LIA24394

LEAD INDUSTRIES ASSOCIATION

292 MADISON AVENUE

NEW YORK 17, N. Y.

Also going to "hu" list on "Lead" 11/?/60

October 28, 1960

SUBJECT: MATERIALS FOR PORTABLE NUCLEAR REACTORS

To Members of the Lead Industries Association:

Attached is a reprint of an article appearing in the October 1960 issue of "Materials in Design Engineering" entitled "Materials for Portable Nuclear Reactors," prepared by a member of the LIA staff. We believe that you will find it both interesting and useful.

We have a limited supply of this reprint, which is available to members free of charge in quantities up to 25 and for five cents apiece in larger quantities as long as the supply lasts.

Very truly yours,

[signature]

Secretary

RLZ:JRH

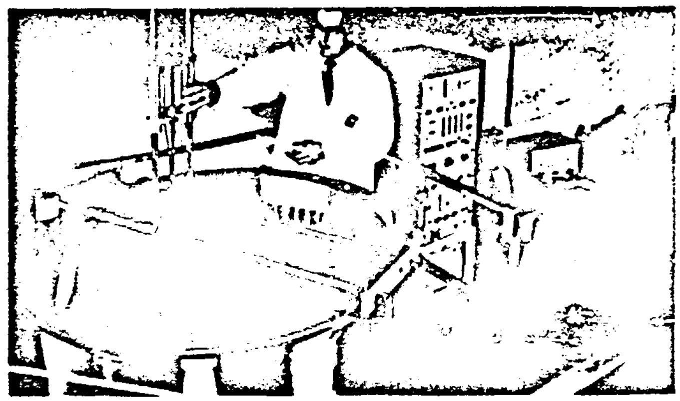
Att.

LIA24395

Materials for Portable Nuclear Reactors

Reactors designed for research and training purposes pose special problems in materials selection. Both cost and weight must be minimized. Here is a look at current practice in fuels, controls, moderators, reflectors and shielding.

by Edward J. [illegible],
Technical Director,
Lead Industries Assn.



NC 9000 reactor core consists of 275 aluminum tubes 1.25 in. in dia by 59 in. long arranged in hexagonal pattern and supported by two grid plates (not shown). The tubes are designed to hold 1 in. dia by 8 in. long natural uranium slugs whose total weight is 5500 lb. Uranium is made available to schools under AEC assistance program.

■ Portable research and training reactors are widely used for instruction and orientation with nuclear physics and to explain the principles of reactor design and operation. They are also especially useful for radiation detection and health physics investigations, and in moderate-level tracer research.

Such reactors differ greatly in design from larger reactors. They are moderately priced and low powered. Also, shipment, installation, operation and maintenance are relatively simple, safe and inexpensive.

Like other reactors, portable reactors involve many compromises in materials selection. Unfortunately, nuclear materials do not always have good structural properties, and are often heavy, massive and expensive.

1. Fuel materials

Fuels can be liquid or solid

The fuel materials used in portable reactors can be liquid or solid and are usually enriched with fissionable U-235 so as to reduce size.

Homogeneous reactors use liquid or solution-type fuels, or fuel uniformly divided and dispersed in a solid moderator. Advanced reactors such as L-77 (Atomics International) and AGN 201 and AGN 211 (both Aerojet-General Nucleonics) are homogeneous reactors and provide the only practical experience with homogeneous systems to date.

Heterogeneous reactors use separate fuel and moderator elements and are typified by the TRR (Nuclear Development Corp. of America) and NC 9000 (Nuclear Chicago) reactors. Heterogeneous portable reactors commonly use a so-called "canned" fuel element which, at the present state of the art, is giving ground to more efficient designs.

Design for minimum critical mass

The reaction rate and flux desired in a reactor fixes four factors: 1) the number of fuel atoms required per unit volume, 2) the ratio of fuel atoms to the atoms in the structure, 3) choice of coolant and moderator, and 4) operating temperature. Also, nuclear physics dictates the spatial distribution of fuel atoms within the core and, in the case of heterogeneous reactors, provides a first approximation of the shape and arrangement of fuel elements.

Distributed by:
Lead Industries Association
292 Madison Avenue
New York 17, New York

In designing a fuel system it is desirable to approach the minimum critical mass with a nonuniform fuel distribution arrangement. This approach, combined with judicious moderator and reflector selection, reduces fuel loading. And, from a safety standpoint, it insures that any rearrangement of the fuel will decrease reactivity.

