LOS ALAMOS SCIENTIFIC LABORATORY

OF THE UNIVERSITY OF CALIFORNIA ○ LOS ALAMOS NEW MEXICO

LAMPRE

A MOLTEN PLUTONIUM FUELED REACTOR CONCEPT

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ABSTRACT

A brief discussion is given of the concept known as Los Alamos Molten Plutonium Reactor Experiment (LAMPRE). A preliminary design is given for the purpose of illustration. The detailed design will be the subject of a later report.

INTRODUCTION

The long-range utility of fission nuclear power depends upon the development of a plutonium fueled reactor capable of being refueled by an integral, or associated, breeding cycle. If full utilization of the energy content in the world's supply of uranium is to be accomplished, the more abundant U^{238} must be converted into the easily fissionable isotopes of plutonium. The need for this full utilization is apparent when it is realized that the economically recoverable U^{235} content of uranium ores[1,2] is sufficient to supply projected world power requirements for only a few tens of years. Breeding on the plutonium cycle extends fission power capabilities by a factor of 140, yielding thousands, instead of tens, of years of world energy reserves.

The high values of the capture-to-fission ratio at thermal and epithermal neutron energies for the plutonium isotopes preclude these types of reactors from an integral plutonium breeding cycle system. To obtain an appreciable breeding gain, a plutonium fueled reactor must be either a fast, or a fast-intermediate, neutron spectrum device where breeding ratios of the order of 1.7 may be expected from suitably designed systems. The power producing reactor of the future must logically be a fast plutonium breeder.

A competitive power producing reactor must have the following characteristics: (1) a fuel which is easily processed and/or capable of withstanding large fractional burnups and (2) a large specific power (> 500 w/g of fuel). The latter requirement is essentially a measure of the fuel inventory for a fixed output machine.

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[1]S. Glasstone, Principles of Nuclear Reactor Engineering, pp. 1-2, D. Van Nostrand Co., Inc., New York, 1955.

[2]P. C. Putnam, Energy in the Future, pp. 214, D. Van Nostrand Co., Inc., New York, 1953.

The use of a mobile metal fuel in a molten, or pseudo-molten, state best satisfies the first requirement above. The second requirement is strongly dependent upon the design of the reactor heat-exchange mechanism and may be met by either a high fuel dilution or an extremely efficient heat-transfer mechanism.

In order to maintain a fast-neutron spectrum, fuel densities in a plutonium breeder will be high, and coolants must be either molten metals or salts. The latter characteristic will permit large amounts of power to be extracted from relatively small volumes, thus obtaining a large figure of merit (specific power). Hydrogenous and organic coolants are eliminated because of their attendant neutron moderation properties, high vapor pressures at high temperatures, and relatively poor resistance to radiation damage. For efficiency reasons the system temperature should be as high as is compatible with a long operating life. Therefore, to be in step with modern electrical generation techniques, this would imply coolant outlet temperatures of the order of 650°C.

The Los Alamos Scientific Laboratory feels that construction of a demonstration reactor aimed toward a solution to the plutonium power reactor problem is one of the best ways to utilize its relatively small pool of reactor manpower and talent and to obtain both design experience and fundamental knowledge. The demonstration reactor will itself be an integral experiment, yielding a large amount of engineering experience, plutonium technology, and information concerning the compatibility of materials under high heat and neutron flux conditions. Such an undertaking is based upon the Laboratory's unique assemblage of plutonium experts, plutonium laboratory equipment, and accumulated experience in handling the element.

BASIC COMPONENTS

Before discussing the LAMPRE proposal in detail, the following résumé will treat some of the possibilities for the three basic components of a power reactor: the fuel, the container, and the coolant.

1. Molten Plutonium Fuels

Plutonium metal melts at 640°C, a temperature that is somewhat high, but not beyond the bounds of utility. Fortunately, there are alloys of plutonium that have significantly lower melting temperatures. Specifically, eutectic alloys of plutonium with iron, nickel, and cobalt all have melting temperatures in the vicinity of 400 to 450°C. Ternary and quaternary alloying agents will further lower these melting temperatures by a few per cent. One characteristic of these transition metal alloys is that they do not dilute the fuel volumetrically to a great extent in their eutectic compositions.

Other alloys of plutonium which are more dilute in fuel and have not too unreasonable melting temperatures are the magnesium-plutonium and bismuth-plutonium alloys. The spatial dilution of fuel atoms alleviates the high power density problem, but, unfortunately, these alloys have melting temperatures significantly higher than the transition metal alloys.

