of beta particles (high-speed electrons) is accomplished by many materials with relative ease. The only known material capable of intercepting gamma rays, which are high frequency, short wave-electromagnetic waves similar to x-rays but much "harder," is dense matter.

Table X presents some structural materials used as gamma and beta shields and the reported densities in gm/cm.

TABLE X. SOME STRUCTURAL MATERIALS FOR GAMMA RAY AND BETA PARTICLE BIOLOGICAL SHIELDS*

Category	Composition	Density H_2O = 1.0
Concrete	Cement, Sand, Gravel	2.3
Barytes Concrete	Cement, Barytes	3.5
Iron Ore Concrete	Cement, Iron and Iron Aggregate	6.0
Cast Iron		7.85
Lead		11.2
Uranium		19.0
Thorium		11.4

*Reference 11, p.78.

The greater the power output of a nuclear heat engine, the greater is the mass of shielding matter that must be provided for tolerable health dosages at the surface of a shield.

Even though it might be possible to develop a nuclear heat source and power plant, which is light in weight and small in size, the size and weight of shielding materials surrounding the nuclear heat engine are enormous by comparison.

4.0 CURRENT NUCLEAR REACTOR TECHNOLOGIES APPLIED TO AUTOMOTIVE NUCLEAR HEAT ENGINES

Problems of research, development, engineering, construction, and operation of automotive nuclear heat engines are comparable in many respects to most automotive engineering programs. With present-day understandings of the fission mechanisms associated with thermal energy production, the nuclear heat reactor can be considered to be a heat source which takes the place of the heat sources now using chemical fuels.

4.1 Nuclear Heat-Engine Parameters

Figure 6 presents a well-known diagram of the relationship of the heat source to other components of a system, illustrating the ideal or theoretical cycle of the simple automotive power plant in which the heat source is a nuclear device. The system is comprised of: (1) the nuclear heat source, which replaces the combustion unit; (2) the engine or turbine, in which work is done by the expansion of the working fluid; (3) a heat exchanger or heat sink, provided to reduce the temperature to permit recompression or pumping by means of (4) a pump or a compressor arranged so that the working fluid can be returned to the nuclear heat source.

The efficiency of any heat power plant is dependent on relationships of pressure ratios and enthalpy changes of the system. The enthalpy changes of the system in turn depend upon the temperature differences of the working fluid entering and leaving the components of the power plant under consideration. The maximum temperature of the cycle establishes the maximum temperature required for the nuclear heat source, so that an efficient heat engine cycle may be attained. Thus, the nuclear power plant engineer is confronted with problems of correlating optimum nuclear engineering parameters with the conventional heat cycle parameters including heat transfer, thermal stress, fluid flow, and construction materials. In addition to the materials requirements for the power plant, the reactor power plant engineer further needs knowledge and development of materials to contain the nuclear fission reaction, of radiation effects on coolants, moderators, reflectors, and safety shielding materials. The resolution of these many problems simultaneously requires extending present-day engineering knowledge to include those necessary data and parameters which are peculiar to nuclear engineering.

The science of nuclear reactor design, therefore, has reached a point where physical concepts no longer are limiting the progress of power reactors, where basic engineering problems themselves will determine the future progress of nuclear power reactor systems.

Some of the areas which engineers must consider for a nuclear heat power system are discussed.