Consider the effects of fuel growth

Solid fuels have a tendency to grow in preferential directions when irradiated. (Since low powered reactors produce low heat levels we can neglect the effects of heat transfer.) This growth is caused by elemental changes in the fuel as well as changes in chemical and structural properties. As burn-up proceeds, each fissioning atom is replaced by two fission product atoms (some existing as gases) which generally have a greater volume than the parent material.

The above effects tend to cause expansions and stresses in the fuel element and have to be accommodated lest they cause distortion. Distortion can affect coolant flow or the distribution of the moderator within the core matrix. And the resulting hot spots and disrupted flux patterns can result in shutdowns and costly repairs. Under such circumstances it is prudent to approach core design with the utmost feeling for safety.

Special liquid fuel problems

In principle, homogeneous reactors are based on the operational characteristics of the KEWB (Kinetic Experiment on Water Boilers) design. Unlike solid fuels, liquid fuels can be changed or removed easily and are free of the effects of anisotropy. Naturally, the materials retaining the fuels must resist corrosion and radiolytic decomposition. Because of its proper combination of structural, nuclear and corrosion properties, stainless steel is generally used in contact with aqueous uranyl sulfate fuel suspensions. Such suspensions should be completely free of harmful chlorides.

The problem of radiolysis with the water moderator in homogeneous reactors is only slight, since the free radicals that form tend to : nbine and establish equilibrium. The L-77 reactor, for example, contains a recombiner unit containing platinized alu-

Nuclear Fundamentals of Portable Reactors

Portable reactors are thermal type

Nuclear reactors are classified by their predominant neutron energy spectrum and fall into three categories: thermal, intermediate and fast. Portable research and training reactors are thermal-type reactors and incorporate a moderator and reflector. The moderator slows neutrons released in the fission reaction to thermal energies where the probability for fission is great. As its name implies, a reflector returns to the core neutrons that would otherwise leak out of the system. The reflector permits a reduction in fuel requirements, thus reducing the cost of both fuel and construction materials.

Subcritical vs critical

Depending on their sustaining features, portable reactors are either subcritical or critical.

An important factor in this relation is the effective multiplication factor, k—the ratio of the average number of neutrons produced by fission in each generation to the corresponding number of neutrons absorbed in the fuel, moderator, etc., or leaking out.

If $k = 1$, the chain reaction is stationary and self-sustaining, or critical. If $k < 1$ the chain is not self-sustaining and is subcritical (without an extraneous neutron source the chain reaction cannot be maintained). If $k > 1$, the chain is divergent and the system is supercritical.

The k values for portable research and training reactors are equal to or less than 1. Flux is confined to 10^7 to 10^{10} n per sq cm-sec to avoid danger of overexposure and needless expense.

Effective multiplication is made up of two factors: the infinite multiplication factor k_∞ and the nonleakage probability. The k_∞ factor is the ratio of average number of neutrons produced in each generation to the average number of corresponding neutrons absorbed. Nonleakage probability, on the other hand, is a measure of the probability that neutrons will not leak out but will remain until absorbed to cause fission.

Some neutron leakage is desirable for research and training purposes. Extent of leakage depends on two factors: The first is the dimensions of the reactor. The second is the distance a neutron travels from its birth as a fission neutron to its ultimate absorption in an experiment. This distance is related to a quantity called the migration length.

Thermal utilization should be high

For every neutron absorbed by a fuel atom, 2.08 neutrons are produced. Of these, one must be captured by another fuel atom to sustain the reaction. Thus, at the most *only* 1.08 neutrons are available for experimentation. Also, some will be captured in the moderator and structural materials in the fuel region. The ratio of the number of captures in fuel to the number of captures in the fuel-plus-moderator-and-structure is the thermal utilization, *f*.

Since one of the 2.08 neutrons is captured in a fuel atom, $1/f$ represents the total number captured in the fuel region and $2.08 - 1/f$ the number that leak out of the fuel region. Thus, if f is 1 there will be 1.08 neutrons per U^{235} capture available for experimentation. This is equivalent to a maximum value of 3.3×10^{10} neutrons per sec absorbed in experiments for each megawatt of thermal power. This maximum figure is a constant independent of reactor design. Thus, to make a research and training reactor *efficient* the thermal utilization in the fuel region should be high and experimental facilities should be properly placed to receive neutrons leaking out.

mina catalyst pellets which recombine circulating hydrogen and oxygen gases to form water. The equilibrium of the water depends on impurities and the fuel solute which can create an excess of either peroxide or hydrogen. An excess of hydrogen tends to suppress decomposition almost completely. Conversely, an excess of peroxide tends to increase decomposition.