A compilation of the interesting fuel alloys, their melting points, and eutectic compositions appears in Table I.

Table I

FUEL ALLOYS

Alloy	Eutectic Composition, at. %	Melting Point, °C	Approximate Density, g/cc
Pu-Fe	9.5 Fe	410	16.8
Pu-Co	10 Co	405	16
Pu-Ni	12.5 Ni	465	16
Pu-Mg	85 Mg	552	3.4
Pu-Bi	Non-eutectic	271-900	

2. Container Materials

A material capable of being fabricated into various shapes and resistant to high temperature corrosion by the fuel alloy is a necessity if practical use is to be made of the low melting temperature plutonium alloys. As the transition metals readily form low melting point alloys with plutonium, the normal constructional materials, steels and nickel alloys, are eliminated.

The next alternatives, the refractory metals, have been used with measurable success to contain the various alloys of plutonium. Tungsten and tantalum have been somewhat better containers than molybdenum and niobium and much better than chromium, vanadium, and titanium.

The requirement of fabricability eliminates several of the refractory metals, such as tungsten and molybdenum, because of the poor state of their peculiar welding art.

The limitations in metallurgical knowledge at present lead to the conclusion that tantalum will be one of the best container materials for these plutonium alloys. The high temperature strength properties and the heat-transfer properties of tantalum are excellent; moreover, it is weldable. The parasitic capture cross section of tantalum would be intolerable in an epithermal or thermal power breeder reactor, and, though relatively large in a fast spectrum, its effect on neutron economy in a fast reactor can be made small, if not minor, by careful design.

Short-term (two-week) dynamic corrosion tests indicate that tantalum's resistance to corrosion by molten sodium, a possible coolant, will be adequate (see Table II). Long-term static corrosion tests (9000 hr at 650°C) indicate that the fuel is compatible with tantalum at proposed operating temperatures.

Table II

Na-Ta SHORT-TERM DYNAMIC CORROSION TESTS

	Corrosion Rate	
	600°C, mils/yr	650°C, mils/yr
Cold-trapped Na	0.8	8.0
Ta hot-trapped Na	< 0.2	< 0.4

3. Coolant

A desire to obtain a high power density at high temperatures and low pressures in a high radiation field dictates the use of molten metal or salt coolant. The list of possibilities is topped by sodium and bismuth. A few words about the properties of these coolants are probably appropriate at this point.

Sodium is advantageous because of its low melting point, good heat transfer properties, low pumping power requirement, and because there has been considerable engineering experience with it. Its poorly known long-term corrosion properties when in contact with the better container materials such as tantalum, and its explosive burning property when exposed to water or moist air, are distinct disadvantages.

Bismuth, on the other hand, does not react explosively with water, nor does it burn in air. Pumping power requirements some five times larger than for sodium, its higher melting temperature, and the polonium build-up problems are disadvantageous factors of a bismuth coolant. However, the corrosion resistance of tantalum in dynamic, high temperature bismuth is excellent, according to the Ames experiments.[3]

LAMPRE

A first step in solving the plutonium power reactor problem is to prove the feasibility of operating and maintaining a molten plutonium power reactor core. To this end, the reactor assembly known as LAMPRE I has been devised. The LAMPRE system has the following essential features:

1.	Fuel alloy	molten plutonium-iron (eutectic composition, 9.5 at. % Fe)
2.	Container	tantalum
3.	Reflector	steel
4.	Shield	graphite, iron, concrete
5.	Coolant	sodium
6.	Power	1 Mw heat
7.	Heat transfer	internally cooled core
		straightforward tube-shell heat exchanger
		heat dumped to air
8.	Breeding	no breeding blanket

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[3]R. W. Fisher and G. R. Winders, High Temperature Loop for Circulating Liquid Metals, Ames Laboratory Report, November, 1955.

1. Core

The LAMPRE core consists of three parts: fuel alloy, container, and coolant. A proposed design, described in detail below, yields a structure which is approximately 50% by volume fuel alloy, 15% structure, and 35% coolant. The minimum tube separation is slightly under 1/16 inch. This configuration has a capability, at reasonable heat-transfer rates, of developing a specific power of better than 250 w/g. More efficient systems can utilize a similar structure but must dilute the fuel volumetrically to obtain a larger heat-transfer surface per unit of contained fuel. The larger area-to-volume ratio can be obtained by going to smaller diameter tubes and/or closer spacing of the tube array. In the tube-shell arrangement, the fuel is located on the outside of the tubes and the coolant flows through the tubes. Such a scheme preserves the volumetric integrity of the fuel. Other radiator-type schemes, which also preserve fuel integrity, are conceivable.