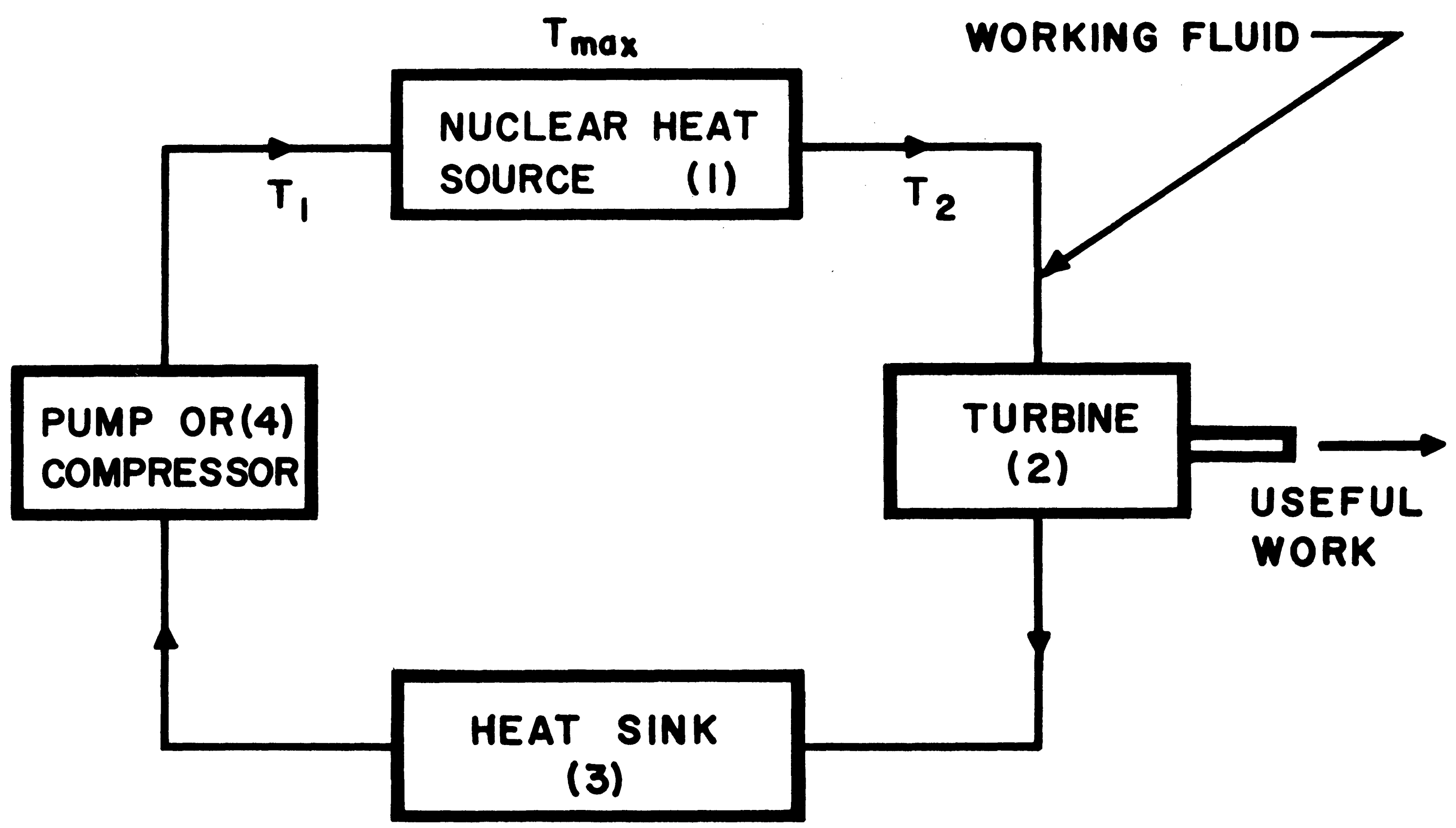

FIG. 6 BASIC TURBINE CYCLE

4.1.1 Heat Transfer Correlations With Nuclear Data

Relationships of heat transfer mechanisms, radiation, conduction, and convection with nuclear reactions and reactor design parameters such as critical mass and volume, involve considerations of materials employed for heat conduction at minimum temperature differences with transfer of the fission energy to a thermal power cycle. Structural materials and nuclear properties of coolants influence the size of the reactor and the power level which can be attained. Since minimum volumes at maximum heat transfer involve the use of high-temperature structural materials, one of the major parameters controlling reactor engineering design for automotive heat sources lies in the development of materials possessing usable physical, chemical, and nuclear properties at high operating temperatures. The extraction of heat from a nuclear reactor to a coolant and the conversion of heat to useful power is affected by maximum temperatures, thermal stress, corrosion of materials, and neutron and radiation damage.

4.1.2 Minimum Pumping Power

Power requirements for pumping of coolants and recompression of working fluids can be significant as well as control reactor design conditions. Pumps may require remote operation, remote maintenance, and/or special decontamination techniques. Mechanical developments for materials, seals, and shafts are also needed for the improvement of pumps. Drivers attendant with high efficiencies are important reactor design problems. The pumping power requirements for sustaining power level in a given nuclear-heat-power reactor must be correlated carefully with the power output of the automotive nuclear heat engine.

4.1.3 Temperature Levels

A nuclear reaction can produce high temperatures. These temperatures can reach millions of degrees if the chain reaction is uncontrolled. In a controlled nuclear reaction, the maximum temperature which can be attained is fundamentally limited by construction materials as well as by the fundamental properties of the coolants used for transfer of energy. The construction materials can be those to contain the fuel in heterogeneous fuel elements, and the container materials for the reactor fuels, coolants, and controls.

4.1.4 Nuclear and Thermal Stabilities of Materials

The following characteristics of materials used in nuclear power plants must be considered:

4.1.4.1 Ultimate strength

4.1.4.2 Yield strength

4.1.4.3 Stress-rupture

4.1.4.4 Creep

4.1.4.5 Fatigue

4.1.4.6 Elongation

4.1.4.7 Reduction in area

4.1.4.8 Hardness

4.1.4.9 Impact

4.1.4.10 Oxidation

4.1.4.11 Corrosion

4.1.4.12 Damping capacity

4.1.4.13 Relaxation

4.1.4.14 Modulus of elasticity

4.1.4.15 Thermal conductivity

4.1.4.16 Thermal expansion

Each of these properties in one way or another is influenced by nuclear interreactions and radiation damage. Theories and basic data for predicting what influence radiation has on such materials require much development. In some cases, the effects of radiation are seriously detrimental whereas in other cases certain improvements result. Some of these characteristics follow.

4.1.4.17 Annealing

A given solid lattice subjected to radiation damage becomes unstable thermodynamically. If the atoms are free to migrate, they may gradually return to their former positions with accompanying evolutions of heat and reductions in hardness of materials. Such a process is known as annealing and becomes a function of temperature. Certain radiation damage effects on materials are irreversible and cannot be removed by annealing. These irreversible effects might include accumulation of fission products in the fuel, induced radioactivity produced by absorption of neutrons and subsequent decay to new types of nuclear species, and accelerated chemical decomposition of the material as a result of radiation intensities. The combination of these may cause dimensional changes resulting in deformation of the material.

4.1.4.18 Changes in Hardness and Strength

In general, the effect of radiation on a metal is to increase its hardness and shear strength (19). This effect is similar to cold-working. The result may be due to distortions of crystalline lattices which retard slippage of one crystal plane over another. Such effects are not appreciable in metals used for fabrication of reactor vessels, and associated mechanical equipment, piping, and controls. The Engineering Test Reactor will do much to further understanding of radiation effects on metals when neutron intensities exceed 10^{15} neutrons per square centimeter per second and high energy radiation of about 10^{9} curies (21).

4.1.4.19 Effects in Electrical Conductivity

Certain experimental investigations (2, 4) have been conducted in this area. The electrical conductivity of a material is essentially the product of the number of electrons which can carry current and the mobility which the electrons can acquire per unit electric field strength. These effects are influenced by temperature, crystal lattice structure, and the dimensions of the crystal itself. Radiation tends to convert an ordered structure to one that is disordered. Consequently, electrical resistivity of materials tends to increase under radiation. This effect has proven to be one of the measuring sticks of determining radiation effects on materials.

4.1.4.20 Effects on Thermal Conductivity

Experimenters have reported that thermal conductivities tend to decrease due to effects of radiation (3).

4.1.4.21 Effects on Non-Metallic Materials

Radiation effects upon organic materials and aqueous materials are severe. Engineers must consider carefully such materials as gaskets, electrical motors, power wiring, lubricants, and any other components using non-metallics. Intense radiations are being considered as catalysts and energy of activation for promotion of chemical reactions, food preservation and medical applications.

4.1.4.22 Other Changes

As maximum temperatures are achieved for various materials used in nuclear-heat-power reactors, much work will be needed to determine influences of radiation on all of the properties and physical characteristics listed.