The L-77 reactor also contains an overflow chamber to offset possible fuel solution expansion caused by bubble formation. If expansion is great enough it will force some of the fuel solution into the overflow chamber, thus making the reactor subcritical (k becomes less than 1) and producing an automatic shutdown.

Hot gases can be beneficial

The gases generated in a reactor can be beneficial. For example, in a liquid fuel reactor such as the L-77, "hot" gas can be transported to remote experimental apparatus, giving the unit great versatility. About 10 curies (15 to 20% of the total) of volatile fission product activity is present in the L-77 under equilibrium conditions.

Unlike gases in the L-77 design, however, the gases generated in the AGN 211 reactor are not beneficial and cannot be used for other gainful purposes. In the AGN 211 core there are about 45 curies of radioactive gases present at steady-state operation. About one-third of the gas is harmful iodine-131. (Maximum permissible concentration for iodine-131 is 5×10^{-9} curies per ml or 5×10^{-9} curies per cu m of air.) However, this quantity of activity should cause no trouble. In order to be hazardous the iodine must first diffuse out of the uranium oxide particles, through the polyethylene element and its coating, and then escape from the water. This likelihood is extremely small.

Life of polyethylene core materials

Polyethylene is somewhat more radiation resistant than water and tends to trap any decomposition products or gases occurring in the matrix. Radiation damage manifests itself in reduced density and loss of hydrogen from the polyethylene after exposures of about one week at a flux of 10^{12} n per cm²-sec. A flux time (nvt) extrapolation indicates that the core life of the material would be more than 10,000 hr based on an average continuous power of 100 w.

2. Control element materials

Reactors are controlled by changing the nuclear reactivity of the core. Change in positive reactivity can be made by moving the fuel, or by changing the moderator density or core leakage.

In the case of a reactor like TRR, simply changing the deuterium oxide level of the heavy water moderator permits fine "tuning" of the excess reactivity available. Fuel consumption can then be compensated for by adding small amounts of deuterium oxide, and the excess reactivity present need never exceed the desired low value of 0.75% k.

The AGN 211 reactor is even more flexible. Aside from certain disadvantages inherent in swimming pool-type reactors, this reactor has unrivaled accessibility and adaptability in its class. It is purportedly the only reactor in which the core materials and critical geometry can be varied in three dimensions without fabricating new fuel elements for each variation.

Changes in negative reactivity are made by changing the concentration of neutron absorbers or poisons in the core region. Such changes are typically accomplished in the AGN 211 reactor by two Boral safety rods: an aluminum-clad cadmium rod for coarse control and a stainless steel rod for fine control.

In a subcritical heterogeneous reactor using natural uranium and light water moderator (such as NC 9000), no control system is needed to prevent it from going critical accidentally. Natural uranium can go critical only when it is used in combination with heavy water.

3. Moderator materials

Neutrons released during fission have very large kinetic energies—as high as 2 mev (million electron volts). Moderation changes this kinetic energy to thermal energy by forcing the neutrons to collide with the nuclides of construction materials. The best moderator materials have low atomic weight, high scattering cross section, large energy loss per collision, and low absorption cross section for thermal neutrons.

Water, beryllium and graphite have good properties

In this discussion we can ignore aqueous homogeneous reactors since their moderator-fuel makeup is largely fixed. Although relatively expensive, heavy water, beryllium and graphite are eminently suited as moderator materials and provide lower fuel loadings than other materials such as light water. However, extra fuel loading in a light water reactor is advantageous since it enables the U-235 fuel to compete more favorably with water for neutrons in the fuel region. Thus, thermal utilization may be almost the same whether heavy water or light water is used.

However, apart from the above, the designer must transport, with minimum losses, the maximum number of excess neutron to where they can be experimentally used. Low absorption materials provide

LIA24398

an efficient "piping system." Deuterium dioxide in particular delivers more neutrons per gram of uranium consumed than any other—its efficiency of delivery is almost 100%.

Organic materials are inexpensive

Less expensive moderator materials are also available with properties approaching those of heavy water, beryllium and graphite. In addition to light water, organic materials such as the polyphenyls, paraffin and polyethylene can be used. These organics are particularly interesting because of their:

1. High hydrogen-to-carbon atom ratio.
2. Compatibility with fuel, can and other structural materials, resulting in low corrosion rates.
3. Low induced radioactivity.
4. Elimination of hazardous chemical reactions.
5. Fair resistance to radiation damage (see table on p 113).

