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HW-78650

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K AND N REACTOR CAPABILITIES

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K AND N REACTOR CAPABILITIES

INTRODUCTION

This report contains data on the relative capabilities of the K and N plants to produce various isotopes. The data are "direct and quantitative" in cases where production plans for the various isotopes have been studied. For isotope studies not completed production capabilities are, of necessity, discussed from only a qualitative standpoint.

The production capabilities and the costs of production are functions of specific fuel elements used in each reactor. Any quantitative information is related to the type of fuel element loading envisioned for production of a particular isotope. There are, of course, many possibilities for fuel designs in both reactors that may enhance the production of particular isotopes.

The production capabilities are directly related to the thermal power levels that have been achieved or that are expected to be reached in the different reactors. For purposes of this comparison the K reactor is shown at its administrative limit of 4400 Mw and projected level of 5500 Mw as compared to N reactor at (a) its design power level - 4000 Mw and (b) a potential level of 5000 Mw representing a 25 percent increase over the design power level. It is estimated that the higher levels can be achieved without substantial additional capital investment.

Reactor capabilities are considered in terms of major reactor products and special isotopes. Major products are plutonium of weapons and non-classified grades; tritium; uranium-233; and to a lesser extent neptunium-237. Special isotopes considered are Pu-238, Po-210, Cm-242, Am-243 and Pu-242.

Production data and estimated costs in connection with the first group of isotopes are more firm than for the second since these potential products have been studied more extensively.

Since the production of the first group of isotopes would probably be distributed widely throughout each reactor, the production capabilities are related to average flux. The isotopes in the second category would probably be produced in high flux regions of the reactor and hence their production rates would be related to peak fluxes.

Steam for the production of electric power is an important product of the N reactor, and income from the sale of steam is a factor in the plant economics. None of the N production cases discussed in this report would interfere with meeting steam delivery commitments. This report, then, deals with capabilities for isotope production independently of steam.

SUMMARYA. General

The design of N reactor and its larger fuel channels allows it to operate with a "harder" flux than the K reactors and thus achieve process economies in Pu production, Np-237 production, and possibly other items. On the other hand, the K reactor is over-moderated with natural uranium loadings and stands to benefit more than N reactor from loadings that increase the reactor-charged productive cross section.

B. Major Production Items

The production rates for major products for the two reactors are shown in Table No. 1 for an equilibrium year. Special loadings K-5 through K-8 have not been demonstrated and some development effort would be required. N-7 loadings to produce tritium from or alloy would require substantial expenditure of development funds.

Weapons-Grade Pu

The design of N reactor is such that the fuel exposure corresponding to minimum unit product cost at rated power is much higher than the exposures required for Pu of six percent Pu-240 isotope. K reactor has its optimum exposure at a lower level, closer to that required for weapons Pu production, and therefore is more naturally suited for weapons-grade Pu production with Pu as the sole product. However, cases for combined Pu and tritium production illustrate economically attractive modes of producing weapons-grade Pu directly in N reactor.

Unclassified Pu

Savings can be made at both N and K by increasing the level of Pu-240 in product. Greatest saving, however, can be made at N reactor.

Two alternate routes are available for the production of unclassified Pu at the K reactors if N's productive capacity is inadequate to meet requirements:

- (1) By irradiating depleted uranium supported by slightly enriched uranium the product formed in the depleted uranium rapidly gains Pu-240 content. The depleted uranium containing product of eight percent Pu-240, or higher, can be discharged simultaneously with the supporting enrichment producing weapons-grade Pu. Thus, up to 25 percent conversion to unclassified Pu can be made at the K reactors utilizing irradiated depleted uranium supported by slightly enriched uranium fuel elements. Some slight increase in conversion ratio can be obtained as compared to natural uranium loadings, and increased quantities of neptunium produced in the slightly enriched uranium used for reactivity support.
- (2) Complete changeout to unclassified Pu at the K reactors requires increasing natural uranium exposures. Some slight decrease in unit cost

