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**PLUTONIUM-238 PRODUCTION IN COMMERCIAL WATER REACTORS.
EXPERIMENTAL AND ANALYTICAL PROGRAM**

Annual Report for Fiscal Year 1973

July 1973

Southern Nuclear Engineering, Incorporated
Dunedin, Florida

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IN COMMERCIAL WATER REACTORS
EXPERIMENTAL AND ANALYTICAL PROGRAM
ANNUAL REPORT FOR FISCAL YEAR 1973

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July 1973

Prepared for the U.S. Atomic Energy Commission
Under Contract No. AT(11-1)-2322

Southern Nuclear Engineering, Inc.
Dunedin, Florida

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I. INTRODUCTION

Under the sponsorship of the U.S. Atomic Energy Commission, Southern Nuclear Engineering, Inc. is conducting an analytical and experimental program to determine the feasibility of producing plutonium-238 in light water reactors. Plutonium-238 is formed by the irradiation of neptunium-237, and the production technique suggested initially by SNE involves the replacement of some of the burnable poison rods in a conventional pressurized water reactor with rods containing neptunium-237.

Analytical effort on the concept began in 1969; this early work led to expanded analytical studies and the commencement, in 1970, of a concurrent program that would result in the irradiation of neptunium-loaded target rods in an operating power reactor. By the beginning of fiscal year 1973, the neptunium irradiation had been completed and the target rods had been removed from the reactor core. The design, fabrication, and irradiation of the neptunium targets, as well as the past analytical work accomplished by SNE, are described in Refs. 1, 2, and 3.

This report describes SNE activities on the program during FY 73. The progression of the program to this point is due to the cooperation of several organizations and many individuals. Two organizations mentioned in this report are the Connecticut Yankee Atomic Power Company (CYAPC)

and Battelle Columbus Laboratories (BCL); for reasons of continuity it has been necessary for SNE to describe generally some work done by, or at, these organizations or their facilities. In the case of Battelle Columbus Laboratories, in particular, a significant amount of effort is described briefly here; for more information on the specifics of the BCL work, the reader should consult the appropriate Battelle reports.

The analytical program described in this report continues, in some cases, overall analyses that were begun in preceding years. Descriptions of that past work are not included here, but are given in earlier SNE reports.

The assistance of Mr. William V. Macnabb, Manager, Fuel Supply Services, NUS Corporation, in performing the economic evaluation presented herein is gratefully acknowledged.

II. ACTIVITIES INVOLVING OPERATIONS AT CYAPC

The Connecticut Yankee reactor of Connecticut Yankee Atomic Power Company was used for the neptunium-target irradiation. The general location of the targets in the reactor core is shown in Fig. 1.

At the end of FY 72, the fuel assembly containing the target rods was transferred from the Connecticut Yankee reactor core to the spent fuel pool in the fuel handling building. The rods were then removed from the fuel assembly and placed in a target rod storage container³; the storage container, with the targets in place, was located in a compartment of the spent fuel storage rack.

On July 17, 1972, representatives of SNE, BCL, and the USAEC were at the Connecticut Yankee site to package the neptunium targets and ready them for shipment to Battelle Columbus Laboratories. Equipment was made ready and on July 18, 1972 the target assembly was removed from the storage container. The two target rods were cut at their upper ends, which freed them from the modified flow mixer that had been used for the target-containing fuel assembly. The flow mixer was returned to the storage container.

On July 19, 1972, each target rod was cut at the approximate mid-point in the solid stainless steel section, so that the four resulting pieces would fit in a steel basket about four inches in diameter. The basket was designed

to fit within shipping cask BMI-1. The four target-rod segments were placed in the basket, and cask BMI-1 was lowered into the spent fuel pool for loading.

On July 20, 1972, the shipping cask (containing the targets) was removed from the pool, decontaminated, and made ready for transport to Battelle Columbus Laboratories.

III. ACTIVITIES INVOLVING OPERATIONS AT BCL

Shipping cask BMI-1 was transported promptly from the Connecticut Yankee site to Battelle Columbus Laboratories, where visual inspection, dimensional measurements, and gamma scans were carried out on the target rods. A meeting was held at BCL on October 10, 1972 to review the gamma scans and to plan in detail the destructive testing program. A flow diagram for the destructive examination of the rods is given in Fig. 2.

Subsequent analyses of the gamma scans were compared to previous three-dimensional calculations. Figure 3 shows the smoothed gamma scan of Target Rod No. 2, which was selected for destructive analysis. The gamma scans were obtained with a differential pulse-height analyzer using a window width of ~ 0.006 Mev centered around a gamma energy of 0.773 Mev. The energy band for the gamma scan was selected on the basis of a gamma pulse-height analysis using a NaI(Tl) crystal spectrometer, which showed a strong gamma component at about 0.775 Mev. Initially, the observed gamma spectrum failed to show the inherent Compton spectrum, apparently due to coincident losses and blanking in the electronics. A repeat analysis showed the same 0.775 Mev photoelectric peak and an additional peak at 0.5 Mev (approximately the energy at which the Compton spectrum from the 0.775 Mev gamma should appear). The shape of the observed spectrum for the repeat

analysis also indicated blanking in the electronics, however, and it appears likely that the 0.5 Mev gamma peak resulted from the overload behavior of the electronic circuitry. Whether the 0.5 Mev peak was due to electronics or to annihilation radiation from a positron emitter, the 0.775 Mev peak was deemed real and the gamma-scan results judged reliable.