4.2 Nuclear Steam Generators

Most water moderated and cooled reactors can be classed in this category of nuclear steam generators and associated steam turbomachinery. The types of reactors which are currently under development for the generation of saturated steam with subsequent conversion to power are the following ones:

4.2.1 Pressurized Water System (Figure 7)

Pressurized water reactor systems are of the heterogeneous type, operating in the thermal range of neutron energies. For propulsion purposes, high enrichments of fuels are required for compact design. Water at high pressures, with the temperature of the water approaching the saturation pressure, is circulated by means of a pump through a high-pressure vessel in which a reactor fuel is located. The thermal energy removed by the circulating water is used to generate steam.

4.2.2 Boiling Water Reactor

A modification of the pressurized circulating water type of reactor is termed a boiling water reactor. In general, this reactor differs from the pressurized water type by producing steam directly from the reactor vessel, thus reducing the design pressures from about 2000 psig.

4.2.3 Aqueous Homogeneous Type

A method by which fuel elements fabrication and a part of the high-temperature problems of heterogeneous assemblages can be avoided is dissolving the fuel in an acid solution of water, forming a fissionable salt, an example of which is uranyl sulfate. When an adequate concentration of fuel is present in solution in a proper geometry, the fission reaction takes place at suitable temperatures and pressures. Heat is transferred from the liquid fuel so that high-pressure, saturated steam can be produced for use in turbomachinery.

NUCLEAR HEAT POWER PLANT

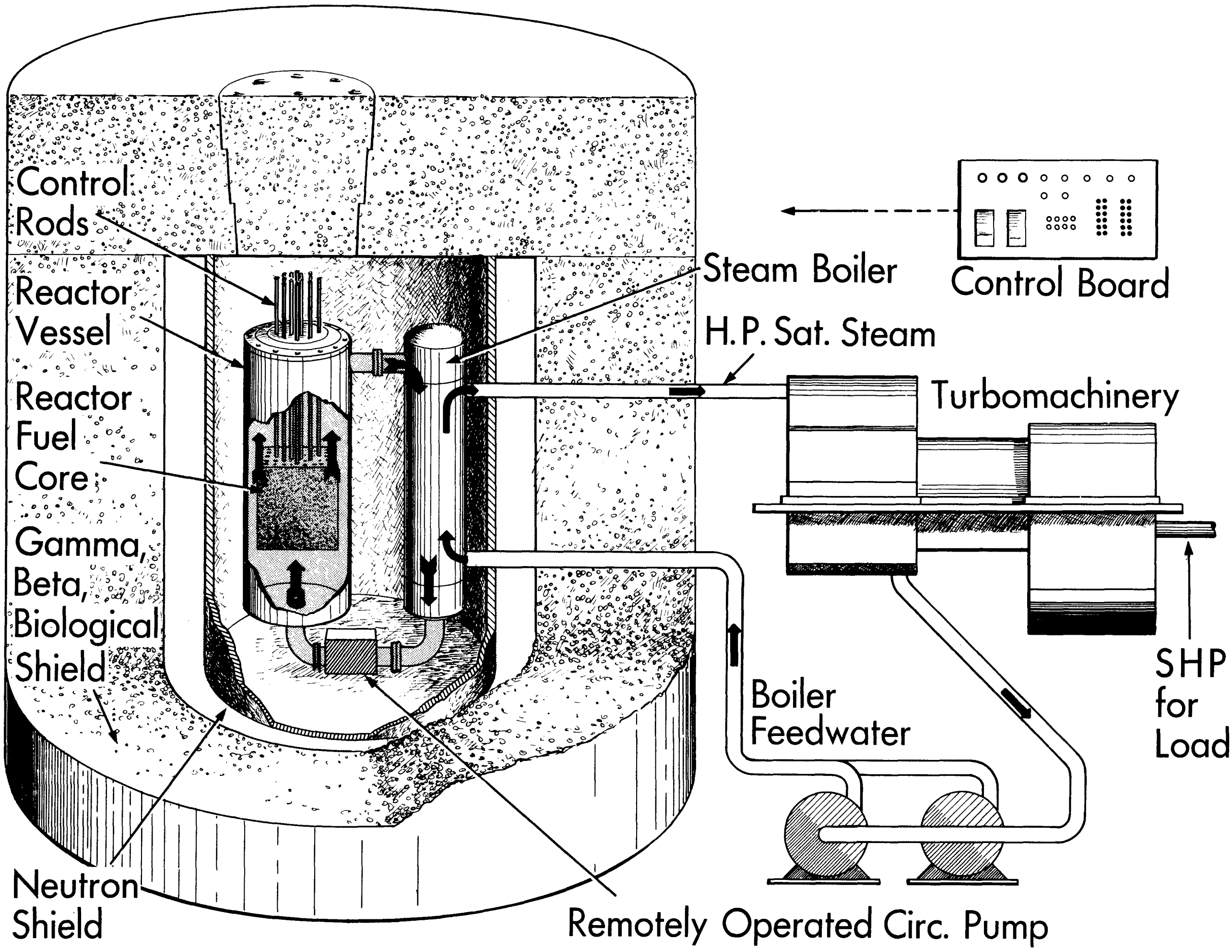

FIG. 7

Pressurized Circulating Water Type

Fuel	—Highly Enriched Uranium
Fuel Assembly	—Zr - U
Moderator & Coolant	—Light Water
Neutron Shield	—Water
Gamma Shield	—Lead

Approximate weight of Nuclear Heat Engine with shield might be reduced to 100,000 lbs. (calculated). At 20 pounds per S H P, minimum size engine would be 10,000 S H P. At 25% efficiency, heat generation would be 29.8 megawatts.

4.3 Liquid Metal Reactors

Temperatures of nuclear heat sources can be increased while reducing design pressures by employing molten metals as coolants. Several types of liquid metal reactors are currently under development.

4.3.1 Heterogeneous Liquid Metal Cooled Reactors

This nuclear heat power source employs a molten metal, circulating through a heterogeneous assemblage of fuel for removal of thermal energy. Molten metals such as sodium and sodium-potassium eutectics are being used. The molten metal exchanges its heat energy with a suitable working fluid for heat engine operation. Such working fluids may be gases for gas turbine operation, steam for steam turbomachinery, and binary materials. The maximum temperature and heat engine efficiency for heterogeneous liquid metal cooled reactors are basically limited by the maximum temperatures which can be achieved for reactor fuel element design.

