mately 500-C temperature and higher.

2. *Slurries*, such as dispersions of inter-metallic compounds or alloys of uranium in low-melting-point alloys.

3. *Fused salts*.

To postpone the need for solving many problems of fluid fuels, solid fuel is preferred choice at present. Yet some of the advantages of fluid fuels can be gained through the use of relatively low-melting materials even though in solid form. Uranium alloy is a reasonable choice for the original effort.

**Exclusion Area.** Present safety rules require a very large exclusion area around an atomic plant. Thus, to build a reactor within the distribution territory of the Detroit Edison Co. would cost, per kw for land alone, 50% of present steam-plant cost. For the first few reactors built this may be a critical factor in total cost.

One way out would be to locate the reactor offshore in a body of water close to the distribution territory. Reactor and appurtenances could be installed on a barge or ship, floated to location and sunk in shallow water, or anchored there. Steel tanks, filled with sand and water, would provide shielding. Initially only the reactor with its integrated separation facilities would be built, to hold down first costs. Heat produced can be readily "dumped" in such a spot. Electrical generation and transmission facilities could be added later.

**Reactor Types.** Table I gives data on mechanical arrangements, which might meet all or part of the desired requirements listed previously:

1. A jet-mixed centrifugally separated liquid-cooled unit with liquid fuel, continuous processing (*C* in table).

2. A design with liquid fuel contained in reactor "pot," with coolant in tubes, (*A-1* in table).

3. Coolant outside fuel tubes with liquid or mobile fuel inside tubes, with or without fast, continuous processing.

Column *B* in table outlines first design to be investigated. It uses a uranium alloy in solid form. This type promises to provide many of the needed characteristics and should be capable of quite early development.

**Future Reactors.** The ultimate objective (*C* in table) should be a fast reactor with a true fluid fuel. It would include metallurgical processing and would not have conventional heat-transfer surfaces. It might be built of refractory materials that would be reasonably good for either thermal (slow) or high-energy neutrons. The core would be all molten metal.

Fertile material (that is, convertible into fissionable material) might be either depleted uranium or thorium, depending on product desired.

Another basically simple type of mobile fuel reactor is one in which a pot of molten fuel is cooled by coolant flowing through it in tubes or metal shells (so-called "radiator" type). Here the container material becomes a critical problem. In table, *A-1*, *A-2* and *A-3* are variations of this.

Type *B* is a variation in which fuel flows in and out of pot in a molten state, but is held as a solid at a somewhat lower temperature during most of its stay in the reactor.

# Monsanto Chemical – Union Electric

**As a first step, these companies favor a sodium-cooled graphite-moderated slow-neutron reactor using natural uranium. For each of two reactor layouts, varying in detail, their report compares power cycles using the heat output in different ways**

The Monsanto Chemical–Union Electric team was asked to study the feasibility of a reactor to produce both plutonium and power—one that could be built within the next few years. Studies assumed production of military plutonium for five years. After that, plant would be run for power alone. Table I summarizes characteristics of two similar reactors considered.

**Hanford reactors** gave a starting point of experience to speed design and construction. Because water as a coolant in a Hanford reactor would not permit high-enough temperature for economical power production, sodium was chosen. Sodium at low pressure can remove more heat than pressurized water. Also, it does not corrode stainless steel up to 900 F or higher. As plutonium production is nearly proportional to heat output, sodium coolant permits making more plutonium from a given size reactor.

**First-Choice Reactor.** For this sodium-cooled and graphite-moderated design, metallic uranium was chosen because it minimizes enrichment required and this material is relatively well known. A maximum uranium temperature of 1100 F was chosen to leave a margin of safety. Two potential designs were arrived at. Both have the same general arrangement but differ in the coolant systems and techniques of loading and unloading (see table).

Moderator and surrounding 2-ft-thick reflector is assembled from graphite blocks to form an octagonal prism 24 ft high by 29 ft across the flats. Cooling-channel holes are spaced in a square lattice. Tubular fuel elements, placed in holes by a suitable loading mechanism, are cooled by sodium flowing both through and around them.

Hot sodium flows through heat exchanger and is then pumped back to reactor. Special protection prevents sodium vapor from diffusing into graphite, spots sodium leaks, and cools graphite.

**Fuel channels** can be loaded and unloaded while running at full load. After a few days "cooling," irradiated fuel assemblies moved from the reactor are transferred to lead shipping "coffins" with 12-in. walls. All fuel handling equipment is remote controlled.

Studies indicate that the most economical plutonium-power reactor uses enriched fuel. Cost of enriching is more than offset by resulting production of more plutonium, lower unit cost.

**Coolant Circuits.** To prevent contact and resulting violent reaction between sodium and water, shell-and-tube heat exchanger would have double concentric tubes with mercury-filled barrier space between. Safety hazards of sodium leaks, and radioactivity of sodium in the recirculating system, require that entire sodium circuit be completely leaktight.

Fortunately, valve stems can be sealed by double bellows with a leak detector between bellows to show failure of the first line of defense.

For pump shafts, the literature suggests such possibilities as canned rotors, floating shafts, canned motors, frozen seals, etc. But the only completely leakproof pump developed to date is the electromagnetic type. It is assumed it will be used for any plant planned in the immediate future.

The sodium-to-water heat exchanger, and sodium pumps and piping, must be shielded for gamma radiation, preferably each unit separately protected.