The gamma scan shows clearly the local flux depression in the vicinity of the fuel-assembly spacers. It also reveals sharply-defined dips in activity, apparently due to separation between target pellets in the rod. This separation was relatively large in Target Rod No. 2, and the possibility of investigating such separation led to the selection of Rod No. 2 for destructive examination. At the time it was observed, the sharpness in apparent separation was taken as an indicator that the pellets had remained intact during irradiation.

The principal sources of gammas are (1) fission-product and induced activity directly related to the initial neptunium loading and to the neutron flux, and (2) induced activity in other materials, which is more nearly proportional to the neutron flux. Figure 3 shows the calculated relative activity from neptunium irradiation (including target self-shielding effects) and the relative neutron flux distribution. These values were normalized so that their sum agrees with the gamma scan at the indicated normalization point in target segment D. The agreement between the sum curve and the gamma

scan gave a preliminary indication that the analytical predictions were satisfactory.

Figure 3 shows a deviation between the sum curve and the gamma scan toward the upper end of target segment D. This deviation was attributed to the use of the calculated axial flux distribution at the end of the irradiation cycle rather than the time-integrated flux distribution. Since the time-integrated flux would show more peaking than the flux used in the calculations, it was concluded that, qualitatively, the gamma scan and sum curve would more nearly agree had the time-integrated flux been used.

The destructive testing program was reviewed at BCL on January 16, 1973. All sections of Target Rod No. 2 had been opened along the length of the targets, so pellets and cladding could be seen. Although some cracking and separation were observed, the pellets were in very good condition. The inside surface of the cladding was in excellent condition and showed no signs of damage from the irradiation period. Pellet locations were selected for metallography as well as chemistry, microprobe and isotopic analyses.

At the time of writing of this report, results of chemical analyses of irradiated $\text{NpO}_2\text{-ZrO}_2$ targets have been received from BCL. These results are presented in Table I, but it should be pointed out that there appear to be anomalies in the reported numbers. Funding levels did not permit an adequate statistical sampling, but it is hoped that mass spectrographic results and microprobe analysis results will yield more consistent plutonium/neptunium ratios.

Table I RESULTS OF CHEMICAL ANALYSES OF IRRADIATED $\text{NpO}_2\text{-ZrO}_2$ TARGETS

Sample number	Specimen [*] type	Inches from top of section	Sample weight, gram	Neptunium, gram		Plutonium, gram	Conversion, percent
				Before	After		
1	D	3.5-4	0.9961	0.1284	0.1052	0.0212	16.5
2	D	14.5-15	0.9824	0.1267	0.0927	0.0238	18.8
4	D	39.5-40	0.8998	0.1161	0.0846	0.0260	22.4
7	C	6.1-6.7	0.9503	0.2136	0.1482	0.0347	16.3
9	B	5.5-6	0.8549	0.3349	0.2741	0.0447	13.3
11	A	5-5.5	0.8415	0.5315	0.4288	0.0484	9.10

* Preirradiation analysis	D	-	14.65%	NpO ₂
	C	-	25.53%	NpO ₂
	B	-	44.47%	NpO ₂
	A	-	71.69%	NpO ₂

IV. TWO-DIMENSIONAL PARAMETRIC STUDY

The series of two-dimensional calculations that was begun³ in FY 1972 was completed in FY 1973, with the calculation of parametric study problems (PP5 through PP10) and other problems covering core conditions for approach to equilibrium (replacing burnable poison with neptunium) as well as equilibrium operation (straight irradiation of neptunium).

The fifth problem (PP5) in the parametric study utilized the same core arrangement as PP4, but the neptunium loading was halved (to 61.5 kg). For the reader's convenience, the core arrangements for earlier 2-D calculations (through PP4) are shown here as Fig. 4. As expected, the lower neptunium concentration specified for PP5 gave a better Pu-238 production rate and a longer core lifetime than PP4. The calculated critical boron concentration as a function of burnup for PP4, PP5, and the reference (no neptunium) case is shown in Fig. 5. The end of core life for PP5 was estimated to be half way between the heavy-neptunium-loading case (PP4) and the no-neptunium case (reference reactor). For PP5, the masses of isotopes of interest at an average core burnup of 16,000 Mwd/mtU are shown in Fig. 6, and the assembly-wise relative power distribution is given in Fig. 7.

The neptunium loading per rod in PP5 was halved for PP6. The results of the PP6 calculations for masses of isotopes of interest are given in Fig. 8,

and the assembly-wise relative power distribution is shown in Fig. 9. The seventh parametric problem used an initial neptunium concentration twice that of the optimum concentration discussed in Ref. 1. Figures 10 and 11 give the isotopic masses and assembly-wise relative power distribution, respectively, for PP7. The high concentration of neptunium specified for PP7 shortened core lifetime significantly, as shown in Fig. 12, which is a plot of critical boron concentrations as functions of burnup for a number of cases.

The results of reference reactor (no neptunium, standard burnable poison) calculations and PP4 through PP7 are compared in Table II. The information given in the table shows that, for the chosen configuration, the different initial neptunium loadings had only a relatively minor effect on the maximum power generation rate (peaking factor) of the core, although the peak power occurred in different assemblies. Increasing the neptunium loading increases the Pu-236/Pu-238 ratio in the final product and reduces the reactivity available for fuel burnup. Neptunium loadings in the range shown in Table II would be usable, with the actual specification of loading dependent upon the desired Pu-238 production.