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Table 1

ONE K AND N REACTOR
PRODUCTION DETAILS
EQUILIBRIUM YEAR

Case	Equivalent Kg ⁽¹⁾					Kg Np
	Weapons Grade Pu	Tritium	U-233	Unclassified Pu	Total	
K1 6% Pu 240	1 100				1 100	6.00 ⁽²⁾
K2 7.7% Pu 240				1 060	1 060	6.10
K3 5.1% Pu 240	1 115 ⁽³⁾				1 115	5.90
K4 E-N .94% ⁽⁴⁾	991	220			1 211	14.05
K5 E-N 1.3% ⁽⁴⁾	826	440			1 266	14.95
K6 E-Th .94% ⁽⁴⁾	958		198		1 156	14.05
K7 E-D .94% ⁽⁴⁾	875			258(8%)	1 133	12.57
K8 E-D .94% ⁽⁴⁾	893			186(18%)	1 079	12.27
K9 E-N .94% (5.1% Pu 240) ⁽⁴⁾	1 011	220			1 231	13.50
N1 12% Pu 240				937	937	26.15 ⁽²⁾
N2 6.9% Pu 240	1 054 ⁽³⁾				1 054	19.39
N3 6% Pu 240	1 075				1 075	16.97
N4 6% Pu 240 + Tr.	820	264			1 084	16.40
N5 6.9% Pu 240 + Tr.	802	261			1 063	18.10
N6 9.5% Pu 240 + Tr.		259		762	1 021	20.00
N7 Tr. Only		1 012			1 012	10.40

- (1) At the projected levels the production for both reactors would be increased by a factor of 1.25.
- (2) Neptunium yields from K reactor are based on values obtained analytically. N reactor yields use theoretical numbers since the higher values for K reactor may not be applicable.
- (3) Weapons-grade achieved by blending these two cases.
- (4) E- " " loadings, such as E-N, E-D, and E-Th are K reactor charges in which target material is reactivity supported by slightly enriched uranium. "-N" targets are Li-Al to produce tritium; "-D" targets are depleted uranium considered for production of higher isotope Pu, and "-Th" targets are thorium elements for production of U-233.

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accrues to the increase in exposure required to deliver 7.7 percent Pu-240 instead of weapons-grade material. The N reactor fuel technology is judged capable of yielding Pu directly with 12 - 15 percent Pu-240 with substantial reductions in unit product cost.

Tritium

The production economics are attractive for tritium producing loads at both K and N reactors (K-4, K-5, N-4, N-5, N-6) providing dual products Pu and tritium are made at the reactors by using slightly enriched uranium as fuel. With a given U-235 level of enrichment for tritium, the productive capability is always slightly higher at K than at N since greater reactivity is gained with increasing levels of U-235 in slightly enriched fuel. The incentive for conversion from plutonium production to plutonium and tritium is greatest, for either reactor, where the original product is low in Pu-240 isotope.

N plant can be operated for tritium-only production by using fully enriched fuel (N-7). Although the unit cost of the tritium is somewhat higher than that of the smaller amounts that can be produced in conjunction with plutonium, the economics are attractive relative to other ways of obtaining large amounts of this product.

With tritium economics favorable at both the K and N reactors, the amount of tritium desired by the Commission may be the criteria for determining which reactor or reactors should be used for production. The range of possible production of up to nearly 20 kilograms of tritium that could be furnished by the two reactors per year is shown below:

Table No. 2

Tritium Producing Loads				Tritium Production (Kg)
<u>Reactor</u>	<u>Load No.</u>	<u>Loading</u>	<u>Development Requirements</u>	
K	K-4	E-N using .94% slightly enriched uranium.	Least development.	2.75
K	K-5	E-N using 1.3% slightly enriched uranium.	Moderate development.	5.5
N	N-6	Uses 1.35% slightly enriched uranium.	Moderate development.	3.5
N	N-7	Uses oralloy fuel.	Considerable development.	13.5

Neptunium-237

N reactor is high in Np-237 production capability because of its high epithermal flux and its higher goal exposures (greater proportion of cycle time in the reactor).

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Substantial neptunium production would be realized at the K plant with fuel loadings employing E-metal, which can be recycled to build up the U-236 content more readily and economically than for natural uranium.

Neptunium production for the various cases is given in Table 1.

Uranium-233 Production

Production of U-233 relatively free of U-232 has been proposed at the smaller production reactors. The moderated flux of the K reactor would be well suited to produce U-233, the production of contaminating U-232 is a direct function of the spectral hardness of the flux. A case for the production of "clean" U-233 has not yet been developed for N reactor.

Depleted Uranium for Pu Production High in Pu-240

Metal stability dictates the use of depleted uranium for production of higher isotope Pu with the aluminum-clad fuel of the existing reactors. An over-all increase in the productive cross section utilized in a reactor irradiating depleted uranium columns reactivity supported by slightly enriched uranium makes this type of loading attractive for the existing reactors. The use of depleted uranium at N reactor has not been fully analyzed.