Organic moderator materials help to reduce cost since they can be used with inexpensive carbon and low alloy structural steels. They also permit weight reductions because of their compatibility with light, low-cross-section materials like aluminum.

Organics plus metals offer good combination

The fair resistance of the organics to radiation damage can be improved by mixing them with appropriate reflector, gamma shield or fuel materials. The composites perform dual roles, improving both the durability of the organic material and the effectiveness of the metal. Combination with lead or lead-lithium pellets, for example, reduces energy absorption by the organic material. This technique is used in the multi-region primary of the L-77 reactor.

The relatively poor heat transfer properties of the organics can also be offset by combining them with other materials. For example, intimately mixing hydrogenous organics with lead or other metals increases thermal conductivity and specific heat, thus allowing higher operating temperatures, eliminating hot spots, etc.

The AGN 211 reactor uses fuel elements made of 20% enriched uranium dioxide particles embedded in a radiation-stabilized polyethylene. This system has an inherent safety advantage due to the negligible time delay in the transfer of heat from the fuel particles to the polyethylene moderator. If something should go wrong the prompt heating of the moderator would increase the thermal energy of the neutrons and tend to reduce fission-to-capture probability. Furthermore, the prompt heat expansion in the fuel-moderator elements causes a decrease in density and increases leakage from the core, resulting in immediate shutdown.

4. Reflector materials

The purpose of a reflector is to return to the core leakage neutrons that are not intended for experimental use. The size of the core (fuel and moderator), its critical mass, and its cost are substantially affected by the presence of a reflector.

Important selection factors

Like the best moderators, reflector materials are characterized by a high scattering cross section and low neutron absorption. They should be chosen so as to:

1. Minimize costs.
2. Provide a large negative temperature and void coefficient (these quantities tend to increase with a decrease in reflector thickness).
3. Eliminate or reduce core-reflector interface flux peaking and smooth flux distribution in the core.
4. Properly control the flow of neutrons into experiments.

Lead reduces weight, cost

One of the most useful reflector materials for portable research and training reactors is lead. Important savings in weight and costs are obtained when it is used in the dual role of reflector and gamma shield. The homogeneous L-47 reactor (now replaced by the more refined L-77) was the first to use lead in this way.

Lead acts as an essentially infinite reflector in the L-47 design. This means that experimental apparatus used at or near the reflector surface will not perturb the neutron balance in the core. Furthermore, no hazard is presented in the vicinity of the reflector when the apparatus is moved during operation.

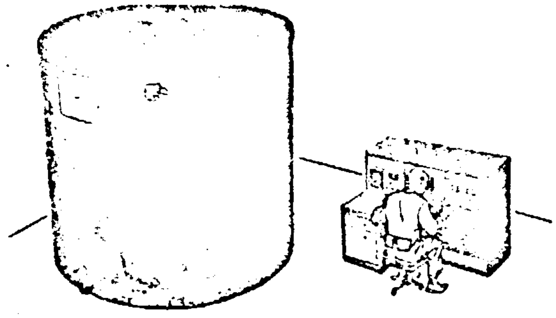
Also, since lead acts as an effective shield against in-core residual gammas, personnel have access to the interior when the secondary shield water tank is drained. In addition, since the lead is cast and bonded around the core vessel it helps improve the resistance of the core vessel to any sudden pressure surges that may occur.

The L-77 carried the use of multipurpose materials even further. Here an intimate mixture of lead shot and diphenyl is used inside the primary structure to provide neutron shielding or moderation in combination with gamma shielding or reflection.

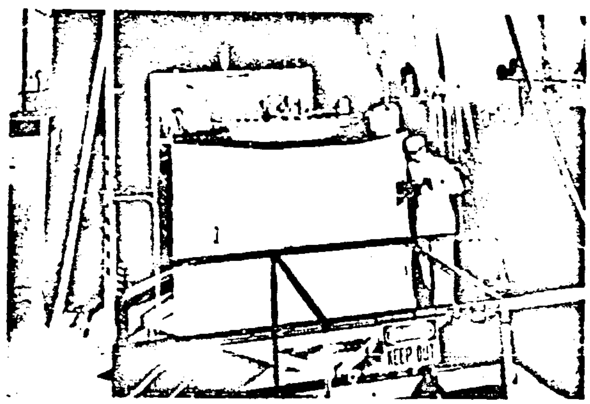
Composition hardboard also low in cost

Another popular reflector material is composition hardboard. Hardboard has good nuclear properties and maintains high neutron flux density within the core and experimental region. It is relatively free of impurities that absorb neutrons and has a large scattering cross section. Furthermore, it is inexpensive, readily available, and offers good resistance to moisture and heat.