4.3.2 Homogeneous Liquid Metal Reactor (Figure 8)

A recent achievement in development by the Brookhaven National Laboratories has indicated that a homogeneous liquid metal fueled reactor has promise for application. Such a reactor has the fissionable fuel dissolved in a liquid metal. An example is to dissolve uranium-235 in bismuth metal. The present level of temperature which might be achieved in this type of a reactor dependent upon structural materials, is reported to be 550°C (5). By improvements of corrosion resistance of materials which can contain uranium-bismuth solutions, possibilities for higher temperature operation are good. Dependent upon the maximum temperatures which can be developed for container materials, this homogeneous liquid metal reactor offers distinct possibilities in applying gas turbine power plants in conjunction with this nuclear heat source.

NUCLEAR HEAT POWER PLANT

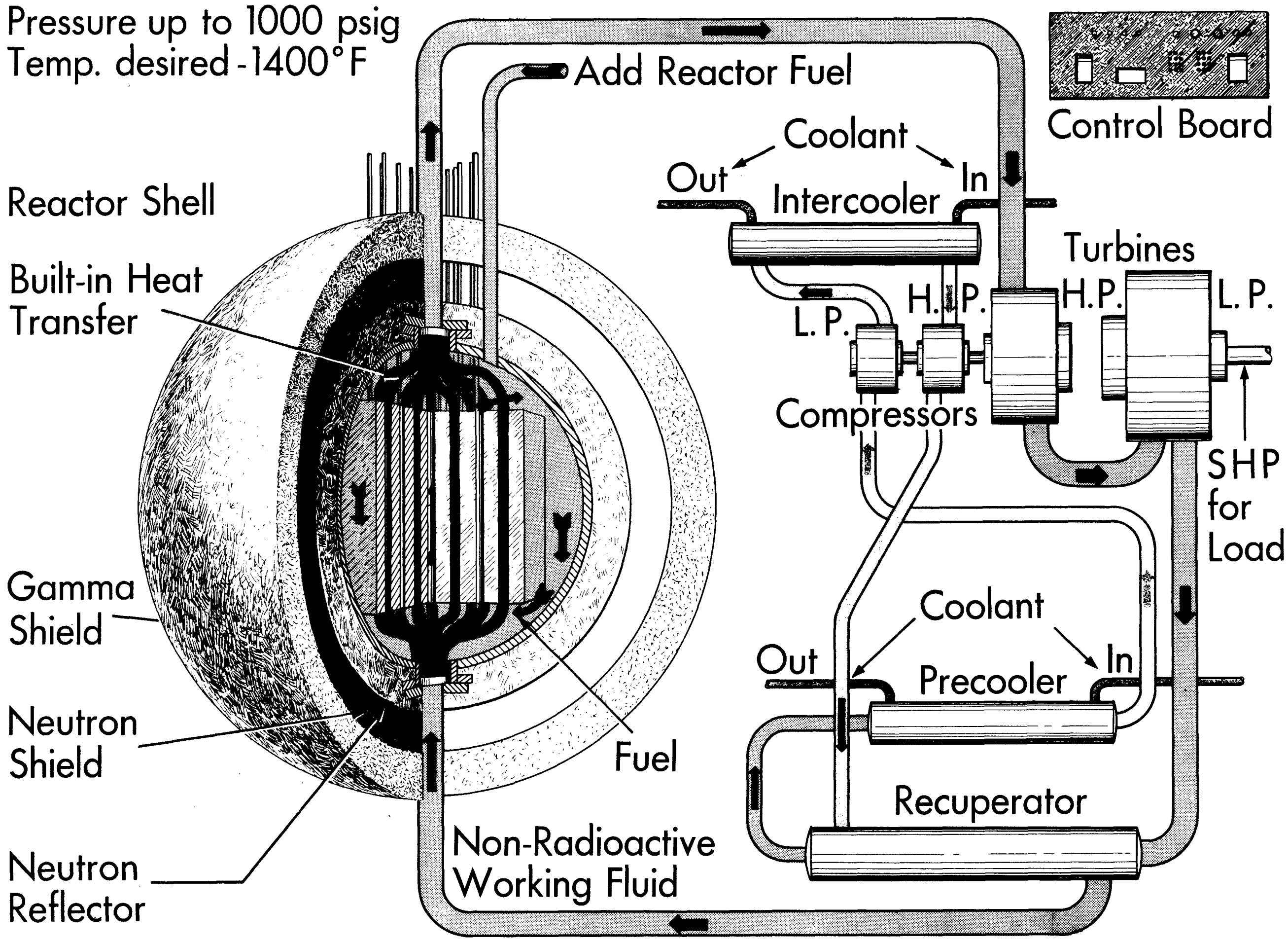

FIG. 8

Fuel Solution	—Possibly U 235 in Bismuth
Moderators	—Carbon
Coolant	—Helium (Maybe)
Reflector	—Carbon
Neutron Shield	—To be discovered
Gamma Shield	—To be discovered

Approximate weight of Nuclear Power Plant might be 50,000 lbs. At 20 pounds per SHP, minimum size engine would be 2500 SHP.

5.0 THE IDEAL POINT SOURCE NUCLEAR-HEAT-POWER ENGINE (Figure 9)

When considering heat engine cycles wherein the nuclear heat source and heat conversion devices are theoretically ideal, it is possible to evaluate the minimum weight for various gamma radiation shielding materials. Figure 10 shows such weights plotted against heat power in megawatts. This figure assumes the nuclear heat engine, including the heat source, power extraction device, and neutron shield, to be a point source. Under such conditions, the weight of an automotive nuclear engine will be controlled solely by available gamma shielding materials. Table XI presents the total weight of gamma shields for presently available materials of construction.

If it is assumed that chemically fueled heat engines have weight-horsepower ratios no more than 5:1, it can be seen that the shaft-horsepower outputs reach a minimum for each material under consideration. Then, to apply an ideal nuclear heat engine to shaft-horsepower requirements less than the figures indicated, major breakthroughs in shielding design and materials are required.