C. Physics Parameters and Special Isotope Production

The N reactor ratio of epithermal to thermal flux is higher than that for the K reactor. However, the average flux through the K reactor fuel is higher than that for N at its rated power level. The production of isotopes from target materials with resonant cross sections would in general be favored at N reactor, especially where such target materials are highly dispersed. $1/v$ absorbers, such as lithium and bismuth-209, would favor the reactor with the higher thermal flux.

Bismuth-209 is a target material of special interest in that its cross section is extremely low. It would not normally be substituted for active fuel columns inasmuch as substantial conversion ratio losses would be sustained. However, where bismuth can be charged replacing either moderator or coolant, the economics are highly favorable. It is not clear which reactor might be able to furnish non-productive space most easily.

DISCUSSION

A high-spot physical description of the K and N reactors, which follows later in this section, reveals more basic similarities than dissimilarities. This is true despite the fact that N reactor recirculates coolant for power takeoff and is designed with larger fuel channels allowing tube-and-tube and tube-and-rod design, whereas K reactor uses coolant on a once-through basis and has smaller fuel channels. Pile inventory of uranium required for each reactor is about the same.

A listing of some of the reactor parameters and physics constants associated with the two reactors is given in Table No. 3.⁽¹⁾

(1) HW-78547, "Comparison of Physics Parameters for N and K reactors," Nichols, P. F. and Nilson, R., dated August 2, 1963.

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Table 3

PHYSICS AND REACTOR PARAMETERS FOR K AND N REACTORS

Reactor Parameters

	<u>K</u>	<u>N</u>
Power Level, MW	4 400 (AEC Administrative limit) 5 500 (projected)	4 000 (name plate) -5 000 (projected)
Exposure Level for Weapons-Grade Pu	680 Nat U (.71% U-235) 920 Enriched U (.94% U-235) 1 230 Enriched U (1.3% U-235)	820 Enriched U (.94% U-235) 1 200 Enriched U (1.3% U-235)
Optimum Exposure Level for Unclassified Pu	7.7 Percent Pu-240 for Nat U (Min. unit cost 7.2%)	12 Percent Pu-240 at 2,100 (postulated limit f/fuel)
Operation Efficiency	80 Percent	83 Percent at 1,200 MWD/T 84 Percent at 2,100 MWD/T

Special Irradiation Facilities

Process Tubes	3 220 Tubes (allows flux, or product changes by "pattern" control and/or poison control.	1 000 - 2.7-inch tubes (allows tube-and-rod or tube-and- tube design)
Controls	20 Horizontal rods and splines (many) can be converted to by- product production.	87 Horizontal rods, initially designed for by-product production.
Loops	Four recirculating loops* and twelve test channels.	Sixty-eight shield penetrations can be used for special targets. Graphite cooling channels available for special irradiations.

Neutron Characteristics

Flux (average Wescott)	2.93×10^{13}	2.67×10^{13} at 4,000 MW 3.34×10^{13} at 5,000 MW
Neutron Temperature	650° K	700° K
r Value	0.0625	0.105

Conversion Ratios

g/MWD at Weapons-Grade Isotope Level (Pu only)	.885	.885
g/MWD, or equivalent, at Weapons-Grade Isotope Level (Pu and equiv. T ₂)	.959	.92

* KE only.

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Flux Relationships - Generalities

N reactor and K reactors being graphite moderated reactors with nearly equal temperatures, demonstrate significant differences only when the nuclear product is extremely sensitive to the changes that exist in the spectral index of the two reactors. The Wescott spectral index for K is 0.0625 and for N - .105. The level of flux is higher in the K reactors for neutrons of 3 ev or lower energy, and higher in the N reactor for neutrons of above 3 ev energy levels.

Traditionally, improvements in plutonium conversion ratio have been made by increasing the uranium to graphite ratio. The greater the plutonium production by resonance capture, the less the loss to graphite and parasitic capture, and the higher the conversion ratio. Thus the N reactor, despite its small core size, has as good neutron economy as the existing K reactors and better than the smaller HAPO production reactors.

Any plan that can add productive cross section in the form of increasing enrichment level or increased target cross section, or both, would be expected to benefit the neutron economy and production economics. In general, the benefits from such plans would be greatest for the over-moderated reactors. Since the existing reactors operate from an essentially unenriched condition, any plant limit on the basis of percentage of enrichment tolerable in fuel would tend to allow greater production of alternate product in the existing reactors; i.e., if the maximum level of enrichment were .94 percent U-235, gain would accrue to existing reactors from an E-N load using this level of enrichment that is not available to N already operating with .94.