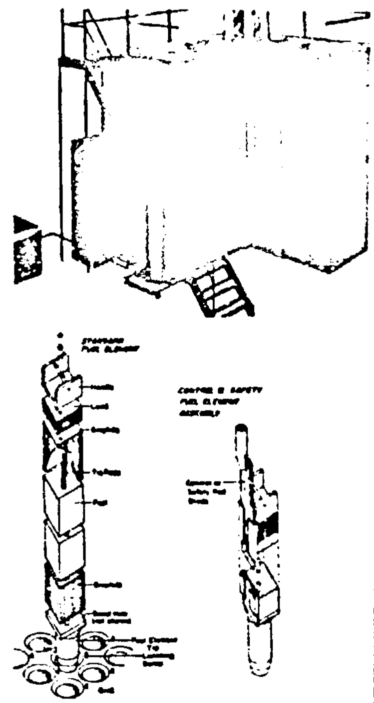
In designing the TRR reactor several reflector materials were considered, such as graphite, heavy and light water, beryllium and wood planking. Because of its low cost and other desirable properties hardboard was chosen



L-77 reactor uses fuel of uranyl sulfate enriched to 20% or more in U-235. Moderator is light water; reflector is lead pellets in diphenyl material.



TRR reactor with shielding removed. Neutron reflector used on sides and bottom consists of 1 ft of graphite sheathed with 3 in. of masonite which in turn is covered with ½-in. layer of borated (8 to 10%) polyethylene shielding. Additional shield (not shown) consists of 6-ft layer of ordinary concrete blocks. Enriched uranium fuel is centrally located in aluminum reactor tank and is cooled by natural convection of heavy water.



AGN 211 reactor and fuel element assembly. Moderator is made of polyethylene, reflector of 3 to 5-in. thick graphite, and shielding of concrete. The center 10 in. of each fuel element is composed of a homogeneous mixture of uranium dioxide in polyethylene. A 5-in. graphite reflector is used at each end of fuel element and a 2-in. lead shadow shield is used at outer ends of graphite.

to supplement graphite and heavy water reflectors. Cost of the hardboard for this application was $1.10 (all prices per sq ft) as compared to $38 for graphite, $600 for heavy water and $3000 for beryllium. Wood planking was rejected because it was less homogeneous than hardboard and more susceptible to warping and shrinking. Light water was rejected since it required a container that would be difficult to erect and modify. The hardboard is used in a 4-in. thick laminate made up of 5 layers, weighs 3.1 lb per sq ft, and is structurally self-supporting.

5. Shielding materials

Shielding falls into two broad classifications: thermal and biological. Thermal shielding is used to dissipate excessive heat from high absorption of radiation energy. It is not needed with small portable reactors because of their low power levels. Biological shielding, however, is needed to reduce gamma and neutron radiation at the outside surface of the reactor to a tolerable level—generally agreed to be 7.5 millirems per hr.

Unfortunately, materials that effectively stop neutrons are poor gamma absorbers. Up to about 3 mev, neutrons are attenuated best by low-atomic-weight materials. Conversely, good gamma absorbers should have high atomic weight.

In addition to having proper nuclear properties, shielding materials must be inexpensive and readily available since they are used in large quantities. Typical good shielding materials are lead, polyethylene, iron, concrete and water. Numerous metals may be used for shielding but lead is preferred because it can be used rela-

LIA24400

Three Important Design Objectives

1. Minimize radiation damage

Although the flux level in portable research and training reactors is usually lower than in other reactors, radiation can still affect the structural integrity of materials and components.

Radiation resistance depends on many variables and cannot be predicted with absolute assurance (see "Radiation Damage in Metals," M/DE, Jan '60, p 89). Complete assemblies may aid constituent parts or materials. On the other hand, the proximity of certain materials may render useless otherwise resistant materials. Some materials may have a lower threshold value than others, but may be more resistant to higher dosages. For example, nylon shows radiation damage sooner than TFE fluorocarbon, but with increasing dosage nylon maintains fair integrity long after TFE fluorocarbon has failed. Similarly, devices such as semiconductor diodes and triodes continue to function with degraded performance at dosages far above the damage threshold. In short, extrapolated damage data should be checked by actual tests.