TABLE XI. SPHERICAL SHIELD REQUIRED FOR POINT NUCLEAR REACTOR

Assumed Radiation Dose Rate at Surface - 6.25 M.R./HR With Maximum Dosage of 36R/YR.

Neutron Shield Mass and Size - Assumed Negligible

	Thickness, Feet		Weight, Pounds	
Heat Power, Megawatts →	1	100	1	100
Shield Material ↓				
Water	17.7	22.2	1,480,000	2,880,000
Concrete	9.18	11.3	463,000	870,000
Aluminum	7.91	9.65	352,000	642,000
Iron	2.83	3.46	45,400	83,600
Lead	1.59	1.89	12,200	20,600
Tungsten	1.012	1.21	5,350	9,100
Uranium	0.972	1.16	4,550	7,760
Material "x" (unknown) -Density 30 g/cm^3	Maybe 0.3	?	Maybe 250	?

AN ULTIMATE NUCLEAR HEAT ENGINE

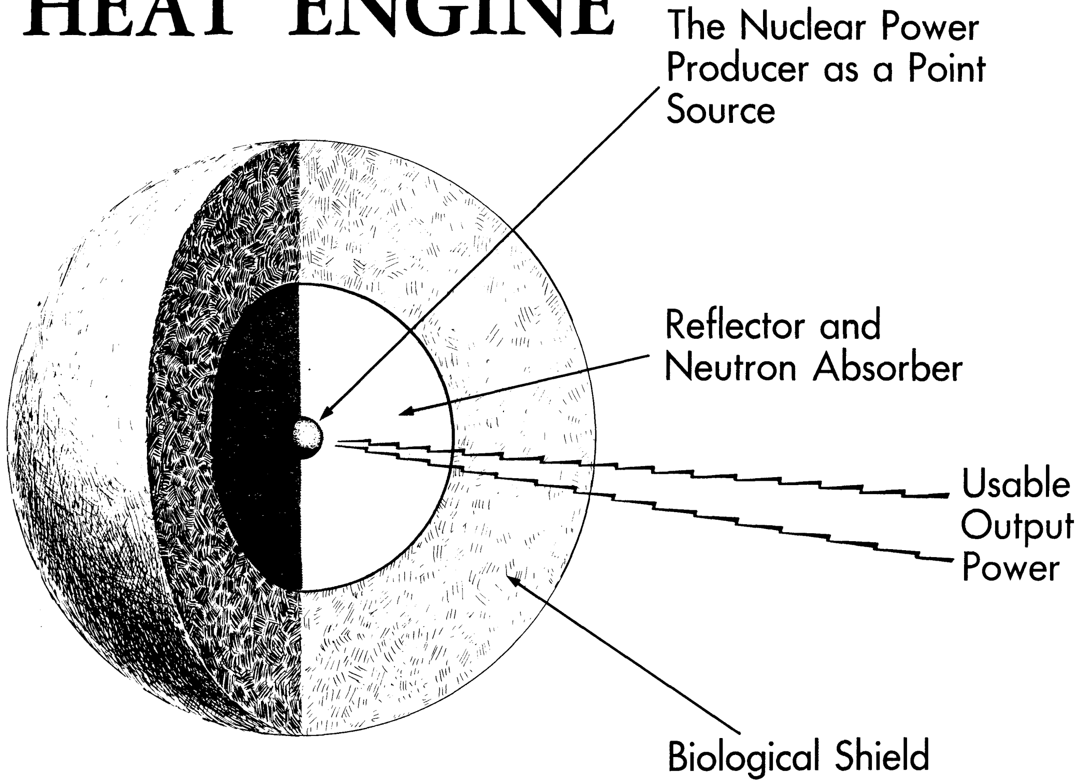

FIG. 9

Probable Required Temperature above 5000° F for Nuclear Reaction

If known biological shields cannot be reduced in weight, and present tolerances of 36 roentgens per year is maximum human dose; minimum weight of automotive nuclear heat engine will be about 12,000 lbs. At 20 pounds weight per shaft horsepower, smallest usable power output will be 600 horsepower.