Following completion of PP7, assembly compositions and analytical procedures were selected and developed for the equilibrium-cycle calculations. The average burnup of discharged fuel was taken as 33,000 Mwd/mtU,

and it was assumed that burnup would be uniformly distributed over fuel of three different burnups: 0, 11,000, and 22,000 Mwd/mtU at the beginning of a fuel cycle, and 11,000, 22,000, and 33,000 Mwd/mtU at the end of the cycle.

Table II COMPARISON OF CALCULATIONS
WITH VARIOUS NEPTUNIUM LOADINGS

<u>Case</u>	<u>Ref.</u>	<u>PP6</u>	<u>PP5</u>	<u>PP4</u>	<u>PP7</u>
Initial neptunium loading, kg	0	30.7	61.5	123	246
Power peaking factor	1.31	1.28	1.28	1.29	1.31
Maximum power assembly [*]	C3	B3, C2	B3, C2	A2, B1	A1
Burnup achievable, Mwd/mtU	17,000	16,700	16,300	15,400	14,200
Pu-236/Pu-238 ratio, ppm	—	3.23	3.40	3.72	4.37
Masses in kg					
Np-237	—	17.7	36.6	76.9	166.
Pu-238	—	9.71	18.8	35.5	63.5
Pu-239	—	1.48	2.73	4.74	7.36
Pu-240	—	.328	.594	1.02	1.49

* See Fig. 9 for coordinate system.

For the incremental burnup of 11,000 Mwd/mtU/cycle, a feed fuel enrichment of 3.2% was used in conjunction with an assumed fuel-assembly geometrical arrangement like that in the Indian Point 2 reactor core.

Approximate assembly-wise isotopic compositions were determined by zero-dimensional calculations at 0, $\sim 11,000$, and $\sim 22,000$ Mwd/mtU, adjusting the buckling in each stage to simulate fuel movement. The actual burnups achieved for each stage at the beginning of an equilibrium fuel cycle were 0, 10,855, and 21,468 Mwd/mtU. At the end of an equilibrium cycle, the assembly-wise burnups were as shown in Fig. 13, which yielded average values of 12,016, 22,052, and 31,124 Mwd/mtU. The apparent mismatch between assumed initial burnups and the cycle burnups achieved was not deemed large enough to warrant performing the iterative calculations necessary to improve the match, since the ultimate purpose of the calculations was to form a base for later calculations to evaluate Pu-238 production in neptunium target rods. The assembly-wise relative power distribution as a function of burnup for the equilibrium cycle of the reference reactor is given in Fig. 14, which shows some slightly high values due to the mismatch discussed above.

Results of a two-dimensional calculation of the reference equilibrium reactor, with neptunium targets, are given in Figs. 15 and 16, which show assembly-wise burnup, isotopic masses, and relative power distribution. These illustrations can be compared, in part, with Figs. 13 and 14, which show results for the equilibrium core with no neptunium. The addition of neptunium target rods to the equilibrium core did not lead to unacceptable

power peaking, but did reduce reactivity lifetime; neptunium cannot simply be added to the equilibrium core without disrupting the "equilibrium" character of subsequent fuel cycles. In order to avoid perturbations to the equilibrium cycle, the reactivity loss from neptunium must be compensated by an increase in fuel enrichment.

A 2-D calculation (PP8) in the parametric-study series was performed to investigate the situation in which fuel enrichment is increased. On the basis of point burnup calculations, it had been determined that an enrichment increase of 0.16% U-235 was required to compensate for the reactivity loss from neptunium loading in what had come to be considered the reference neptunium case, PP4. With enrichments of 2.36%, 2.86%, and 3.36% in the three core zones, PP8 showed an initial cycle lifetime of 17,200 Mwd/mtU, which compared to a value of 17,100 Mwd/mtU for the reactor without neptunium. The PP8 values for assembly-wise burnup, isotopic masses, and relative power distribution are shown in Figs. 17 and 18. The amount of Pu-238 and the level of Pu-236 contamination are about the same as those for the reference PP4 case, and the effect of increased enrichment on the power distribution is negligible. The conclusion from this calculation of an initial-cycle case is that enrichment can be increased in neptunium-loaded cores to obtain reactivity lifetimes as long as those in cores not loaded with neptunium.

With the determination that reduced reactivity lifetime need not be a penalty of Pu-238 production, a comparison was made between neptunium irradiation in the first (approach to equilibrium) cycle and the equilibrium cycle itself. The comparison was made in terms of grams Pu-238 produced per Mwd/mtU lost and was based on four calculations:

- The reference reactor (no neptunium added);
- PP4 (the reference reactor with some of the burnable poison replaced with neptunium);
- the equilibrium reactor (equilibrium cycle — no burnable poison); and
- the equilibrium reactor loaded with the same mass of neptunium as used in PP4.

Figure 19 gives the critical boron concentration as a function of burnup for the reference reactor and for PP4, as well as the masses of Pu-238 and neptunium as a function of burnup for PP4. The Figure shows that 2290 Mwd/mtU were lost as a result of the neptunium irradiation and that 34.6 kg of Pu-238 were produced. Figure 20 gives the critical boron concentration as a function of burnup for the equilibrium reactor and for the equilibrium reactor with neptunium, as well as the masses of Pu-238 and neptunium as a function of burnup for the neptunium-loaded case. This figure shows that 4210 Mwd/mtU were lost as a result of the neptunium irradiation and that 24.3 kg of Pu-238 were produced.