The tables at far right show the approximate levels at which damage occurs for various reactor materials and components exposed to irradiation. These levels are conservative, and in most cases the specimens also received an equal number of gamma photons. From the data and considering power levels it is apparent that organic materials and some electrical components are most likely to be affected by irradiation. Selection of the most resistant material should be consistent with nuclear and cost requirements. Most instrumentation prone to damage can be relegated to remote consoles and positions. However, this may be impossible with electrical machinery, drive mechanisms, etc.

Electrical failures can be caused by insulation or lubrication breakdown. Formex and polyvinyl formal insulations for magnet wire appear to be quite resistant at medium temperatures. Nylon, polystyrene, polybutyral, mineral-filled phenol formaldehyde, polyester and furane plastics are all good organic insulations capable of withstanding high radiation dosage, although their physical changes must be considered in specific applications. Acrylic, TFE and CFE fluorocarbons, vinylidene chloride copolymers, casein, vinyl, epoxy and all cellulosic materials become poor insulations when exposed to high dosage. Alnico permanent magnets are not appreciably affected. Increasing radiation resistance is exhibited by the inorganic, inorganic-filled and heat resistant insulation materials. The best known insulations under intense radiation are glass and quartz which deteriorate very slowly.

No physical damage is observed in temperature sensitive devices such as thermocouples and resistance thermometers below dosages at which the basic materials are affected. The damage in these components is primarily caused by temperature rise due to irradiation. Radiation heating is a characteristic problem in energetic-type reactors and requires the use of pressure shells and special heat dissipation shields. It is not normally encountered in low-power "package" reactors.

2. Minimize corrosion

Salts containing boron are frequently used in water shields to further attenuate neutrons and to reduce radiolysis. Tests show the following range of corrosion rates (in mils per year) of metals in several borated solutions: lead, 0.1 to 0.6; mild steel, 0 to 0.3; mild steel-lead combinations, 0.3 to 0.9. These rates are negligible. Stainless steel can be expected to have still lower rates. Aluminum, however, despite its good corrosion resistance, is susceptible to galvanic attack.

An example of how corrosion can occur in portable reactors is provided by the NC 9000 reactor. Corrosion was traced to galvanic action between core components and the tank material. It was found that galvanic action could be stopped by replacing tap water with purified water having higher electroylytic resistance.

Corrosion can also be prevented by using suitable inhibitors in solution. Tests conducted with a 1630 ppm lithium chromate solution show that its inhibiting action is effective for at least six months with carbon steel, copper and lead.

---

tively thin, thus providing cost and weight savings.

Designing primary and secondary shielding

The primary or first shielding immediately surrounds the core or core structure. It is made of solid materials, is invariably leakproof, and in such reactors as AGN 201 and L-77 is made integral with the package. Great attention is required in its design since it comprises much of the overall cost and weight.

By nature of their design, swimming pool reactors such as AGN 211 do not have a leakproof primary shielding. However, the induced core radiation level of this reactor is low enough for safe fuel handling while providing sufficient flux for many activation experiments.

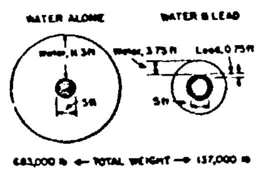
Secondary shielding is not considered part of the reactor package since it is usually erected on the site. Water and/or concrete blocks are frequently used as secondary shielding. Unlike primary shielding, secondary shielding is not used in equal thickness around the entire reactor. Secondary shielding requirements above or below the reactor can be minimized by taking into account the benefits of the foundation or floor below the reactor and uninhabited air space above the reactor.

In most designs access to the

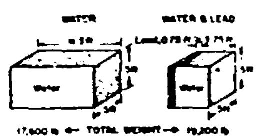
3. Minimize weight

Naturally the weight of portable reactors has to be kept to a minimum. However, compromises in materials selection are inevitable, and the usual practice is to use mixtures or layers of gamma and neutron absorbers.

Simple geometry tells us that considerable weight savings are obtainable with circular polyshields. The first drawing below shows the approximate weight difference in two shields designed to provide a same dose constraint. As indicated, the lead-water design has a considerable weight advantage over the all-water design. Similar comparisons for slab-type shields are shown in the second drawing.



