APPENDIX VI-B

LEVEL II DEDICATED FACILITIES

by

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Introduction

If, for military or political reasons, a nation embarking on a nuclear weapons program via dedicated plutonium production facilities must keep the existence of the program secret, then the individual components of the program - the reactor, the plutonium recovery plant, and so on - must be restricted in size and capacity. This effectively limits the reactor power level to the order of 25 megawatts (MW). While such a small reactor might be concealed, a much larger reactor could not. A small 25 MW reactor producing about 10 kg of plutonium annually is called a level I facility.

On the other hand, if the nation openly undertakes a nuclear weapons program, there are no such restrictions. Like any other military program, it is limited only by the availability of funds, personnel, and critical

materials. Facilities capable of producing about 100 kg of plutonium per year, enough for between 10 and 20 nuclear weapons, are termed level II facilities. In this report, some of the more reasonable options are considered for the construction of these types of facilities.

Magnitude of Program - Plutonium Production Rate

It is safe to assume that any dedicated plutonium production reactor would be fueled with natural uranium, since if facilities for the enriching of uranium were available, it would be more logical to base a weapons program entirely on enriched uranium rather than reactor-produced plutonium. The conversion ratios of most practical natural-uranium fueled reactors are approximately the same, namely, about 0.8. With this conversion ratio, Pu-239 is produced at a rate of o.368 kg per year per megawatt of operating power.

Some of this Pu-239 is consumed within the reactor, either in fission or by conversion to Pu-240 and Pu-241, at a rate that depends on the thermal flux in the reactor. At a flux of 10^{12} neutrons/cm^2-see the exponential time constant (mean life) for the depletion of the Pu-239 is 35.3 years; at a flux of 10^{13} it is 3.53 years. Except for reactors operating at a flux much in excess of 10^{13}

neutrons/cm^2-see the net production rate of Pu-239 can therefore be taken to be roughly 0.37 kg/MW-year.

In order to produce 100 kg of Pu-239 per year would require a reactor operating at a power of about 100/0.37 = 270 MW, provided that the reactor operated continuously throughout the year. While small reactors can, in fact, be operated continuously over long periods of time, it has been found by experience that larger reactors are ordinarily shut down the order of 30 percent of the time. This means that in order to produce 100 kg of Pu-239 per year, the reactor must actually operate at a power of almost 400 MW. This is the power level that will be assumed for level II facilities in the present report.

Reactor Options

The distinguishing features of a plutonium production reactor, once the type of fuel has been determined, are its moderator and coolant. Several different choices are possible. For a natural-uranium fueled reactor, the moderator can be either heavy water or graphite. No other practical moderating material will provide a critical system with natural uranium as fuel. The coolant, however, can be either ordinary or heavy water, or any one of a number of gases. Presumably a nation would opt to construct

that type of reactor which is the cheapest and easiest to build. As shown below, this would most likely be a graphite-moderated, water-cooled reactor.

Heavy water moderated reactors. As a moderator, heavy water is far superior to graphite. Fission neutrons slow down more rapidly in heavy water than in graphite because of its lower atomic/molecular weight, and once thermalized, the neutrons are not as readily absorbed in heavy water as in graphite because of its lower absorption cross section. A heavy water moderated reactor therefore has a higher multiplication factor than a comparable graphite moderated reactor, and, as a result, a heavy water reactor more easily goes critical - that is, a smaller amount of fuel and moderator is required than for a similarly fueled graphite reactor.

These facts notwithstanding, it does not appear likely that any small and/or developing nation would be successful, certainly at an early date, in producing plutonium in" a heavy water moderated reactor. The reason is simply that heavy water would be exceedingly difficult to obtain. There are only two major producers of heavy water in the world today - the United States and Canada, and both of these countries control its export. Under current regulations, heavy water is not exported except to

signatories to the Nonproliferation Treaty, and presumably only for the use in recognized power reactors.

With heavy water not generally available on the world market, a nation would be forced to produce it on its own. Approximately 300 kg of heavy water moderator are required per MW of reactor power. A 400 MW reactor would therefore require a total of about 120 Te of heavy water. The production of this amount of heavy water presents a formidable problem. The production of heavy water is not a simple undertaking. Wile in principle it can be made in a number of different ways, the presently universally adopted process for producing heavy water involves chemical exchange reactions between hydrogen sulfide (H_2S) and water. A gas, H_2S is both corrosive and lethal. Successful heavy water plants therefore require a high level of technical sophistication in their design and operation. Indeed, one plant built in Canada of American design simply did not work. In the opinion of experts in heavy water technology, only a nation with a major chemical industry and high-trained personnel could possibly produce the heavy water required for a level II plutonium production reactor.

For the above reasons, heavy water moderated reactors for level II plutonium production can be largely ruled out.