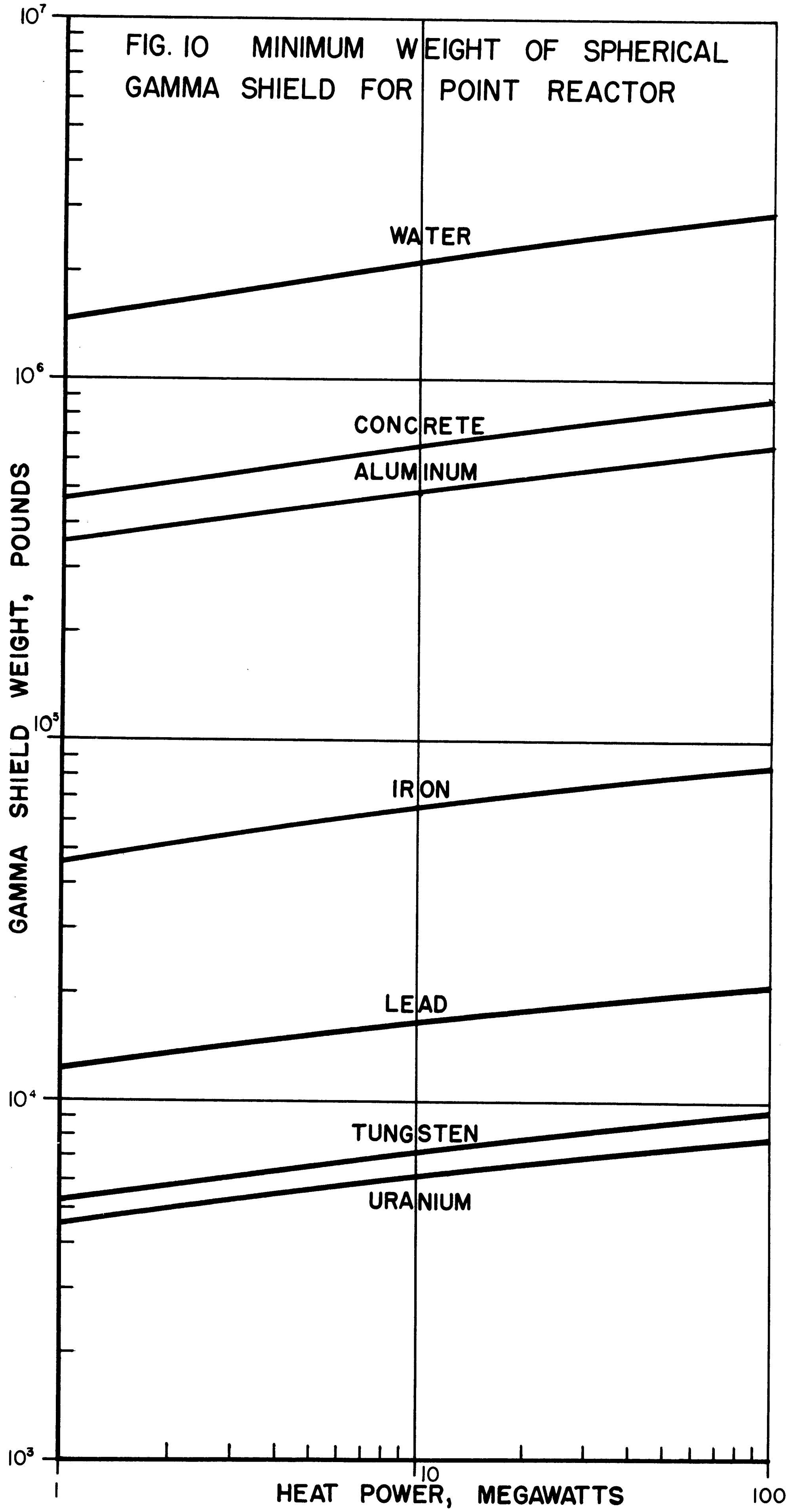
FIG. 10 MINIMUM WEIGHT OF SPHERICAL GAMMA SHIELD FOR POINT REACTOR
WATER
CONCRETE
ALUMINUM
IRON
LEAD
TUNGSTEN
URANIUM
GAMMA SHIELD WEIGHT, POUNDS
HEAT POWER, MEGAWATTS
10^7
10^6
10^5
10^4
10^3
1
10
100

6.0 SOME WORDS AND DEFINITIONS OF TERMS USED IN NUCLEAR ENGINEERING

Absorber	A material which has a high affinity for neutrons but does not fission as a result.
Albedo	A unit used to measure ratios of negative to positive neutron currents, and is the ratio of the number of neutrons reflected back to the number of neutrons entering a reflector material.
Alpha Particle	A radioactive particle consisting of helium nucleus with positive charge made up of two protons and two neutrons.
Atom	The smallest part of an element which retains its chemical and physical properties.
Atomic Mass Unit (AMU)	A method of relating atomic mass to oxygen. 1 AMU = 931.8 Mev = 1.657×10^{-24} gm.
Atomic Mass	Relative weight of atoms when oxygen is 16.000. For practical purposes the mass equals the total neutrons and protons in the nucleus.
Atomic Number	The number of protons or positive charges in a given nucleus.
Barn	A method of expressing probability of nuclear interaction. Practically can be considered as "target" area where one barn = 10^{-24} cm^2.
Beta Particle	A positive or negative electron emitted from radioactive species.
Breeder Reactor	A device in which a controlled chain reaction takes place so that the production of fissionable atoms is greater than the number consumed.
Burnup	The percentage of fissioning fuel used in a controlled chain reaction. Includes the amounts that are destroyed or converted to other materials by neutron capture.
A Chain Reaction	A nuclear reaction occurring so that sufficient numbers of neutrons are conserved to prompt fission in other atoms for sustained periods of time.

Coolant	A liquid or gas, used for extracting thermal energy (heat) from a nuclear reactor.
Critical Condition	The zero power level of a reactor which sustains a controlled chain reaction.
Electron	A negative charged particle which weighs 9.107×10^{-28} grams.
EV	An amount of energy required to transfer an electron through one volt of potential difference. $= 15.2 \times 10^{-23}$ Btu
Enrichment	Normally refers to increasing the properties of fissionable atoms to non-fissionable atoms.
Fertile Materials	Normally considered to be materials which on neutron capture result in eventual production of fissionable atoms.
Fissile Materials	Materials capable of fission with the energy ranges of neutrons present.
Fission	The nuclear process by which a heavy element on reaction capture splits up into two or more fragments.
Fission Products	The light elements, radioactive and non-radioactive, resulting from fission.
Flux	In nuclear interaction is considered the product of the number of particles per unit volume and their mean velocity.
Gamma Rays	A short wave electromagnetic radiation similar to x-rays but much more intense. Energies range from 10 Kev to 10 Mev.
Half-Life	The length of time for radioactivity to reduce to one-half value.
Ionization	A method by which an atom or molecule acquires an electric charge.
Isotope	Varieties of elements which have common chemical properties but whose atomic weights are different.
Kev	One thousand electron volts.
Mev	One million electron volts.

Moderator	A material of low atomic mass which is used to slow down neutrons without capturing them.
Multiplication Constant	The ratio of neutrons of one generation to the neutrons of a preceding generation.
Neutron	A particle with no charge and whose atomic mass number is 1. Symbol $-{}_0n^1$
Neutron Producer	A reactor which produces neutrons for isotope production.
Photon	A quantum of energy known as the smallest amount of energy travelling at the speed of light.
Poison	A material in nuclear reactors which absorbs neutrons for no useful purpose.
Positron	An electron with a positive charge.
Power Density in Reactors	The power produced per unit volume of nuclear fuel.
Proton	A particle whose atomic mass is 1.0 with positive electric charge.
Radiation Damages	Undesirable changes in structural, chemical and physical properties resulting from nuclear radiation.
Radioactivity	The process by which an unstable atom releases energy in the form of alpha particles, beta particles and/or gamma rays.
Reactivity "k"	Reactivity "k" is equal to the ratio of $\frac{k(ex)}{k(eff)} = \frac{k(eff) - 1}{k(eff)}$ The ratio establishes the control of the power level of a nuclear reactor where: $k(ex)$ = excess neutron multiplication factor; $k(eff)$ = effective neutron multiplication factor. When reactivity is negative, a power reactor becomes subcritical; when it is zero, the power reactor is under control; and when it is positive the reactor becomes supercritical.
Reflector	A material incorporated in and surrounding the reactor fuel which reflects neutrons at energies so that they are useful in fission.