***Comparative weights** of spherical shields made of water alone and double layer of water and lead.* (Hammid)



***Comparative weights** of slab shields made of water and water plus lead.* (Hammid)

SUMMARY OF DAMAGE THRESHOLDS FOR REACTOR MATERIALS AND COMPONENTS

Material or Component	Radiation Level, nvt[a]
Ductile and Fluid Metals (control poisons, shields, reflectors)	3 x 10[illegible]
Many Simple Inorganic Compounds	3 x 10[illegible]
Plastics (moderators, shields, reflectors)[b]	1 x 10[illegible]-1 x 10[illegible]
Bearings in Special Lubricants	6 x 10[illegible]
Permanent Magnets	3 x 10[illegible]
Capacitors and Small Motors[b]	1 x 10[illegible]
Resistors, Small Transformers, Electron Tubes[b]	3 x 10[illegible]
Dry rectifiers	1 x 10[illegible]
Organic Fluids (oils, greases, shields, moderators)[b]	1 x 10[illegible]
Silicon Diodes	1 x 10[illegible]
Transistors	1 x 10[illegible]

[a] In most cases samples also received an equal number of gamma photons.
[b] See also tables below.

RADIATION DAMAGE TO REACTOR AND SHIELD COMPONENTS[a]

Material ↓	Type of Damage	Estimated Threshold Damage (25%), rads
Water	Gas evolution, corrosion	Infinite
Paraffin and Olefin Hydrocarbons	Gas evolution, polymerization	1 x 10[illegible]
Monopheyl Hydrocarbons	Same as above	3 x 10[illegible]
Diphenyl and Polyphenyl Hydrocarbons	Same as above	1.4 x 10[illegible]

[a] From V. P. Calkins, "Radiation Damage to Nonmetallic Materials," (unclassified AEC report).
[b] 1 x 10[illegible] rads corresponds approximately to combined radiation of 8 x 10[illegible] thermal neutrons/sq cm, 8 x 10[illegible] fast neutrons/sq cm (above 0.1 mev), and 1.6 x 10[illegible] gammas/sq cm (average energy = 1 mev).

RADIATION DAMAGE TO CONTROLS AND INSTRUMENT COMPONENTS

Component ↓	Radiation-Susceptible Material	Estimated Threshold Damage (25%), rads
Capacitor	Paper or oil dielectric, phenolic or wax paper cover	4.5-7 x 10[illegible]
Resistor	Plastic cover	4.5-7 x 10[illegible]
Microswitch	Plastic case and actuator	4.5-7 x 10[illegible]
Selsyn	Organic wire insulation, brush holder, slot liners, and punchings and casing insulation	4.5-7 x 10[illegible]

reactor is lateral or radial and it is in these directions that shielding requirements and dimensions are greatest. Thus, reactors are generally somewhat wider than they are high. However, overall diameter is usually kept under 8 ft to facilitate transport. When water or some other liquid is used for secondary shielding the tank can double as a structural support for the core and/or the primary shielding.

The AGN 211 and NC 9000 reactors differ from others in that experimental access to the core is from the top of the reactor. Shielding for the AGN 211 in the radial directions is provided by 40 in. of concrete in the form of overlapping blocks. Vertical shielding is provided by 6 in. of graphite, 2 in. of lead and 4½ feet of water.

Attenuating neutrons

Neutrons are absorbed in two stages. First, high energy neutrons passing through a shield are slowed by elastic or inelastic scattering; the capture cross section for neutrons at high energies is extremely small. The second stage of capture occurs only when the energy of neutrons drops to low values. Large cross sections of most elements will produce quick capture of low energy or slowed neutrons. Therefore, the usefulness of neutron shield ma-

LIA24402

terials depends largely on their ability to attenuate high energy neutrons.

Elastic and inelastic scattering are produced by collisions between high energy neutrons and the shield nuclei. In inelastic scattering the recoil nucleus is left in an excited state and it therefore absorbs a larger fraction of energy than it does with elastic scattering. In general, inelastic scattering is more important with heavier nuclei which can be more easily raised to excited states. Elastic scattering is more important with light nuclei which can absorb a large amount of energy via recoil.

Neutron shielding must also be designed to protect against secondary gamma radiation produced by inelastic scattering and capture. This can be done by incorporating absorbers such as boron which reduce the energy of capture gammas and remove low energy neutrons as they are produced. Boron can be used in the form of soluble or insoluble salts, depending on the medium, or in the form of Boral, a mixture of aluminum and boron carbide. The TRR reactor uses a borated plastic; the L-77 reactor uses borated paraffin.