The over-all assembly will be designed so that the core will be completely filled during operating conditions. The estimated core height is 6.5 inches. Tantalum expansion, filling, and draining tubes will be attached to the core structure. A reference core assembly would be:

Container	tantalum
Tubes (547)	3/16-in. o.d., 0.015-in. wall, hexagonal array
Cage shape	right cylinder, 6.25-in. o.d., 6.5-in. height
Headers and shell	0.040 to 0.080 in.
Critical mass	~ 26 kg plutonium alloy

2. Reflector

No attempt to breed will be carried out in the first LAMPRE concept. Although the over-all coolant container will be made of stainless steel, the fast-neutron reflector will be made of steel and will be cooled by the main sodium stream. The thickness of the radial steel reflector will be adjusted to be thin enough, neutron-wise, to obtain adequate external reflector control but will be too thick to allow the thermalized neutrons returning from the graphite shield to build up a power spike at the core surface. The core, though slightly coupled to the reflector and shield, will have a mean fission energy greater than 500 kev, ensuring a high possible breeding gain. The top and bottom stainless steel reflector slugs will also be sodium-cooled and will be essentially "infinitely" thick to fast neutrons. The coolant channels will be drilled or machined into solid slug or disk castings.

The whole structure will be encased in a double-walled thimble arrangement and immersed in a graphite-concrete shield pit. A schematic arrangement of the core, reflector, and shield system is given in Fig. 1.

3. Control

The control of LAMPRE will be effected by reflector-type mechanisms. An annular shim control displacing the innermost 4 inches of shield with aluminum will be used as a coarse criticality adjustment mechanism. Several replacement cylinders, replacing the inner portions of aluminum with void, will be used as fine controls. A rotating control cylinder will be built into the system in anticipation of safety and neutron kinetics experiments.

The radial thickness of the steel fast-neutron reflector is adjusted so that the fast and intermediate neutrons returning to the core from the aluminum reflector and water shield are worth approximately 10% to the core critical mass. Displacement of the aluminum reflector effectively reduces the neutron reflection back to the core, yielding an external large effect control mechanism adequately