The information on Figs. 19 and 20 showed clearly that, on the basis of Mwd/mtU lost, Pu-238 production is greater in the first cycle, where burnable poison rods are replaced, than in the equilibrium cycle. For the first cycle, 15 grams of Pu-238 were produced for each Mwd/mtU lost, whereas the equilibrium cycle yielded only 5.8 grams of Pu-238 per Mwd/mtU lost.

To complete the parameter study of the effect of neptunium loading in the target rods of the reference reactor (initial cycle), a calculation (PP9) was performed for zero neptunium loading. Although PP9 represented a fictitious case, it served to verify the endpoint in the study of various neptunium concentrations and thus increase confidence in the validity of the calculations. With the neptunium content of the target rods reduced to zero, a fuel cycle burnup of 17,250 Mwd/mtU was achieved, compared to a value of about 17,000 Mwd/mtU in the reference reactor. Since PP9 and the reference case differed only in the number of boron rods present, and in the presence of target rods of zero neptunium content, the agreement between the two calculations verified the analytical procedure used. A slight difference in end-of-cycle burnup was expected because the boron burnable poison rods are not consumed completely, and the small residual boron at the end of cycle causes a slight reduction in achievable burnup, depending upon the number of rods. Assembly-wise burnup and relative power distribution for PP9 are

given in Figs. 21 and 22. The maximum power peaking factor for PP9 of 1.29 was the same as the maximum for PP4, in which neptunium was added. Thus, the particular geometrical arrangement chosen for the target rods in PP4 had not perturbed seriously the power distribution in the reactor core.

The final calculation in the 2-D parametric study, PP10, was for the equilibrium core with enrichment increased to compensate for the presence of neptunium target material. In PP10, the neptunium targets remained in the core throughout the three fuel cycles of each fuel assembly and were shuffled with the fuel assembly in which they were loaded initially. Assembly-wise burnup, isotopic masses, and relative power distribution for PP10 are shown in Figs. 23 and 24. Because the equilibrium-cycle targets remained in the core longer than the targets in an initial-cycle irradiation, there was a small reduction in the level of Pu-236 contamination. The maximum power peaking factor in PP10 (neptunium plus increased enrichment) was slightly lower than the maximum in the equilibrium core with no neptunium added. It was concluded that PP10 represented a feasible method of producing Pu-238 in the equilibrium cycle, with no adverse effect on power distribution in the core.

V. REVISION OF THREE-DIMENSIONAL MODEL

Three-dimensional studies using 8-plane PDQ-07 calculations were reported³ for the contract period FY 72. Those calculations were performed on a monthly basis to follow the performance of the Connecticut Yankee core during the period of irradiation of the neptunium targets. As burnup progressed, the calculations showed a large oscillation in axial power; the reason for the axial power distortion had not been determined at the end of FY 72 and was the subject of continuing investigation early in FY 73.

A small error in the boron concentration in one fuel assembly was discussed in the 3-D calculation that had been performed in March, 1972. Since the error occurred at about the time axial power distortions were observed, it was felt that the error should be corrected and the calculation for March repeated. This was done, but the only effect on the correction was a slight change in the assembly-wise power distribution. Inasmuch as no significant effects were seen, the calculations for April and May, 1972 were not repeated.

To investigate further the apparent distortion in axial power distribution obtained in the 8-plane PDQ-07 calculations, a simplified one-dimensional study was carried out to determine the significance of the number of axial planes (mesh points). For the 1-D study, the average planar composition

in a fuel assembly was taken from a PDQ-07 calculation performed before the axial power distortion appeared. In the 1-D calculations, five fueled planar regions were described with various numbers of mesh intervals, ranging from 11 — simulating the PDQ-07 planar description — to 99, the maximum number available in the 1-D program. The results of the 1-D calculations are given in Table III, along with the axial average region power distribution from the base (pre-distortion) PDQ-07 calculation.

Table III AVERAGE REGION POWER DISTRIBUTION (AXIAL)

<u>Number mesh intervals</u>	Relative power in axial zone				
	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>
99 (96-plane model)	0.715	1.58	1.63	1.29	0.690
27 (24-plane model)	0.754	1.53	1.55	1.25	0.704
16 (13-plane model)	0.723	1.45	1.52	1.30	0.841
11 (8-plane model)	0.826	0.665	0.831	0.979	1.71
PDQ-07 (8-plane model)	0.976	0.701	0.841	0.939	1.37

Table III shows that, for the 1-D calculations, the axial power distribution became increasingly distorted as the number of axial mesh intervals was reduced. For the smallest number of mesh intervals, the general shape of the power distribution was reversed compared to the 99-mesh-interval calculation. Results of the 8-plane calculation, however, generally conformed with the axial power distribution from the PDQ-07 calculation. In view of

this, it was concluded that the PDQ-07 calculations were incorrect due to the coarse axial mesh spacing used. The 1-D calculations indicated that an acceptable axial power distribution would be obtained with 13 axial planes, but that the use of 24 axial planes would give better results. Therefore, a 24-plane axial model was selected for further PDQ-07 calculations.

An isometric drawing of the 24-plane, three-dimensional geometric model used for the reanalysis of the Connecticut Yankee core is given as Fig. 25. Calculations using the 3-D model with 24 axial planes were performed for Connecticut Yankee based on actual plant values of soluble boron concentrations and thermal energy production furnished by CYAPC. These values are given in Table IV. The calculated x, y power distributions for the different burnup steps are shown in Figs. 26 through 32. A comparison was made between calculated and measured values of power peaking: at 843.9 Mwd/mtU (equilibrium Xe and Sm), the calculated relative power peaking for the assembly that contained the targets was 1.26, which compares favorably with the measured value of 1.23 at beginning of life.

