GATEWAY

TO NUCLEAR PROGRESS

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The key to the economical development of the nuclear reactor as a source of power lies in the development of the materials which go into its construction.

The Ford swimming pool-type reactor is shown in this picture from a view that portrays the reason for its strange name. These young scientists keep a complete record of all fluctuations in the functioning of the reactor in order to gain a fuller understanding of its behavior.

An important phase of the American economy is the production of power. At the present time, obtaining heat from coal is a major means of producing electric power. However, coal supplies are not unlimited, and the efficiency of the coal-turbine-generator supply of power has almost reached its limit . In order to reduce costs of electricity, which would increase with the decreasing coal supply, the trend has been, in the past several years, to suggest use of the nuclear reactor as a source of heat, which can be easily converted into electric power. However, nuclear power has not proven itself capable of producing electricity economically as yet, primarily because of its relattively recent development aand the lack of knowledge concerning component materials.

Before proceeding further, it is helpful to classify the different types of reactors, both proposed and in use at the present titme. There are several systems for classifying reactors:

a. The reactor may be of the power or power-breeder type, the former utilized solely for power production, while the latter is used to produce additional fuel as well.

b. Reactors are often classified by their neutron energies as either fast, intermediate, or slow ("thermal") neutron reactors.

c. A homogeneous reactor is one in which the fuel is in solution form and thus homogeneous; in the heterogeneous reactor, fuel elements are used, and thus the reactor gets its name.

d. There are solid and liquid-fuel types of reactors; these should be self-explanatory.

e. Reactors are built to be either mobile or stationary.

The Basic Reactor Parts

The conventional power plant generally consists of the heat source, the turbine, and the generator, or similar devices. In the nuclear reactor power plant, the turbine and generator remain unchanged; it is the heat source which is revised. In the heat source ,or reactor, are several basic components, some of which are absent in some types of reactors.

The first requirement of all reactors is the fuel, which is usually given a protecttive metal coating or cladding, except in homogeneous reactors, where the fuel is in the form of either a solution or a fine dispersion. The three presently used fuel are Uranium-235, Uranium-233, and Plutonium-239.

All reactors utilize a coolant to carry the heat from the core, where the fission take place; commonly used coolants are water, sodium, sodium-potassium alloys, and occasionally air.

Moderators are employed in all reactors except the fast-neutron type, for the purpose of slowing down the neutrons from

Demonstrating the agility that can be achieved in using mechanical hands, this worker at the Phoenix Project watches her actions on the television screen.

the reacton; the moderator thus serves for an effective control over the reaction.

Reflectors are used to prevent excessive loss of neutrons from the core area, and by doing so, to reduce the fuel necessary, and thus lowering costs.

Shielding is utilized for the dual purpose of neutron economy and safety. It surrounds the entire core area and is the final stop for all fission products.

Control elements normally consist of a number of cylindrical rods inserted into the core itself. These rods absorb neutrons, thus providing the fine control for the reaction.

Auxiliary systems, including the coolant cycle and control handling system, are also directly concerned with the reactor and present problems of their own.

Some General Problems

Before discussing the problems presented by each component part of the reactor, it serves a useful purpose to discuss the general material problems of the reactor.

The most widespread single problem is presented by the nuclear properties of a potential material. With the exception of the control elements and the shielding, all materials used in the core should have a low affinity for neutrons; this is expressed as a *low neutron cross-section,* in Barns. Table I lists the thermal neutron cross-section of several nuclear materials:

TABLE I

Hydrogen	0.33	Barns
Deuterium	0.00057	Barns
Boron	4,000	Barns
Carbon	0.0045	Barns
Sodium	0.49	Barns
Iron	2.4	Barns
Aluminum	0.22	Barns
Zirconium	0.18	Barns

High absorption of neutrons by parts of the reactor would result in excessive changes in the parts due to the neutron radiation. Very few materials possess this low neutron cross-section, so this limitation dominates others in reactor construction; and materials with satisfactory nuclear properties do often lack the necessary strength, corrosion resistance, thermal characteristics, and similar properties for ideal reactors.