**Internal Cooling.** Power cycle for *Case A*, Table I, is based on receiving sodium from the reactor at 650 F and returning it at 300 F. Heat exchangers generate 3 million lb per hr of dry saturated steam at 150 psi. Turbine cycle has a gross thermal efficiency of about 22%. Electrical output is about 220 mw from two units. Auxiliary power totals about 5.5% of gross capability.

Such a bulky low-pressure turbine-generator is a far cry from today's typical unit. It requires four 18-in. steam inlets with live-steam reheat between stages. Regenerative feedheating can't be used because condensate must go back to heat exchangers as cold as possible. This is to take advantage of low sodium inlet temperature and also to get lowest capital cost per kw even at a slight decrease in efficiency.

**Internal, External Cooling.** Two power cycles are considered for the *Case B* reactor with internal and external cooling. One cycle uses heat output of sodium over entire temperature range of 300 to 900 F. The other rejects heat of coolant below 500 F. This greatly reduces investment and gives a power output of more readily marketable size.

For both cycles, steam conditions have been taken as 400 psia and 746 F to the turbine. Absolute pressure at condenser is 1.5 in. Hg. In the first cycle, about 8.8 million lb of steam per hr is fed to turbine, with a gross thermal efficiency of about 28%. Resulting gross electrical output runs about 878 mw from five units. Auxiliary power, including sodium pumping, is about 5% of gross capability.

In the second scheme, about 4.8 million lb per hr is used, with same efficiency as in the first. Gross electrical output is about 579 mw from three units. Net output is about 554 mw. Heat from the coolant in temperature range from 300 to 500 F would be rejected by producing steam at 25 psia and condensing it at 20 psia in a water-cooled heat exchanger.

**Electric Power Only.** Studies assume limiting plutonium production to a 5-yr period. Power plant should be amortized in this period unless there is some way of making it useful later. After five years there would be several ways to continue power production in an era when power, rather than plutonium, would be the controlling factor.

For example, the reactor could be run for power alone. But even with equipment fully amortized, cost of electricity from such a source might be just as high as from conventional fuel-burning plants. Yet such operation could be advantageous from a national point of view; the reactor, in continuous operation, would be immediately available as a military plutonium producer when needed. Value of having a standby plant in operating condition should be credited to reactor operation. This would reduce power cost.

Another course would be to shut down the reactor and replace it by a modern high-pressure boiler and high-pressure topping unit. Or, again, a high-pressure boiler alone might be built to supply the turbine. This assumes the original plant to have been designed to produce steam at some high pressure where cycle efficiency could be later improved through use of superheat.

Costs in Table II, based on preliminary information, do not include such items as land, financing charges, public liability, insurance, Federal income taxes and profit.

## I—Characteristics of Sodium-Cooled Graphite Reactors

| | Case A | Case B |
|---|---|---|
| Purpose | Plutonium and power | Plutonium and power |
| Neutron energy | Thermal (slow) | Thermal (slow) |
| Heat output, mw | 1000 | 3000 |
| Materials and amounts: | | |
| Percent enrichment of U235 | 0.83 | 0.95 |
| Amount of uranium, kg | 214,000 | 214,000 |
| Fuel elements | Internal cooled tubes | Internal, external cooled tubes |
| Moderator | Graphite | Graphite |
| Reflector | Graphite | Graphite |
| Shield | Concrete | Concrete |
| Primary coolant | Sodium | Sodium |
| Fertile material | U238 | U238 |
| Fuel; max uranium temp, F | 1100 | 1100 |
| Coolant | | |
| Inlet temperature, F | 300 | 300 |
| Outlet temperature, F | 650 | 900 |
| Maximum velocity, fps | 20 | 20 |
| Gpm at 300 F | 70,000 | 120,000 |
| Cfm at 300 F | 9000 | 16,000 |
| Pumping power (50% eff), kw | 3000 | 5000 |
| Dimensions: | | |
| Core | Octagonal prism 20 ft high, 35 ft across flats | Octagonal prism, 20 ft high, 35 ft across flats |
| Reflector thickness, ft | 2 | 2 |

## II—Estimated Electric Power Costs

| | Case A | | Case B | | Modern steam plant | |
|---|---|---|---|---|---|---|
| Capital costs, $\$10^6$ | 26 | | 61 | | 44 | |
| Net output, kw | 210,000 | | 554,000* | | 260,000 | |
| Cost, \$/kw | 124 | | 110 | | 169 | |
| | $\$10^6$/yr | Mills/kwhr | $\$10^6$/yr | Mills/kwhr | $\$10^6$/yr | Mills/kwhr |
| Depreciation** | 5.20 | 3.30 | 12.20 | 2.94 | 1.26 | 0.65 |
| Property taxes, insurance | 0.52 | 0.33 | 1.22 | 0.29 | 0.88 | 0.45 |
| Fuel cost (coal @ 23¢/$10^6$ Btu) | 0.0 | 0.0 | 0.0 | 0.0 | 4.63 | 2.37 |
| Operating cost | 0.79 | 0.50 | 2.10 | 0.50 | 0.98 | 0.50 |
| Total | 6.51 | 4.13 | 15.54 | 3.73 | 7.75 | 3.97 |

Assumptions: Plutonium sale offsets all fuel costs; operating time, 7500 hr/yr; taxes, insurance, 2%; depreciation, 20%. *Heat rejected below 500 F. **20% on cases A, B; 2.86% for coal plant