Attenuating gamma radiation

The effectiveness of a material in shielding against gamma radiation depends strongly on its specific gravity or atomic number, i.e., electron density. It is useful to remember that a gamma intensity of 2 mev is reduced by a factor of ten by 19 in. of water, 10 in. of concrete, 2.6 in. of iron and 1.7 in. of lead.

Gamma shields in themselves are also a source of neutron-produced gamma radiation or secondary radiation resulting from capture. This adds to the secondary emission of hydrogenous shields and to the attendant weight of shielding required. According to *Jansen et al*, a lead-lithium alloy shows good potential protection. Because of its thermal neutron absorption properties, lithium is effective in suppressing gamma ray production resulting from neutron interaction with lead. The alpha radiation produced has an extremely short range—several microns in lead—and is comparatively harmless. Although the alloy tends to corrode in air and water, corrosion can be prevented by incorporating it in hydrocarbon materials. Lead is virtually inert to nonpolar hydrocarbons and only slightly attacked by most polar materials.

Use of a lead-boron alloy for gamma shielding has not proved feasible because boron is only slightly soluble in lead. Similarly, production of the alloy by powder metallurgy has not worked out because of segregation problems. However, a cementation technique developed by Battelle Memorial Institute appears promising (see *Williams et al*).

Composite shielding combines advantages of single materials

Organic-lead mixtures are advantageous where it is desirable to have a hydrogenous material for neutron attenuation together with a heavy material with a high neutron inelastic cross section but low gamma ray production efficiency as the gamma attenuator. Since carbon is a good source of hard gammas when bombarded by high energy neutrons, it is desirable to distribute lead throughout carbon shields. In addition to satisfying nuclear requirements, mixtures of lead pellets and organic materials provide good design flexibility and inherent safety. Also, homogeneous mixtures are easily cast into shapes and easier to work with than laminated layers.

Spherical lead pellets have been used to advantage in the unique primary shield of the L-77 reactor. This shield consists of three concentric regions. The innermost region is composed of a mixture of lead pellets and diphenyl which surrounds a stainless steel sphere containing uranyl sulfate. It acts primarily to reduce neutron leakage, moderate escaping neutrons, and attenuate gamma radiation. The central shield region is composed of borated paraffin which further moderates radiation and captures a significant portion of thermalized neutrons. The third region, made of a mixture of lead pellets and paraffin, acts as a neutron-gamma shield.

Mixtures of lead and paraffin should be made as light as possible. Since neutrons create hard gammas in the carbon of the paraffin, there is no need to have more lead than is necessary to reduce the core gamma strength to approximately the same level as the neutron-induced secondary gamma strength. (Boron additions can serve to reduce the secondary gamma level. Lithium on the other hand could reduce the contribution of lead and the hydrocarbons.) This may suggest use of lead powder suspensions; however, these could tend to separate by gravity over prolonged periods at moderate temperatures. This would not be the case with pellet shields.

According to *Race*, cylindrical pellets would be less expensive than most spherical pellets. Also, the effective density of composite shielding can be varied without affecting the packing factor by using a cylinder of one material (e.g., carbon steel) with a liquid core or core of another metal (e.g., lead). This arrangement permits uniform materials distribution—more so than a random mixture of solid pellets of different materials. Also, by using cylindrical pellets to realize a specific packing factor, it is possible to obtain a range of gamma and neutron stopping ratios by changing pellet core size and the filling material. The average packing factor for a random arrangement of single-size cylinders (with length equal to diameter) is 0.366—slightly less than that of random-packed, single-size spheres which have a packing factor of 0.4.

References

Herwald, P., "Air Research and Development Command Technical Symposium," July '58, OTS PR 151457.

Jansen, D. H., Hoffman, E. E., and Shepherd, D. M., "Lead-Lithium Shielding Alloy. Metallurgical Studies," ORNL-2404, Metallurgy and Ceramics, TID-4500, Oak Ridge Natl. Lab., '60.

Race, H. H., U. S. AEC Publ. KAPL-448, '58.

Williams, D. N., Houck, J. A., and Jaffee, R. I., "A New Class of Lead-Base Alloys," *Metal Progress*, Feb '58.

Reprinted from MATERIALS IN DESIGN ENGINEERING, *October 1960 issue*

Reinhold Publishing Corporation
430 Park Avenue, New York 22, N. Y.