A major problem is that of mechanical strength; very few suitable nuclear materials have high tensile or yield strengths, as mentioned above. Since the nuclear properties must be considered first, the core is often comparatively bulky due to the relative weakness of the material in use.

Corrosion presents a considerable problem at times, primarily at the points of contact of the coolant and fuel. The useful fuels, uranium and plutonium, possess poor corrosion resistance against the usual coolants, water and liquid metals; this necessitates the use of cladding to protect the fuel. (This cladding also serves the very useful purpose of retaining fission products in the fuel, thus preventing excessive radiation contamination of the coolant.) Fortunately, liquid sodium and sodium-potassium alloys (NaK), and water, if demineralized, are not highly corrosive on most piping metals, and the former can effectively be utilized as coolants. The high temperatures of a reactor core accelerate corrosion in two ways: heat itself directly elevates the corrosion rate, while all parts heated by neutron absorption must contact the coolant for heat removal, and thus need further protection, from the corrosive effects of the coolant. Shorter life of core parts results

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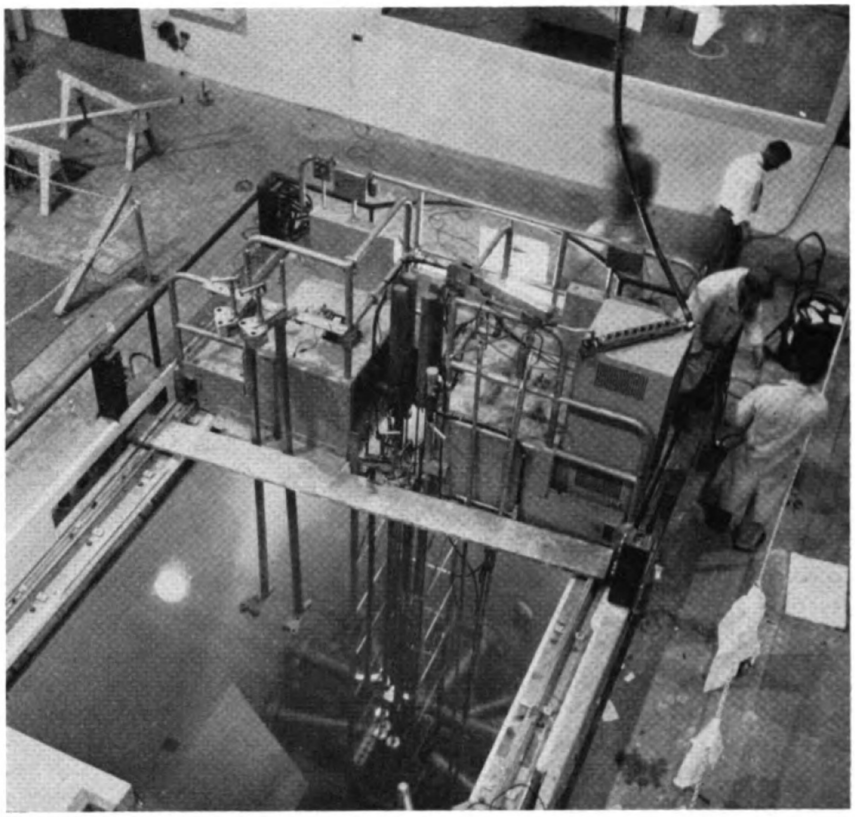
at least partially from increased corrosion, both from the increased temperatures and from the radiation effects, which are discussed in a later paragraph. In Table II are listed the temperature limits for several metals when used with liquid sodium:

Metal	*Max. Temp.*
Plain C Steel	900°F
18-8 St. Steel	1600
Monel (30% Cu)	1100
Copper (Comm.)	800
Zirconium	1100
Aluminum	500
Beryllium	1200

Since considerable heat is generated in the core, it is very important to conduct this heat away from the core, to prevent softening and melting of the parts. The fuel, cladding, and coolant predominate in this respect; all must possess a high thermal conductivity, since high heat transfer through the cladding between the fuel and the coolant must be effected. A good metallurgical bond between the fuel and cladding and a high coefficient of heat transfer between the cladding and coolant are necessary to carry out the heat of fission from the core in an effective manner.