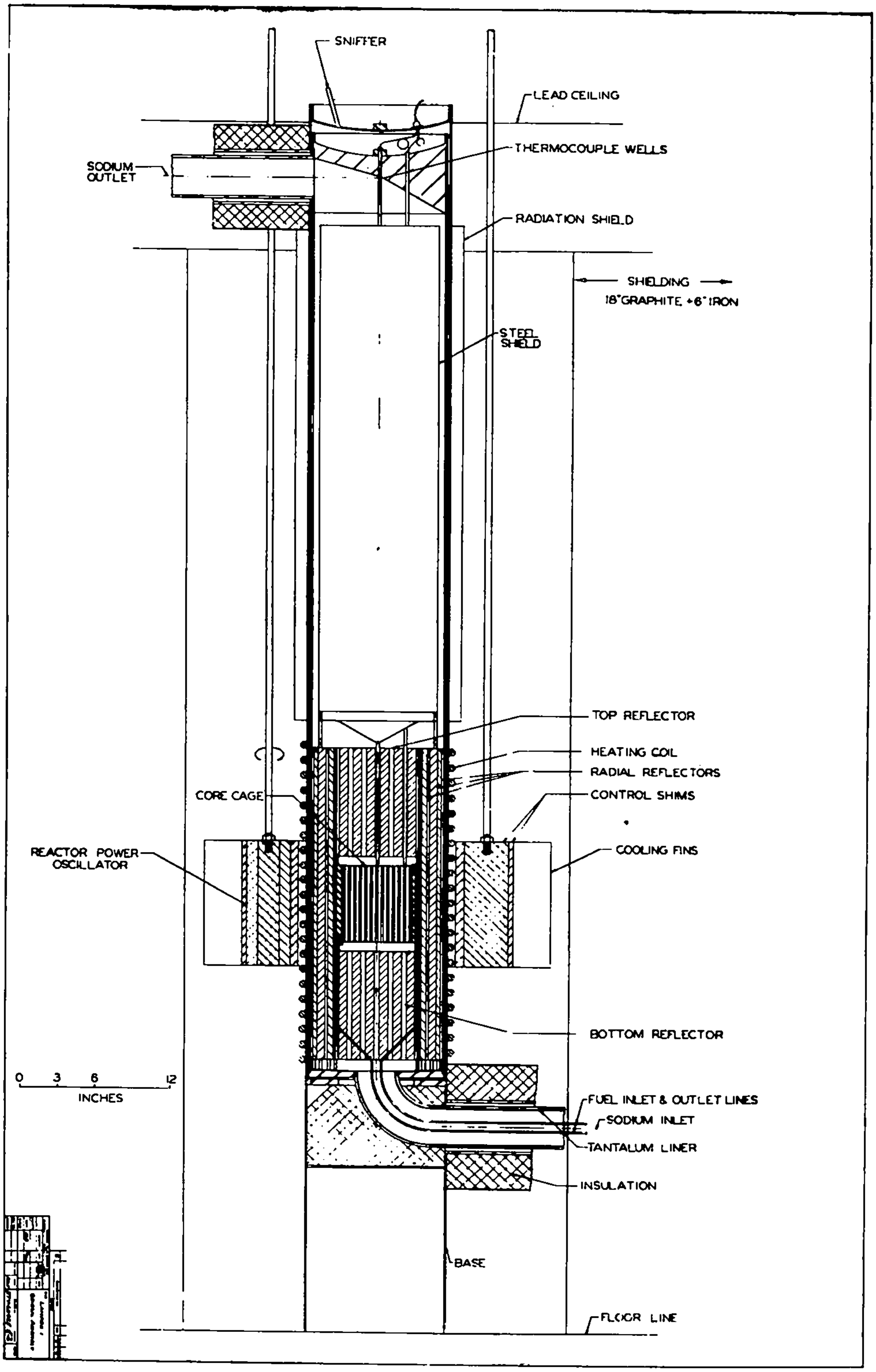

Fig. 1. Core, reflector, and shield system

cooled by aluminum conduction and air convection.

The LAMPRE Critical Experiments have proven that aluminum-void replacement mechanisms are effective and operable. The annular shim has been shown to be almost ineffective at distances greater than 2 inches above or below the core height for the geometry. These results have been incorporated into the LAMPRE design as presented in Fig. 1.

4. Coolant Circuit and Heat Transfer

The first choice of coolant for LAMPRE will be the liquid metal sodium. Removal of a megawatt of heat from the LAMPRE core will require a flow of sodium of the order of 150 gallons per minute entering the reactor proper at a nominal temperature of 450°C, traversing through the side reflector, the bottom slug reflector, reactor core, and top slug reflector, and exiting at a nominal temperature of 600°C.

The hot sodium will be pumped through the reactor by electromagnetic pumps to an external air radiator, where the thermal energy will be dissipated to the atmosphere.

Considerable effort will be expended in auxiliary equipment to purify the sodium and keep it as oxygen-free as possible. The purpose of this extensive cleanup system will be to keep the sodium-tantalum corrosion rate as low as possible. Tantalum hot-traps will be operated continuously to maintain the low contaminant level of the sodium.

Under the flow conditions and for the mechanical core design given above, the following nominal heat-transfer conditions are obtained for an output of 1 core megawatt:

Na flow	~ 150 gpm
Na inlet	450°C
Na outlet	600°C
Na Δt	~ 150°C
Max. Na linear speed	3.5 ft/sec
Pump flow	2-100 gpm (EM)
Pump pressure	25 psi at rated flow
(Δt_w) Tube walls	~ 6.5°C
(Δt_c) Coolant bulk	~ 8.5°C
(Δt_f) Fuel hot-spot	~ 22°C
Tube hoop stress	~ 800 psi

In case of a system failure or shutdown, the core will have to dissipate, on a short-term basis, approximately 5% of its steady state power by convection, conduction, and radiation.

The large value of total heat-leak (~ 50 kw) will require that the start-up heating units (to melt the sodium and the fuel) be somewhat large since they must accommodate the heat-leak losses until nuclear power is generated.