The axial power distributions calculated with the 24-plane model for each burnup step are shown in Figs. 33 through 39. These calculated values show marked improvement over those calculated with the 8-plane model. No oscillations occurred, and the axial distribution maintained the expected modified cosine shape throughout burnup. The change in shape of the axial

Table IV CONNECTICUT YANKEE REACTOR CORE 3 SOLUBLE
BORON CONCENTRATION AND THERMAL ENERGY
PRODUCTION USED IN THE 24-PLANE MODEL

<u>Date</u>	<u>Critical boron concentration, ppm</u>	<u>Energy increment, Mwd/mtU</u>	<u>Total energy, Mwd/mtU</u>
May 26, 1971	1360	0	0
July 1	870	843.9	843.9
September 1	748	1648.1	2492
November 1	544	1626	4118
January 1, 1972	373	1670	5788
March 1	191	1621	7409
May 1	19	1693	9102
June 9	0	1090.0	10192

power distribution with time is given by the set of curves in Fig. 40; each curve describes, for a given time, the pointwise average power as a function of fuel height at an x,y point in the target assembly. The planes identified at the top of Fig. 40 correspond to the planes shown in Fig. 25, the isometric drawing of the 24-plane model.

The last data to report from the three-dimensional calculations relate to isotopic masses and burnup in the targets. These data are given in Table V, along with Pu-236/Pu-238 ratios.

Table V CALCULATED MASSES OF ISOTOPES IN TARGETS, THROUGHOUT BURNUP

Target	Mwd/mtU	Masses in grams of isotopes in targets				Pu-236
		Np-237	Pu-238	Pu-239	Pu-240	Pu-238
Initial Values						
D	0	109.8	0	0	0	0
C	0	49.81	0	0	0	0
B	0	100.0	0	0	0	0
A	0	207.2	0	0	0	0
Total	0	466.8	0	0	0	0
As of June 30, 1971						
D	881.7	107.6	1.979	0.01918	0.0002903	5.033
C	1366	48.48	1.177	0.01340	0.0002483	5.949
B	1244	98.04	1.752	0.01490	0.0002141	7.357
A	1002	204.9	2.053	0.01037	0.0001432	10.57
Total	—	459.0	6.961	0.05785	0.0003959	—
As of August 31, 1971						
D	2844	102.9	6.500	0.1918	0.008830	4.667
C	3977	46.04	3.491	0.1122	0.006069	5.511
B	3753	94.19	5.437	0.1341	0.006869	6.790
A	3274	199.8	6.969	0.1088	0.004970	9.732
Total	—	442.9	22.40	0.5469	0.02674	—
As of October 31, 1971						
D	4795	98.30	10.65	0.4919	0.03577	4.510
C	6356	43.90	5.431	0.2612	0.02176	5.308
B	6089	90.71	8.663	0.3218	0.02584	6.520
A	5504	194.8	11.64	0.2795	0.02014	9.304
Total	—	427.7	36.38	1.354	0.1035	—
As of December 31, 1971						
D	6832	93.72	14.63	0.8962	0.03767	4.363
C	8663	41.89	7.161	0.4404	0.04830	5.121
B	8400	87.35	11.65	0.5548	0.05934	6.273
A	7811	189.8	16.26	0.5074	0.05093	8.924
Total	—	412.8	49.70	2.399	0.2462	—
As of February 29, 1972						
D	8792	89.46	18.14	1.344	0.1615	4.231
C	10790	40.09	8.635	0.6245	0.08275	4.948
B	10540	84.31	14.26	0.7982	0.1038	6.046
A	9994	185.2	20.48	0.7555	0.09415	8.569
Total	—	399.1	61.52	3.522	0.4422	—
As of April 30, 1972						
D	10840	85.16	21.50	1.849	0.2632	4.094
C	12950	38.31	10.01	0.3218	0.1273	4.775
B	12720	81.28	16.76	1.062	0.1620	5.813
A	12240	180.5	24.65	1.032	0.1528	8.211
Total	—	385.2	72.92	4.765	0.7053	—
As of June 9, 1972						
D	12140	82.50	23.48	2.182	0.3412	4.005
C	14310	37.21	10.83	0.9489	0.1602	4.658
B	14090	79.41	18.25	1.234	0.2054	5.666
A	13650	177.5	27.19	1.213	0.1971	7.985
Total	—	376.6	79.75	5.578	0.9039	—

VI. COMPUTER PROGRAM DOCUMENTATION

Documentation of the PDQ-07 — HARMONY modeling, and of the auxiliary program package used to prepare data for PDQ-07 — HARMONY, began in August, 1972. All documentation was completed by March, 1973 and submitted to the U.S. Atomic Energy Commission for review and comment.

The program documentation is not included here; rather, it is published as a separate document that is a supplement to this report.

VII. SPECIAL TASKS

The following paragraphs describe special tasks that were carried out in response to USAEC requests or in support of the contract scope of work.

A. Neptunium-237 and Plutonium-238 Production

At the request of the USAEC, during the first quarter of the contract period, Southern Nuclear Engineering (1) projected neptunium production through the year 1980, (2) commented on possible Pu-238 production in the equilibrium cycle of a current PWR, and (3) discussed the possibility of producing Pu-238 in fast breeder reactors.