Workmen are shown in the assembling stages of the Ford Reactor. The disheveled apparance soon gave way to the spotless white atmosphere that now exists there.

Heat also presents a severe problem in the fuel element itself. The coolant keeps the surface of the fuel relatively cool, as much as several hundred degrees Centigrade cooler than the center. These large temperature gradients set up large thermal stresses in the fuel element. The available fuels are rather poor with respect to thermal stress (that is, they possess low thermal conductivity, coupled with a high coefficient of thermal expansion), and special fabrication procedures imparting certain crystal forms to the fuel have been developed to either reduce these stresses or to enable the fuel to better withstand them without distortion or rupture. Another phenomenon, related to thermal stress, is creep, also aggravated by the elevated reactor core temperatures. Choice of materials, a usually effective way of controlling creep, is limited by nuclear properties, as mentioned above, but alloying with Fe, Ni, Cr, Co, Zr, W, Ti, and Mo is permissible in small amounts and aids in retarding creep.

Radiation itself produces pronounced effects on the metals used in the core. Its effect on the mechanical properties are strikingly similar to those of cold work. Tensile and yield strengths are increased while elongation is reduced; also, the effects of radiation are considerably greater on annealed metals as compared with hardened metals. Table III indicates this:

	Annealed	*Hardened*
Stainless Steels	55,000psi	25,000psi
Zirconium	8,000psi	5,000psi

Radiation has an unpredictable, detrimental effect on the resistance of metals to corrosion. The effect of radiation on metals has been shown to be due to neutrons, since metals are conductors and

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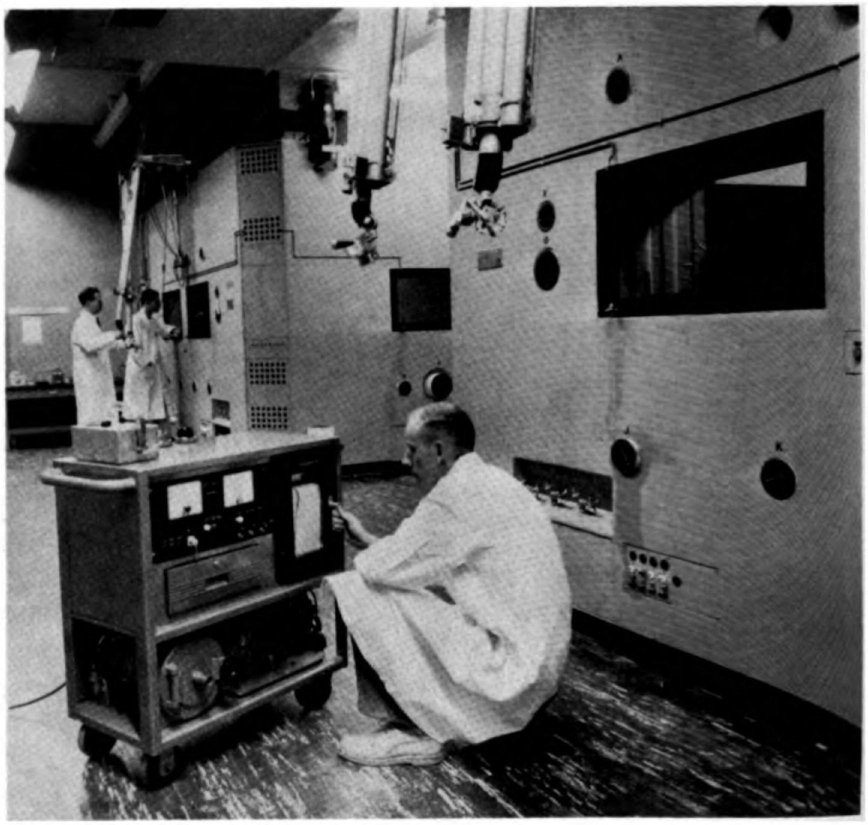
are affected only by neutral particles. The collison of neutrons in a reactor core with metallic atoms results in disturbances to the crystal lattice of the metal which cause not only the above cold work effects (Table III), but also dimensional and density changes and their associated stresses, too often quite severe.