Recovery of Reactor Fuels	Processes for recovery of reuseable reactor fissile and fertile materials with adequate separation of fission products, spent structural materials, etc.
Roentgen	A standard unit of radiation close. The quantity of x-rays or gamma rays which produce one electrostatic unit of electricity per cubic centimeter of air at standard pressure and temperature.
Shield	A radiation absorbing structural material which reduces radioactivity and nuclear particles to levels to permit human operation within reasonable distance from radiation source.
Temperature Coefficient	The change of reactivity divided by a change in temperature.

$$\alpha_1 = \frac{\partial \delta}{\partial T} = \frac{(\delta - \delta_o)}{(T - T_o)}$$

When the coefficient is negative increase in temperature decreases reactivity; when the coefficient is positive increase in temperature <u>increases</u> reactivity.

7.0 REFERENCES

1. AECU-2040, "Neutron Cross Sections."

2. Allen, A. O., "Effects of Radiation on Materials," MDDC-962, 1947.

3. Berman, R., Proc. Royal Society, London A, 20890, 1951.

4. Billington and Siegel, "Effects of Nuclear Reactor Radiation on Materials," AECD-2810, 1947.

5. Brookhaven Report.

6. Downs, J. E., "Margins for Improvement of the Steam Cycle," ASME, April 1, 1956.

7. Glasstone and Edlund, The Elements of Nuclear Reactor Theory, 1954.

8. Goodman, Clark, The Science and Engineering of Nuclear Power, Volume II, October, 1948, Addison-Wesley Press, Inc.

9. Hausner and Roboff, "Materials for Nuclear Power Reactors."

10. Johnson, J. R., "Ceramic Fuel Materials for Nuclear Reactors," Preprint 110.

11. Katz, D. L., Ohlgren, H. A., and Weech, M. E., et al., "Nuclear Engineering--Engineering Applications of Nuclear Energy."

12. Landrum, Leslie H., and Zagnoli, Sinesio A., "Some Engineering and Economic Aspects of Atomic Power," Spencer Chemical Company, Kansas City, Missouri.

13. Lustman, Benj., and Kerze, Frank H., Metallurgy of Zirconium, National Nuclear Energy Series, VII-4, McGraw-Hill, 1955.

14. "Operational Power Reactors," Nucleonics, September, 1955, pp. 40-50.

15. Paine, S. H., and Kittle, J. H., "Irradiation Effects in Uranium and Its Alloys," Preprint 94.

16. "Peaceful Uses of Atomic Energy," report of the panel on the Impact of the Peaceful Uses of Atomic Energy to the Joint Committee on Atomic Energy, January, 1956, Volumes 1 and 2.

17. "Reactor Materials," Nucleonics, September, 1955, pp. 64, 69, 71.

18. Staniar, William, Ed., Plant Engineering Handbook, McGraw-Hill, 1950.

19. Stephenson, Introduction to Nuclear Engineering.

20. Weech, M. E., and Bulmer, J. J., "Peacetime Survey of Nuclear Energy from an Industrial Viewpoint," IP-100.

21. Zartman, J. F., "Effects of Nuclear Reactor Radiations on Structural Materials," Preprint 89.

8.0 ADDITIONAL REFERENCES

Benesovsky, F., Kieffer, R., Leszynski, W., Schwarzkopf, P., Refractory Hard Metals, The MacMillan Co., New York, 1953, p. 477.

*Blizard, E. P., "Reactor Shielding," Preprint 11.

Brewer, L., et al., "Thermodynamic and Physical Properties of Nitrides, Carbides, Sulfides, Silicides, and Phosphides," Rept. cc-3307, USAEC, Oak Ridge, Tenn., 1947.

Bruch, C. A., McHugh, W. E., and Hokenbury, R. W., "Embrittlement of Molybdenum by Neutron Radiation," Trans., AIME, Vol. 203, p. 281, 1955.

*Bruggeman, W. H., "Purity Control in Sodium Cooled Reactor Systems," Preprint 66.

Branstetter, D. R., Kling, H. P., and Alexander, B. H., "The Tensile Properties of Zirconium at Elevated Temperatures," Sylvania Electric Products, Inc., Bayside, New York, NYO-1126, April, 1950.

Cleland, J. W. Billington, D. S., and Crawford, J. H., Phys, Rev., Volume 91, p. 238, 1953.

Coobs, J. H., "Fabrication and Properties of Beryllium Carbide," NEPA, IC-51-3-21, 1951.

*Cooper, W. E., "Proposed Structural Design Basis for Nuclear Reactor Pressure Vessels," Preprint 8.

Crawford, J. H., and Wittels, M. C., "A Review of Investigations of Radiation Effects in Covalent and Ionic Crystals," U.N. International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955.

Curtis, C. E., "Development of Zirconia Resistant to Thermal Shock," Jr. Am. Ceram. Soc., 30 (6), pp. 180-196, 1947.

Evans, U. R., "The Oxidation of Metals--A Simplified Quantitative Discussion Review of Pure and Applied Chemistry," The Royal Australian Chemical Institute, Vol. 5, No. 1, March, 1955.

Everhardt, J. L., et al., "Mechanical Properties of Metals and Alloys," Nat. Bur. Standards Cir., CC-447, December, 1943.

*Finlay, G. R., "Boron Compounds for Nuclear Applications," Preprint 112.

Green, A. T., and Stewart, G. H., "Ceramics, A Symposium, The British Ceramic Society, Stoke-on-Trent," 1953, p. 887.

Harman, C. G., and Mixer, W. G., "Review of Silicon Carbide," Report No. BMI-748, 1952.

*Hausner, H. H., and Tambrow, J. L., "Powder Metallurgy of Uranium," Preprint 124.

*Huddle, R. A. U., "Oxidation Behavior of Reactor Materials," Preprint 108.

*Huddle, R. A. U., "The Uranium Steam Reaction," AERE, M/R-1281, 1953.