1. Projected Neptunium Production in Light Water Reactors Through 1980

On the basis of Np-237 production rates calculated for the Connecticut Yankee fuel (see Table VI), a reasonable value for production in PWR's appeared to be ~ 0.014 grams Np-237 per Mwd. Decreasing this value slightly to account for a lower neptunium production rate in BWR's, and expressing the rate in terms of Mw(e) of reactor power, a figure of ~ 10 grams Np-237 per year per Mw(e) installed capacity (operating at 80% plant factor) was obtained. Assuming as a first approximation this value of 10 grams Np-237 per year per Mw(e) installed capacity, the total anticipated production capability of Np-237 in the U.S. nuclear power industry was estimated. Using the

Table VI SPECIFIC MASS OF Np-237 (kg/mtU)
IN CONNECTICUT YANKEE FUEL
AS A FUNCTION OF BURNUP AND ENRICHMENT

<u>Mwd/mtU</u>	<u>3.00%</u>	<u>3.24%</u>	<u>3.67%</u>	<u>4.00%</u>
0	0	0	0	0
2000	0.0086	0.0085	0.0083	0.0081
5000	0.0310	0.0306	0.0301	0.0297
8000	0.0619	0.0613	0.0604	0.0599
12000	0.1131	0.1126	0.1118	0.1113
15000	0.1577	0.1575	0.1574	0.1566
18000	0.2059	0.2067	0.2075	0.2073
21000	0.2565	0.2585	0.2610	0.2620
24000	0.3081	0.3116	0.3165	0.3189
27000	0.3603	0.3657	0.3738	0.3780
30000	0.4116	0.4196	0.4314	0.4382

growth projection of nuclear power prepared by the USAEC, the total neptunium production rate (availability values) is shown in Fig. 41. Since the fuel is resident in-reactor for approximately three years in an equilibrium fuel cycle, and an additional year is needed for spent-fuel cooling and reprocessing, the neptunium produced in the reactor fuel does not become available until four years later. The curve of the neptunium production rate, which was added to the USAEC information, was therefore displaced by four years to account for these factors. During the early years, prior

to 1975, some neptunium will be available from reactors operating prior to 1971, and from non-equilibrium fuel cycles employed in the early stages of operation of the reactors shown in the figure.

Maximum Pu-238 production rates may be estimated by assuming recycle of the neptunium produced, using an average value of 30% of the neptunium loaded as an estimate of Pu-238 production. An additional 2- to 3-year delay following neptunium availability dates is necessary to allow for target fabrication, the irradiation period, and subsequent processing to recover the Pu-238. Thus, potential Pu-238 production rates may be estimated from the attached figure by assuming a value of 30% of the neptunium production rate, displaced in time by two to three years. This estimate did not allow for further recycle of neptunium recovered from chemical processing of the irradiated target material, nor were possible limiting factors (e. g., power peaking, permissible reactivity losses, etc.) considered in estimating the maximum Pu-238 production rates.

2. Plutonium-238 Production in the Equilibrium Cycle of a Light Water Reactor

Production of Pu-238 by irradiation of neptunium target material in the equilibrium cycle of an operating power reactor does not differ in principle from production in the initial cycle. Those differences that do exist arise mainly from (1) neutron spectral changes due to the presence

of fuel of various levels of burnup, and (2) the absence of boron burnable poison rods used initially as a means of reactivity control.

The first of these, differences in neutron spectrum, is an inherent characteristic over which the reactor operator has little or no control. While the difference in neutron spectrum from the initial core will not likely be a major factor, the effect on Pu-238 production (and level of Pu-236 contamination) remained to be evaluated. Perhaps the greatest effect on Pu-238 production in the equilibrium cycle results from the absence of boron burnable poison rods, and the operating philosophy necessary to accommodate the cyclic nature of the power demand in most utility systems. The reactor operator is usually constrained with regard to scheduled outages for refueling. Hence, the duration of a fuel cycle or refueling interval becomes a very important consideration.

Of the two means of compensating for the loss of reactivity due to the presence of neptunium target rods (when boron rods are no longer used), i. e., (1) reduction in fuel cycle duration or (2) increased feed enrichment, only the latter affords the operator the needed flexibility to meet system power requirements. Consequently, the effect of increased feed enrichment on reactor operating parameters (e. g., power peaking, etc.) when neptunium target material is present must be evaluated for a selected Pu-238 production rate and for a refueling interval equal to that of the reactor without neptunium

targets present. This approach will not restrict the reactor operator's flexibility, and the cost of Pu-238 production will be determined largely by the increase in feed enrichment.

3. Comments on the Possibility of Producing Pu-238
in Fast-Breeder Reactors

In assessing the feasibility of Pu-238 production by irradiation of Np-237 target material in a fast-breeder reactor, it is convenient to compare Np-237 nuclear properties with those of U-238, which is used as target material for Pu-239 production in an analogous process. For the light water reactors currently being studied, the spectrum-weighted microscopic cross section of Np-237 is about twenty times larger than the corresponding absorption cross section of U-238. Consequently, it is possible to achieve the desired Pu-238 production with reasonably small loadings of Np-237. However, in the much-higher-energy neutron spectrum characteristic of fast reactors, the absorption cross sections of Np-237 and of U-238 are more nearly comparable, leading to a requirement for comparatively larger neptunium loadings. Figure 42 shows the microscopic absorption cross sections of Np-237 and U-238 in the 0.1 to 10 Mev range as measured by Nagle, et al.⁴ These curves imply that the spectrum-averaged absorption cross section for Np-237 will be only a factor of 2 (or less) greater than that for U-238. Below 0.1 Mev, the strongly absorbing resonance region of U-238 will reduce this ratio even more.