Material purity becomes very important in particular component materials, where even fractions of one per cent of impurity can greatly alter the nuclear properties of the material. Zirconium is especially useful because of its extremely low thermal neutron cross-section, 0.18 Barns, while hafnium, a common impurity in Zr because of the occurrence of the two elements together in nature, has a neutron cross-section of 1800 Barns. Hafnium and zirconium have very similar chemical properties, and only in recent years has success to any degree been obtained in removing Hf from Zr. It is easily seen that a very small amount of hafnium raises the effective thermal neutron cross-section of zirconium to a level much less effective than that of pure Zr. Another difficulty of zirconium lies with gases; zirconium has a remarkable affinity for gases, which convert it to a brittle, difficult-to-work metal, even when dissolved in very small quantities.



A graph showing the radioactivity from a specimen within the chamber on the right, is examined by this North Campus technician.

Problems of Each Part

It is easier to grasp the problems in materials of a nuclear reactor if the components are considered individually, each with its particular difficulties, in the light of the previously discussed general material problems.

To begin with, the fuel and its cladding present difficulties primarily due to intense heat and radiation, because the fuel is in the heart of the core. Since fuels are limited to the three already mentioned (U-235, U-233, Pu-239), all that can be said about the fuel elements is that they must be free of all impurities of high thermal neutron cross-section. To strengthen the rather long, slender fuel elements, alloys of metals of low thermal neutron cross-section (A1 and Zr, principally) have been successfully used. Fuel cladding has a double duty to perform: it protects the fuel from corrosion and retains fission products. To perform these, it needs several properties; it must itself resist coolant corrosion; it must necessarily posses a low thermal neutron cross-section; and it needs a high coefficient of thermal conductivity. These properties limit the possible materials to aluminum, zirconium, stainless steels, and some ceramics. Aluminum and zirconium find widest use, zirconium being employed when the temperature exceeds about 500° F. Cladding is most satisfactorily attached to the fuel element by means of a metallurgical bond, which results in the highest heat transfer and a minimum of radioactive fission products escaping into the coolant stream. Impurities, which have a generally detrimental effect on corrosion resistance, are undesirable (not only in the fuel and cladding, but in most parts of the reactor). In addition, impurities of a high thermal neutron cross-section (most metals tend in this direction) are not wanted in all core parts, except for the shield and control elements, where high thermal neutron cross-section is a key necessity, because these impurities absorb neutrons, decreasing neutron efficiency. On absorbing neutrons these impurities suffer the ill effects of radiation, inducing stresses in the parent metal and lowering its corrosion resistance.

Another very critical component in the reactor is the coolant. Its most obvious necessary property is that it be a good conductor of heat and possess a high heat capacity. Also, the coolant should not be excessively corrosive; Na-K alloys are not, and purified water is satisfactory. For the reasons discussed previously, the coolant must have a low thermal neutron cross-section. Air is used only because of its economy, and only in smaller reactors. Water is commonly used because of its high heat capacity. Sodium and 44% Potassium Na-K alloys are used most widely because of their lower pressure requirements at elevated temperatures than with water, and because of the relatively high heat capacity of Na-K. A point well worth mentioning is the melting point of 44%, Na-K; sodium melts at 208°F, potassium at 145°F, but Na-K melts at only 66°F; this of course is another point in its favor. An example of a material unusable as a coolant because of one reason only is liquid fuel, because of its severe corrosiveness.