Weapons-Grade Plutonium

Both reactors can produce weapons-grade plutonium, but for six percent 240 content the N plant would have to operate at about 820 MWD/T which is far below its economic optimum on the bases of either plutonium mixed isotopes or plutonium-239. The most economic method of operation, if weapons-grade plutonium were the only product desired from Hanford, would be through blending of plutonium from the N and K plants. K plant, on the other hand, is operating closer to its optimum at 680 MWD/T at which it produces plutonium with six percent 240 isotope.

Unclassified Plutonium

Unclassified plutonium (by definition, plutonium above 7.7 percent 240 isotope) may be economically produced in either K or N reactor by different methods:

In N plant the entire production capacity could be used to produce unclassified plutonium by a homogeneous fuel loading of .947 percent irradiated uranium (the starting fuel load) at exposure levels up to 2100 MWD/T, or possibly higher.

In K plant unclassified plutonium could be produced in quantities corresponding to roughly one-quarter of the production capacity of the reactor, by the irradiation of depleted uranium, the remainder of the capacity being devoted to weapons-grade plutonium production in supporting slightly enriched uranium columns. Complete conversion to unclassified Pu can be accomplished at K by extending natural uranium exposures but losses in conversion ratio and slightly reduced operating efficiency largely nullify savings from reduced through-put.

In general, unclassified plutonium can be produced most economically in N plant.

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Tritium From Lithium-6 Target

1/v absorbers would normally favor that reactor having highest thermalized flux. However, the amount of lithium-6 which can be charged into the reactor is so large that conversion rate for the individual atom does not limit production; rather it is limited by the number of neutrons which can be spared from other uses in the reactor. Production gains from plutonium production along with tritium formation from lithium-6 result primarily from three factors:

- (1) Reduction of losses to parasitic cross section by hardening the neutron spectra with the addition of greater productive cross section (percent of neutrons to parasitic cross section reduced).
- (2) Reduced plutonium burnout. Plutonium burnout is reduced by adding competitive uranium-235 cross section, and formation of substitute tritium atoms for plutonium with rather negligible destructive neutron cross section.
- (3) Better thermal neutron utilization by reduced neutron leakage from reactor accomplished by "blanket" loading.

With regard to the first item, both K and N reactors would benefit, with K estimated to have a somewhat greater potential benefit in that it starts out from a more over-moderated condition than does N.

With regard to the second item, both reactors will benefit. Economically, N plant will benefit more than K plant if weapons-grade plutonium and tritium are the desired product because it permits operation of the reactor at higher fuel exposures, closer to the optimum, while still meeting six percent 240 isotope requirements. At K plant fuel exposures are starting at a point already closer to optimum and the gains from this particular effect are smaller.

With regard to the third item, K plant seems more likely to benefit from a blanket loading. Such a blanket would obviously change the flat power distribution now associated with the N reactor, and may prove disadvantageous.

Additional Np-237 beyond that formed from present natural uranium loadings would be formed at the K reactors if slightly enriched uranium with recycle was used as a fuel.

Uranium-233 From Target Thorium-232

The use of thorium-232 as target material in the production of uranium-233 is a bulk irradiation limited only by the reactivity that can be supplied from fuel columns in the reactor. The contribution of the resonance integral to the over-all cross section is of little interest in such a concentrated form.

Contamination of uranium-233 with highly radioactive uranium-232 results from high energy neutron reactions. The more thermalized flux distribution of K reactor, the shorter fuel exposures to which it is suited, and the spatial separation available between fuel and target elements would favor K plant for the production of clean uranium-233.

Neptunium-237 Production

Neptunium-237 production for irradiation and processing into Pu-238 is formed by two reactions:

- (1) U-238 (n, 2n) Np-237
- (2) U-236 (n, λ) Np-237

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On a once-through basis, the production from the second reaction contributes only fractionally to the total neptunium-237 formed. However, by recycling the fuel, the U-236 in the fuel can be increased and incremental Np-237 production achieved. The higher energy flux of N reactor coupled with increased goal exposures will make it a much more efficient Np-237 producer by U-236 conversion than K reactor. Thus the cost of incremental Np-237 will be less at N reactor than at K. This cost is essentially the cost of restoring with higher U-235 isotope the level of the U-235 in the depleted fuel. Based on the higher cross section of the U-236, the cost per gram of Np-237 at N from recycling fuel is one-half that at K. However, substantial Np-237 can be obtained at K reactor even though it converts less of the U-236 per reactor cycle than N. Thus, one way of increasing the net amount of Np-237 formed at HAPO is to convert natural uranium irradiation to special loadings using slightly enriched fuel with recycle of the depleted fuel. Recycling slightly enriched uranium costs less than natural uranium recycle, and is fundamentally a more easily controlled and efficient process than recycling depleted natural uranium to save U-236 values.