The requirement for a larger loading of neptunium does not, in itself, necessarily demonstrate that fast reactor production of Pu-238 is unattractive, without consideration of other factors such as fuel cycle duration, neptunium recycle, spatially-graded loadings, etc. Consideration of these factors, which could possibly tend to counteract the disadvantage of a higher neptunium loading, cannot be accomplished without detailed calculations.

An additional consideration is that in the higher energy spectrum of a fast reactor, the $n-2n$ reaction on Np-237, leading to Pu-236, will be considerably more significant than in a thermal reactor system. Not only does the higher energy neutron spectrum enhance the weighted $n-2n$ reaction probability, but also decreases the Np-237 absorption cross section producing Pu-238. Consequently, it would not be surprising to find that Pu-238 produced in a fast reactor might have several orders of magnitude greater Pu-236 contamination than Pu-238 produced in a thermal reactor system.

A further consideration is the appreciable fission cross section associated with Np-237 in a fast neutron spectrum. Not only is the fission threshold for Np-237 lower than for U-238, but the fission cross section at higher neutron energies in Np-237 is about twice that for U-238. Hence, any design employing Np-237 target material for Pu-238 production in a fast reactor must account for neptunium consumption by fissioning and must provide means for removing the heat so generated.

On the basis of the considerations discussed above, it was Southern Nuclear's conclusion that irradiation of Np-237 in a fast reactor did not appear to be an attractive alternative method for producing Pu-238. However, a definitive conclusion can only be reached after performing some of the detailed analyses necessary to provide a sound basis for determining the technical and economic feasibility of such a process.

B. Neptunium Recovery, Target Fabrication, and Target Processing

Discussions were held with personnel of Battelle Columbus Laboratories, Allied-Gulf Nuclear Services, and the General Electric Company regarding neptunium recovery from spent reactor fuel, the fabrication of neptunium-bearing targets, and/or the reprocessing of irradiated targets. The discussions are outlined below in the order in which they were held.

1. Battelle Columbus Laboratories

A visit was made to Battelle Columbus Laboratories on March 20, 1973, to discuss neptunium target fabrication and reprocessing. Results of that visit are given below.

a. Np Recovery in Existing Reprocessing Plants

The salvage of Np in existing fuel-reprocessing plants will require an additional stage for the separation of neptunium and its conversion to the oxide. GE has apparently provided for such a stage, in which Np, U,

and Pu are extracted from the fission products and Np recovered in a subsequent extraction stage. (Note: Most reprocessors are using tri-butyl phosphate for the extraction, with selectivity accomplished by adjusting the oxidation state of the uranium and trans-uranium elements. Allied-Gulf will also employ ion-exchange columns for the final purification. The French have recently been developing trilaurel amine as an extractant.) The new Allied-Gulf plant does not now plan a stage for Np recovery, but has proposed (if the value and demand for Np warrant) a once-a-year campaign to recover all of the Np accumulation with the fission products in the waste storage tanks. Since the radiation level from Np is greater than that of U or Pu, additional shielding will likely be required. Allied-Gulf may not, as yet, have thought through on the Np recovery process sufficiently to allow for the additional shielding needed with this recovery regime.

b. NpO₂ Target Fabrication

Fabrication of Np target rods is a complex procedure, which, at present, is not adequately understood in detail. Major outstanding questions involve the blending procedures and the pressing-sintering stage. It is recognized, however, that the cost of a fabrication plant is determined largely by required glove-box train and the inherent shielding required. A plant capable of processing ~ 500 kg Pu-238 per year will cost perhaps \$5 million, and little cost reduction would result from a plant of smaller capacity.

In addition to the capital contribution (usually written off in three to five years), operational charges ($\sim$ \$2 million per year) and the cost of clad material must be added to the final cost of the finished product.

Because of the radiation level of both Np and Pu-238 ($\sim$ 16,000 n/sec-g) and the need for shielding, shipping costs are expected to be quite high. (The Savannah River shipping cask can handle up to 350 grams Pu-238.) For this reason, there are strong economic incentives for locating the target-rod fabrication and reprocessing facilities either on the same site or in close proximity to each other.

c. Target Rod Reprocessing

After irradiation, the chemical processing of the target rods to recover Np and to separate (and purify) the Pu-238 produced represents a relatively modest extrapolation of techniques now being used for reprocessing fuel. The presence of large quantities of ZrO_2 imposes the most serious problem and will require development of an acceptable (and compatible) process for dissolving the target material. (Note: The HCl-HF dissolution technique, while adequate for laboratory use in the analysis of Np target samples removed from the Connecticut Yankee reactor, is not adaptable to large-scale head-end use in Np reprocessing nor compatible with current extraction or ion-exchange purification-separation stages.)

Assuming a satisfactory resolution of the head-end dissolution problem, the balance of the Np reprocessing plant can utilize existing

extraction or ion-exchange techniques, or perhaps some combination of the two. Cost of a reprocessing plant capable of handling 500 kg Pu-238 per year (~ 2 kg Pu-238/day + ~ 8 kg Np/day at a maximum concentration of 3 g Np/liter is a plant processing capability of ~ 3000 liters per day)* will be about \$7 million, with little effect on cost for a plant of smaller capacity. The basic cost of a reprocessing plant regardless of throughput capacity would be a minimum of \$5 million, and additional capacity results in only a relatively small increment in cost. Annual operating charges for a 500 kg/yr plant would amount to about \$3 million. Licensing, safeguards, and inventory requirements imposed by the AEC account for a sizable fraction of the operating charge (~ 10 -20%), which, together with the fact that the plant would require a certain number of employees regardless of throughput, means that the annual operating charge is relatively independent of plant capacity over a reasonable size range. About 10-20% of the operating cost would be more directly related to the plant throughput.