Graphite moderated reactors. These types of reactors were the first to be built, and they do not require a high level of technology for their design or construction. While graphite is not as good a moderator as heavy water, it is relatively cheap and readily available on the world markets. Should graphite ever become a nationally controlled substance, it can readily be produced domestically. Graphite is easily machined and structurally sound, it can be stacked to necessary heights, it maintains its dimensions, and it is essentially inert at normal temperatures.

While a small level I graphite reactor can be cooled with air in a once-through system, at the more elevated power levels of a level II reactor air is not the advisable

coolant. in order to compensate for the poorer heat transfer properties of a gas, gas-cooled reactors **are** normally opera ted at high temperatures, and at high temperatures air reacts with graphite. A more chemically inert gas, such as helium or CO_2, must therefore be used to cool graphite reactors, but these coolants create other problems. For one thing, for obvious reasons, the y can only be used in closed loops, which means that heat exchangers and secondary coolants must be used to remove the reactor heat. This is an entirely reasonable procedure for a reactor used to produce electrical power, since steam can be generated in the secondary loop, but it introduces needless complications in a plutonium production reactor. A closed primary loop requires that either the entire *core a- large structure* when the fuel is natural uranium - must be enclosed in a gas-tight pressure vessel or the individual coolant channels must be enclosed in gas-tight tubes.

Another negative feature of gas-cooled reactors of the natural uranium type is that again because of the poor heat transfer properties of gases, a significant fraction, upwards of 10 percent, of the reactor power is required to provide the necessary flow of coolant through the reactor to cool the core. Finally, with regard to

helium as a coolant, this gas has only limited availability in the market places of the world, and its use poses unique technological problems of its *own*. It should also be mentioned that any closed cycle cooling system introduces serious difficulties in the loading and unloading of fuel - difficulties that should be avoided if possible, especially in a production reactor.

In contrast to closed cycle gas cooling, once- through water cooling is simplicity itself. Water, obtained from a suitable natural source such as a river, is passed along the fuel rods, collected at the far end, and returned to the source. However, water does absorb thermal neutrons, so that the introduction of water into a thermal reactor tends to reduce the multiplication of the system. Indeed, during the Manhattan Project when the Hanford plutonium production reactors were being designed, it was not clear that a natural-uranium fueled, graphite - moderated reactor containing the amount of water necessary for cooling and constructed with graphite of uncertain purity would ever go critical. Until early in 1943, in fact, it was generally assumed that the plutonium pro- duction reactors would have to be helium cooled. Water also has other problems, especially the fact that it is highly corrosive. Special care must be taken to assure

that the proper materials are used throughout a water-cooled reactor in order to reduce corrosion to a minimum.

Small Hanford-Type Reactors

In view of the foregoing discussion, it would appear that a logical choice for a level II production facility would be a once-through, water-cooled, graphite-moderated, natural-uranium-fueled reactor. Such a reactor would be similar to the first reactors built at Hanford, Washington in the Manhattan Project. A total of **nine such reactors were built at Hanford during and subsequent to World War II. The first reactors operated at a power level of between 1800 and 2500 MW; later reactors operated at 4000 to 4400 MW.** The total power of all the Hanford reactors taken together was about 21,000 MW. At this power level, and with an average plant availability factor of 70 percent, the Hanford facility was capable of producing the order of 5000 kg Of plutonium per year. One by one, the Hanford reactors were shut down during the 1950's and 1960's as the nation’s need for additional plutonium diminished, and production shifted to the more modern heavy water reactors at Savannah River, South Carolina. Only one reactor, the so-called N Reactor, is still in operation

at Hanford, having been converted into a dual plutonium-producing and electricity-producing (860 MWe) system.

Th e first Hanford reactors, of necessity, were fueled with natural uranium. However, the excess reactivity of these reactors was inconveniently small. Early in the Hanford program, therefore, about 15 percent of the fuel was replaced with slightly enriched uranium (0.947 weight percent). Most of the excess reactivity of the Hanford reactors was required to compensate for equilibrium Xenon. The high power levels of these reactors requires a high thermal neutron flux, and this, in turn, leads to xenon reactivity levels on the order of two percent. A somewhat smaller amount of reactivity was needed because of the negative temperature coefficient. Almost no reactivity was included for burnup, since one-fifth of the fuel was removed for reprocessing every 5 to 6 weeks.

While a nominal 400 MW level II reactor would operate at only about one-fifth the power of an early Hanford reactor, the nuclear designs of the two systems would be very similar. In particular, it would be reasonable to construct the new reactor with the same fuel-coolant-moderator lattice as a Hanford reactor. The overall dimensions of the lower-power reactor would

be smaller, however, because the reactor, operating at lower neutron flux and temperature, would require less excess reactivity.