5. Installation

The proposed installation site for LAMPRE will utilize hot-cell, shielding, and auxiliary facilities in existence at Los Alamos Scientific Laboratory which were designed for the handling of kilocurie radioactive sources. As the cell was not designed for power reactor experimentation, and particularly not for sodium plants, some modifications and compromises have to be made with straightforward reactor design principles. A proposed plant layout is depicted in Fig. 2. The lack of elevation prevents a large convective head from being incorporated easily into the system. Remote fuel handling means will be located at the south end of the cell proper. The reactor will be located in the water shield at the north end of the cell. Sodium pumps, and cleanup and heat removal equipment will be in the adjoining rooms as shown in Fig. 2.

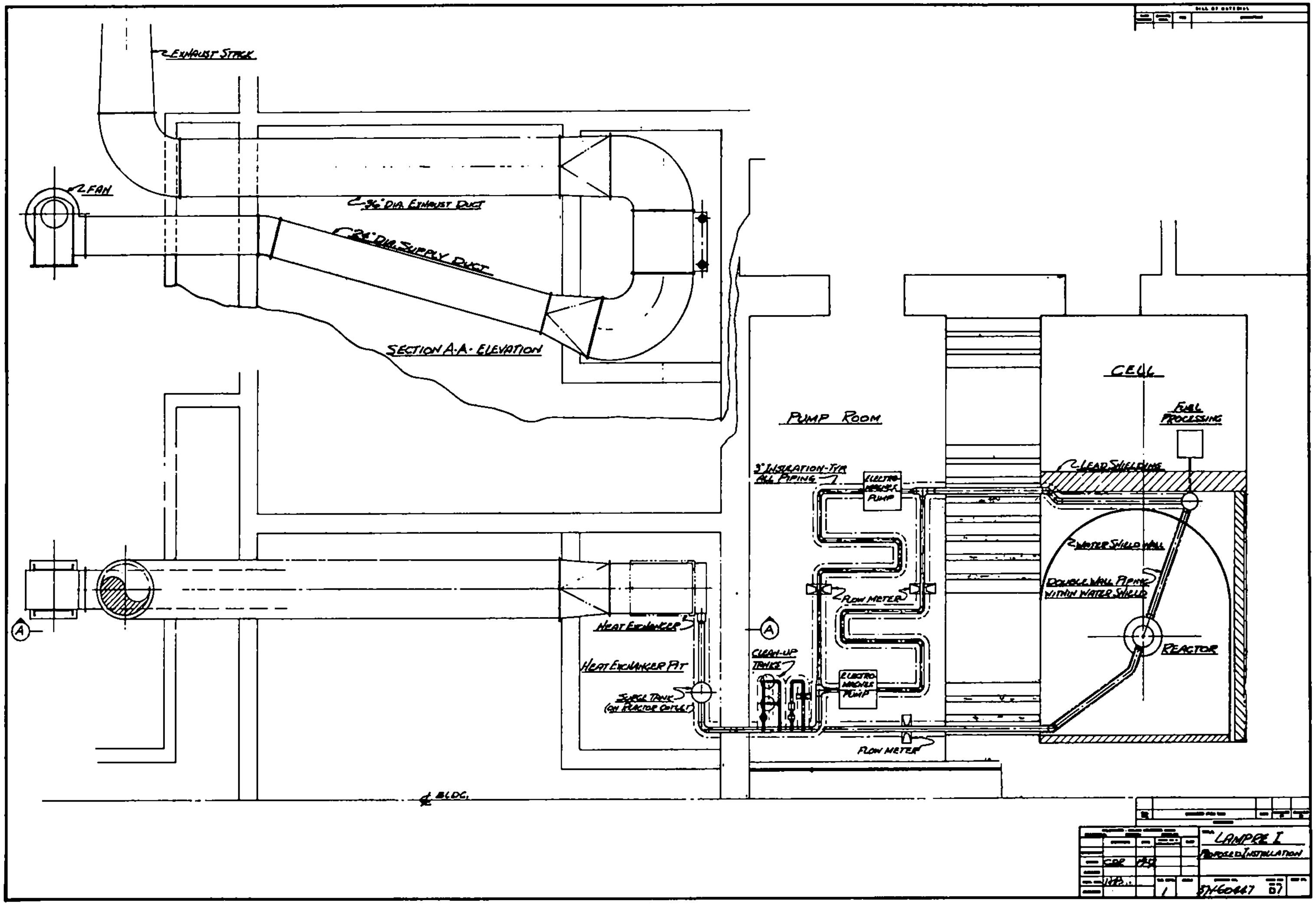

Fig. 2. Proposed installation for LAMPRE