Other Isotopes

At least five other target isotopes are of interest, although the particular problems of their production have not been extensively studied as yet for either reactor. However, relative rates for production per target atom have been calculated and are tabulated below:

<u>Target Isotope</u>	<u>Product Isotope</u>	<u>Ratio of Rates of Formation $\frac{N}{K}$</u>
Pu-240	Pu-241	1.28
Pu-241	Pu-242	0.85
Pu-242	Am-243	1.29
Am-241	Cm-242	0.98
Am-243	Cm-244	1.12

*Relative rates of conversion per target atom assuming exposure at peak of fuel flux in both cases and self-shielding can be made negligible in all cases.

The differences in conversion rates are due both to variations between the reactors in their flux levels at various neutron energies and to the manner in which the target cross section varies with energy.

Apart from the tabulated differences in conversion rates, no significant differences between the K and N reactors have been identified for these target isotopes so far. These isotopes would be produced in high-flux regions, and the above reactor rates are computed taking into account that K plant has peak cosine flux values in central tubes as much as a factor of two higher than its average flux. Flux traps could be employed in both reactors.

K Reactors

The K reactors, constructed in 1953 at Hanford, can be considered a second generation graphite production reactor. In it, the graphite lattice spacing was reduced from

the design for the smaller reactors and the size of the plant was scaled up to allow economies in operation. This design for the K reactors resulted in reactor conversion ratios improved by a factor of six percent, and total operating costs comparable to the smaller reactors (but with production roughly doubled).

Each K reactor consists of a graphite stack pierced by 3,220 process channels from front to rear, 20 horizontal control rod channels from side to side, and 47 channels from top to bottom for vertical safety rods. Four recirculating loops were incorporated in the design of KE and are used for higher temperature and/or pressurized operation. Twelve test channels also traverse the core from side to side in the active zone at each K reactor.

The average Wescott flux in K reactor fuel at 4400 Mw is 3.0×10^{13} . The peak flux in the center of the reactor is about 5×10^{13} . The neutron temperature is 650 K and the Wescott r is 0.0625.

The 3,220 individual process tubes in the reactor can be charged and discharged independently, and flow controlled and monitored independently. Neutron flux can be regulated by "pattern" control in the adjacent tubes, or poison spline control in the individual tubes. In this manner flux can be varied from the values shown above to a "peaked" flux in the neighborhood of 2×10^{14} , or possibly higher. Such peaking would require significant R&D support as well as incrementally higher expenditures.

N Reactor

The N reactor, presently being constructed, is the first plutonium production reactor to be designed for coolant recirculation with generation of steam at temperatures and pressures suitable for electric power generation. The graphite lattice spacing was increased from that of the K plants, and voids were left in the graphite moderator to permit the escape of steam in the event of a process tube rupture. The reactor has less moderation than other Hanford units. The conversion ratio is substantially the same as that of the K plants.

The graphite stack of the N reactor is pierced by 1,004 zirconium alloy tubes from front to rear. A total of 87 horizontal control rods enter the reactor from the sides, roughly half from each side. There are 108 vertical Ball safety channels. In fringe zones of the reactor are 68 openings in the graphite for possible future process tubes. The graphite block is pierced from side to side by 640 graphite cooling zirconium tubes. The nozzles for these tubes have been designed so that provisions for the insertion of materials to be irradiated can be added.

As with other graphite-moderated reactors, the individual process tubes can be charged or discharged independently, and the individual tube flow may be controlled. Reactor flux can be regulated by the flexible control rod system.

At the design rating of 4,000 MW, the average Wescott flux in N reactor fuel is 2.67×10^{13} , the neutron temperature is 700°K, and the Wescott r is 0.105. The flux would be proportionately higher at the 15 to 25 percent higher thermal power levels expected to be achieved without major added capital cost. With flux traps, the thermal flux in limited reactor volumes can be increased by a factor of four to five.

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