Rough calculations given in the Appendix indicate that a 400 MW Hanford-type reactor would be a cubical pile, the core of which would be about 33 ft on a side. The total amount of natural uranium in the reactor would be 387 metric tons. At a nominal cost of $25 per kilogram, this would cost about $10 million. The total amount of graphite, including the reflectors would be 2250 metric tons, and at $2 a pound the graphite would also be about $10 million.

Beyond the costs of the fuel and moderator, it is very difficult to make meaningfuel estimates of the cost of a Hanford-type reactor. Cooling water must be brought to the face of the reactor, pumped through the 2200 channels, collected, and returned to the source. This obviously involves costly problems of a plumbing nature. Mechanisms must be provided for the loading and unloading of fuel - mechanisms that must work smoothly in view of the short intervals between fuel changes. Massive shielding must be erected around the reactor which does not interfere with either the coolant piping or the fuel handling equipment. The structural framework and

foundation supporting the reactor must be designed with some care in view of the large floor loadings and the need to maintain the system motion free. Finally, the reactor must be instrumented and controlled.

It is clear that the construction of a 400 MW production reactor would be a difficult undertaking for most nations. Most nations would be far better advised to construct a number of smaller air-cooled reactors, which can be built one by one, tested and operated to prove their design. In view of the time and effort required and the risks involved to realize significant amounts of plutonium from a larger reactor project, the gradual buildup of plutonium production capacity with small reactors would seem to be a much more reasonable strategy.

ANNEX

Calculations of Small Hanford-Type Reactors

Reactor calculations can be divided into two parts: those concerned with reactor physics and those pertaining to the engineering of the system. In the actual design of a reactor there is considerable interplay between these two areas, especially in connection with any effort to optimize the design. No such optimization is attempted in the calculations which follow. They are intended merely to indicate the types of calculations which would be involved in the design of a small Hanford-type reactor.

1. The Hanford lattice.

The fuel for the early Hanford reactors was in the form Of natural uranium slugs **1.359 in. in diameter and** about 8 in. long (their exact **length is unimportant for** present purposes), which were **clad in aluminum, 0.0405 in.** thick. These clad slugs were **loaded into an aluminum** tube 0.072 in. thick that had **two supporting ribs as** shown schematically in Figure **1. These fuel elements were placed in aluminum process tubes (later replaced with zircaloy) also approximately 0.072 in. thick, which passed through the horizontal holes in the graphite. This provided an 0.086 in. thick annulus for cooling**

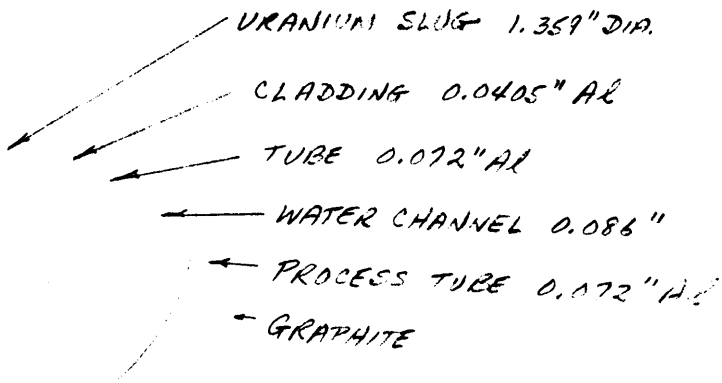

Fig. 1. Cross section of fuel, cladding, and coolant. channel of Hanford reactor.

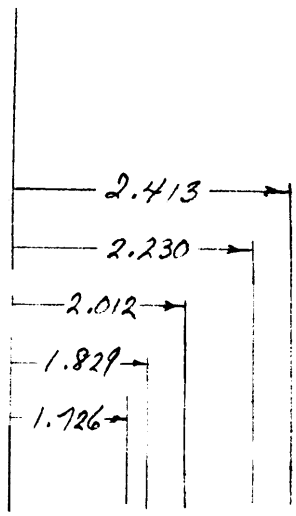

Fig. 2. Dimensions in cm of Hanford process channel.

water around the fuel. The fuel rods were arranged in a square lattice with a spacing Of 8.375 in. between the axes of nearest rods. The relevant dimensions are shown in Figure 2.