Hurd, D. T., "Chemistry of the Hydrides," John Wiley and Sons, Inc., 1952.

*Hyde, C., Quirk, J. F., and Duckworth, W. H., "Preparation of Dense Beryllium Oxide," Preprint 126.

Jackson, C. B., et al., "Liquid Metals Handbook, Sodium-No K Supplement," U. S. Government Printing Office, Washington 25, D. C., 3rd Edition, July, 1955.

Jeppson, M. R., Mather, R. L., Andrew, A., and Yockey, H. P., "Creep of Aluminum under Cyclotron Irradiation," Jnl. App. Phys., Vol. 26, p. 365, April, 1955.

Jones, E. R. W., Munro, W., and Hancock, N. H., "The Creep of Aluminum During Neutron Irradiation," Jnl. Nucl. Energy, Vol. 1, No. 1, p. 76, August, 1954.

Katz, J. J., and Rabinowitch, E., "The Chemistry of Uranium," Part I, McGraw-Hill Book Company, New York, 1951, p. 609.

Kingery, W. D., Francl, J., Coble, R. L., and Vasilos, T., "Thermal Conductivity: X-Ray Data for Several Pure Oxide Materials Corrected to Zero Porosity," Jnl. Amer. Ceram. Soc., Part II, 37 (2), pp. 107-110, 1954.

*Kosiba, W. L., Dienes, G. J., and Gurinsky, D. H., "Some Effects Produced in Graphite by Neutron Irradiation in the BNL Reactor," Preprint 93.

Kubaschewski, O., and Hopkinson, B. E., "Oxidation of Metals and Alloys," Butterworth Scientific Publications, London, 1951.

Kunz, F. W., and Holden, A. N., "The Effect of Short Time Moderated Flux Neutron Irradiations on the Mechanical Properties of Some Metals," Acta Met., Vol. 2, No. 6, p. 816, 1954.

Laing, J., "Gas Phase Reactions of Zirconium, A Review of the Literature," AERE, M/Tn., 9, 1951.

Lambertson, W. A., and Gunzel, F. H., Jr., "Refractory Oxide Melting Points," Argonne National Lab., AECD-3465, November, 1952.

Leeser, D. O., "How Nuclear Radiation Affects Engineering Materials," Materials and Methods, Vol. 40, p. 115, July, 1954.

*McCullough, H. M., and Kopelman, B., "Review of Solid Hydrides," Preprint 352.

Miller, D. R., and Cooper, W. E., "Structural Problems of a Sodium-Cooled Nuclear Reactor," ASME Paper No. 54-SA-75.

*Murray, R. L., "Nuclear Engineering Literature," Preprint 239.

Murray, G. T., and Taylor, W. E., "Effect of Neutron Irradiation on a Super-saturated Solid Solution of Beryllium in Copper," Acta Met., Vol. 2, No. 1, p. 52, 1954.

*Nagey, T. F., and Wochtl, W. W., "Special Technical and Economic Aspects of Small Nuclear Power Packages," Preprint 134.

*Ogdon, H. R., Goldhoff, R. M., and Joffee, R. I., "The Strengthening of Thorium by Alloying Heat Treating and Cold Work," Preprint 103.

Peterson, D. T., Russi, R. F , and Mikelson, R. L., "The Effects of Some Impurities on the Mechanical Properties of Thorium Metal," Preprint 102.

Reynolds, M. B , "Study of the Radiation Stability of Austenitic Type 347 Stainless Steel," Trans., AIME, Vol. 203, p.555, 1955.

*Saller, H. A., and Keeler, J. R., "The Fabrication and Properties of Thorium," Preprint 99.

*Schultz, J., Tripp, H. P., King, B. W., and Duckworth, W. H., "Enameling of Zirconium" Preprint 128.

Schwope, A. D., and Chubb, W., "Mechanical Properties of Zirconium-Tin Alloys," Battelle Memorial Institute, Columbus, Ohio, BMI-798, December, 1955.

Seitz, F., "On the Disordering of Solids by Action of Fast Massive Particles," Dics. of the Faraday Soc., Vol. 5, p. 271, 1949.

Siegel, S., "Effects of Pile Radiation on Be Metal," Clinton Labs., Oak Ridge, Tenn., AECD-4045, June, 1947.

Siegel, S., "Radiation Damage as a Metallurgical Research Technique," Modern Research Techniques in Physical Metallurgy, American Society for Metals, 1953, p. 312.

Siegel, S., and Bullington, D. S., Effect of Nuclear Radiation on Metals," Metal Progress, Vol. 58, 1950, p. 847.

Slater, C., "The Effects of Radiation on Materials," Journal of Applied Phys., Vol. 22, No. 3, 1951, p. 237.

Steel, R. V., and Wallace, W. P., "Effect of Neutron Irradiation on Aluminum Alloys," Metal Progress, Vol. 68, July, 1955, p. 114.

*Sternberg, Virginia, "Literature on Nuclear Power Reactor Technology," Preprint 238.

Sutton, C. R., and Leeser, D. O., "How Irradiation Affects Structural Materials," Part I, Iron Age, Vol. 174, No. 8, p. 128, August 19, 1954; Part II, Ibid, No. 9, p. 97, August 26, 1954.

Tate, R. E., "Report on National Bureau of Standards Ceramic Coatings on Inconel and Stainless Steel," Tennessee Eastman Corp., Oak Ridge, Tenn., AECD-4073, July, 1945.

Thomson, William R., Fundamentals of Gas Turbine Technology, London, 1949.

Trocki, T., Bruggeman, W. H., and Cover, F. E., "Sodium and Sodium-Potassium Alloy for Reactor Cooling and Steam Generation," Transactions of First United Nations Sponsored Conference on Nuclear Energy, August, 1955.

Uhlig, H. H., "The Corrosion Handbook," John Wiley and Sons, New York, 1948.

*Wilson, J. C., and Billington, D. S., "Effects of Nuclear Radiation on Structural Materials," Preprint 91.

Witzig, W. F., "Creep of Copper Under Deuteron Bombardment," Jnl. App. Phys., Vol. 23, p. 1263, 1952.

*Full Reference--AIChE meeting, December 11-16, 1955, Nuclear Engineering and Science Congress.