The moderator of the reactor also requires a material of low thermal neutron cross-section, for the above-mentioned reasons, and a high coefficient of thermal conductivity. Also, the moderator should have an atomic weight of no greater than twelve. This follows from the mechanics principle which reasons that a moving particle, such as a neutron, is most effectively slowed down by collison with a particle of mass about equal to its own. For this reason, materials of low atomic weight must necessarily be used as moderators. But high thermal neutron cross-sections rule out all possibilities except hydrogen, deuterium, beryllium, and carbon, usually in graphitic form. Hydrogen and deuterium are most frequently used in the oxide form as water and heavy water, respectively, which find great use because of their relatively high power to slow down fast neutrons, and low cost in the case of water. Beryllium, while costly at present, possesses excellent moderator properties; it has the highest atom density (atoms/cc) of any element, which gives it a high moderating efficiency, in addition to having the necessary atomic weight and neutron cross-section. It also has a high melting point, 2345°F, and low density, 1.83 g/cc, both of which are desirable properties. It presents somewhat of a problem in that it has a great affinity for O_2 and N_2, forming the high thermal neutron cross-section oxide and nitride, considerably reducing its moderating efficiency, and is quite brittle at room temperature. At elevated temperatures, however, its ductility increases markedly. Graphite is an excellent moderator, because of its low thermal neutron cross-section, good thermal conductivity, strength and creep resistance at the elevated core temperatures, and high resistance to thermal shock, a condition encountered when starting and stopping fission in a reactor, due to the temperature changes accompanying such operations. As with all moderator materials, graphite must be very pure — no impurities can be tolerated, especially those with high thermal neutron cross-sections. This requirement is especially stringent in the case of the moderator because of the great quantity of moderator material very near to the fuel; excessive neutron loss, with its associated high fuel cost, would be experienced with even very small quantities of impurities.

Reflector requirements are essentially the same as those for the moderator, since its purpose is that of attenuating and reflecting neutrons which would otherwise be lost. Identical materials are often used in both parts.

An important component of any reactor is itts control system, control usually being accomplished by the insertion of control rods into the core itself. Control rods perform their function by absorbing neutrons produced in the core fission, thus preventing further reactions by these neutrons, hence slowing down the overall fission rate. Obviously, the most necessary single property of a control rod is that it have an extremely high thermal neutron cross-section. Control rods should also be reasonably strong, to prevent structural problems. Boron finds the widest use, because of its extremely high neutron cross-section, 4,000 Barns, and its high melting point, 4170°F. Cadmium, also useful, is more limited because of its low melting point, 610°F; it is weaker at elevated temperatures than boron. Samarium and gadolinium, with cross-sections of 36,000 Barns, are excellent control materials, but cost inhibits their wide use.

The final reactor component is the shielding. Since its purpose is to absorb neutrons which have escaped the reflector and are lost to the reaction, it must necessarily possess a high thermal neutron cross-section. But radiation from the core must also be absorbed by the shield, this is the major problem. Alpha and beta radiation is easily stopped by thin sheets, but the high energy gamma radiation, the most deadly of the three from a safety standpoint, requires large quantities of mass of any type to be absorbed. For this reason, the shield is often concrete, to which can be added materials to perform the other necessary functions of the shield. Iron (steel) is useful as a material for shielding, as is lead; both are, from the standpoint of mass, and iron is from the standpoint of strength at high temperatures. Steel is usually necessary as a barrier to the heat radiated by the core. If the coolant is circulated into the shield, corrosion resistance and thermal stress must be considerations in selecting the shielding material. At the Oak Ridge National Laboratory, boron carbide, boron oxide, aluminum oxide, and B-A1 were successfully used as thermal shields. As yet, insufficient work has been done with water to establish its usefulness as a shield; one obvious detriment is its liquid state; it can support no weight, as steel, lead, or concrete can.

Additional problems are induced by the auxiliary reactor systems, especially the coolant cycle. Liquid sodium and potassium must be kept in the piping with no leakage. Pump and valve seals present a particular problem because of the dangerous nature of the liquids if exposed to the air. Electromagnetic pumps, with no moving parts and no seal problems, show promise, but these require more research and development to reduce their present cost.

A Summary

The general impression obtained on surveying the present situation with nuclear reactor materials is that little about metals, with regard to their nuclear properties, is known. There is now no way to predict the nuclear properties and usefulness of an alloy from its parent metal, nor is there a way to predict the effect of radiation, with any accuracy, on a metal; these are vitally important fields where research is urgently needed. Materials without a doubt now hold the key to the development of nuclear reactors as a practical means of supplying the world with power.

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