2. Infinite multiplication factor.

The infinite multiplication factor of the lattice is given by the usual four factor formula:*

$$k_\infty = \eta_T f p \varepsilon. \tag{1}$$

The value of η_T is 1.32; f can be computed from the equation

$$\frac{1}{f} = \frac{\Sigma_{aM}V_M + \Sigma_{aAl}V_{Al} + \Sigma_{aW}V_W}{\Sigma_{aF}V_F} F(\kappa_F a) + E(\kappa_M c, \kappa_M b); \tag{2}$$

p is given by

$$p = \exp\left(-\frac{N_F V_F I}{\xi_W \Sigma_{SW} V_W + \xi_M \Sigma_{sM} V_M}\right), \tag{3}$$

where

$$I = A + C\sqrt{a\varsigma}. \tag{4}$$

*The meanings of the symbols in the equations are all standard and given in the references.

The formula for ξ is complicated, but ε was computed during the design of the Brookhaven Graphite Research Reactor for a lattice of the Hanford type and is reported in BNL - 152. Its value is 1.035.

Using the following values:

$\Sigma_{aM} = 0.0003851\ cm^{-1}$	$V_M = 434.097\ cm^3$	$\mathcal{H}_M = 0.0203$
$\Sigma_{aAl} = 0.01386$	$V_{Al} = 6.028$	$\mathcal{H}_F = 0.645$
$\Sigma_{aW} = 0.0222$	$V_W = 2.905$	
$\Sigma_{aF} = 0.3668$	$V_F = 9.359$	
$a = 1.726\ cm$	$\xi_W\Sigma_{sW} = 1.46\ cm^{-1}$	$A = 2.8$
$b = 12.0$	$\xi_M\Sigma_{sM} = 0.0608$	$C = 38.3$
$c = 2.413$		$\rho = 18.6\ g/cm^3$

in Eqs. (2,3, and 4) gives f = 0.8826 and p = 0.8685. Then from Eq. (4) it follows that $k_\infty = 1.0472$.

3. Excess reactivity.

The negative reactivity introduced into a reactor due to equilibrium xenon-135 is given by the formula

$$\rho = \frac{\gamma_X + \gamma_I}{\nu p \varepsilon} \frac{\phi_T}{\phi_T + \phi_X}, \qquad (5)$$

where ϕ_T is the average thermal flux and ϕ_X is the constant 0.77×10^{13}. If it is assumed (this can be checked and

iterated upon later) that $\phi_T \approx \phi_X$, then with $\nu_X + \nu_I$ = U.0663, ν = 2.42, p = 0.8685, and ε = 1.035, it is found that ρ = 0.0152 or about 1.5 percent.

The reactivity also decreases as the temperature increases due to the negative temperature coefficient. A reasonable value of reactivity to compensate for this temperature defect is about 1 percent.

A nominal excess reactivity is therefore about 2.5 percent. For conservatism, it is probably a good idea to add about 0.5 percent, perhaps less, for miscellaneous Other negative reactivity effects - control rod sheaths, fuel and moderator impurities, instrumentation, and so on. With a total of 3 percent required excess reactivity, the corresponding value of the multiplication constant for the reactor is then

$$k = \frac{1}{1 - 0.03} = 1.0309. \qquad (6)$$

4. Reactor dimensions.

The reactor buckling is

$$B^2 = \frac{(k_\infty/k) - 1}{M^2}, \qquad (7)$$

where

$$M^2 = \tau_T + (1 - f)L_{TM}^2. \qquad (8)$$

With the values $\tau_T = 368\ cm^2$, $f = 0.8826$, and $L_{TM} = 49.3$ cm, $M^2 = 653\ cm^2$. Introducing this value of M^2 and the earlier obtained values of k_∞ and k into Eq. (7) yields $B^2 = 2.421 \times 10^{-5}\ cm^{-2}$.

For a bare cubical reactor of side ℓ,

$$B^2 = 3\left(\frac{\pi}{\ell}\right)^2. \qquad (9)$$

Inserting the above value of B^2 and solving for ℓ gives $\ell = 1106$ cm = 36.3 ft.

By surrounding the core of the reactor with a reflector, the size of the core can be reduced. The reflected length of the core becomes

$$\ell_{ref} = \ell_{bare} - 2\delta, \qquad (10)$$

where δ is the reflector savings. For the present reactor, $\delta \simeq 49.3$ cm so that $\ell_{ref} = 1007$ cm = 33 ft. This was the actual dimension of some of the smaller Hanford reactors.

5. Fuel and moderator masses.

With the reactor 33 f t on a side, there would be 33 x 12/8. 375 = 47 fuel channels per side or a total of $(47)^2 = 2209$ channels altogether. The total mass of uranium

is then 387 Te. The mass of U-235 is 0.00711 x 387 = 2.75 Te.

The moderator mass, assuming a reflector 2.5 ft thick around the entire reactor except the bottom, is then 2.25 **x IQ** ^{6} **kg**.

REFERENCES

Information on the Hanford reactors has been declassified only for the last one and a half to two years. There apparently is no single report which describes these reactors. A description of the lattice for the earliest Hanford reactors is given in

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