The possibility of using a fuel reprocessing plant for a special (perhaps once-a-year) campaign for Np target reprocessing was considered. No clear economic incentive is evident, and the inventory charges accumulated against Np rods in storage, the additional shielding needed, and the

* The Allied plant is capable of processing 3000 liters/day and is expected to cost $\sim$ \$100 million. A Np recovery plant would be $\sim 1/15$ that size.

change in operating routine all argue against the use of such a reprocessing scheme.

2. Allied-Gulf Nuclear Services

Allied-Gulf Nuclear Services in Barnwell, South Carolina was visited on April 10, 1973 to discuss the recovery of neptunium from spent power reactor fuel. Allied-Gulf personnel indicated that their organization's contracts with utilities have options for the recovery of neptunium, but that facilities for such recovery are not presently included in the Barnwell plant. As the contracts are now written, the option is the utility's, but the utility must pay for the required additional Barnwell plant capability if it chooses to recover its neptunium. The only cost information obtained at Allied-Gulf was an opinion, given orally. The cost range discussed was \$5,000 to \$6,000 per ton throughput at 75% neptunium recovery.

3. General Electric Company

The General Electric Company is the only fuel reprocessor now equipped to recover neptunium from spent power reactor fuel. Information regarding G.E. activities was obtained during discussions held in San Jose, California on May 10, 1973.

General Electric has three types of contracts with the utilities:

- The utility retains ownership of the neptunium;
- ownership of the neptunium is shared equally between G.E. and the utility; or

—the utility does not want the neptunium and G.E. owns it.

The G.E. reprocessing plant at Morris has been designed to accommodate neptunium recovery on a switch on — switch off basis. However, G.E. management must decide very soon whether it will recover neptunium at Morris; without a firm commitment on the part of the U.S. Government, the G.E. decision will be negative.

The number given orally by General Electric for the cost of recovery of neptunium was \$15 per gram.

C. Presentation to USAEC

In May, 1973, a briefing on the project status and future projections of plutonium-238 production in commercial light water reactors was given to the USAEC. The principal topics discussed in the presentation are listed below.

- Current program summary.
- Advantages of plutonium-238.
- Commercial production of plutonium-238.
- Experimental target fabrication and post-irradiation examination.
- Physics considerations.
- Economic considerations.
- Five-year plan.
- Organization.

A document of approximately one-hundred pages was given to those attending the presentation, and additional copies have been produced for a distribution to be specified by the Commission.

VIII. ECONOMIC STUDY

A. Summary

This section summarizes the results of an economic analysis of the potential cost of producing Pu-238 in U.S. commercial facilities, i. e., processing plants, fabrication facilities and power reactors. The estimate of the total cost of production (in current dollars and with current technology) is dependent upon annual production rates and is given as follows:

<u>Production, kg/year</u>	<u>Cost, \$/g Pu-238</u>
30	165
60	140
120	120

The following subsections develop the bases for these values.

B. Method of Analysis

As a first step in the cost studies, each step in the production process which has an assignable cost was segregated. Figure 43 is a flow chart of the assumed processes required to produce significant quantities of Pu-238 from Np-237 contained in irradiated power reactor fuel. These cost analyses stop at the box entitled "Ship to Encapsulator," although there are costs beyond that point not considered in this study. In addition, the possibility of "recycle"

of Pu-238 sources from missions which have ended has not been evaluated but could represent significant savings to more than offset the cost of reuse.

After segregating each step in the process, some further assumptions were made in order to simplify the analyses. These assumptions are given below.

- 1) All cost estimates are based on current prices for 1980 delivery in the UO₂-PuO₂ commercial reactor fuel market, extrapolated to a Np/Pu-238 industry.
- 2) A commercial industry capable of handling 120 kg of Pu-238 per year exists by 1980.
- 3) A fuel cost penalty is suffered by power reactors based on both SNE's nuclear analysis and a baseline fuel cost of 3 mills/kw-hr.
- 4) No credit is taken for
 - a) future technological advances
 - b) further optimization
- 5) Production of Pu-238 occurs during the startup cycle of PWR's, and the Np target rods are removed at the first refueling outage.
- 6) Each Np target rod contains 200 grams of Np initially, 20% of which is converted to Pu-238 during the assumed irradiation time.

C. Results

Table VII shows the estimated cost to produce Pu-238 over the near term, by 1980 and beyond 1980, in which the phrase "near term" implies fabrication of 100 Np bearing rods in order to produce roughly 4 kg of Pu-238, whereas the other two columns apply to annual production rates of 120 kg of Pu-238 per year.

Table VII COST SUMMARY, \$/g Pu-238

	<u>Near term</u>	<u>By 1980</u>	<u>Long term</u>
Recover Np [*]	75	75	75
Fabricate Np targets	187.50	45	35
Ship and assemble targets	1.50	1.50	1.50
Fuel cost penalty	40	40	30
Ship irradiated targets	3.33	—	—
Recover Pu-238 and Np	—	4	4
Unburned Np value [*]	(53)	(53)	(53)
Ship Pu-238 to encapsulator	<u>—</u>	<u>10.00</u>	<u>10.00</u>
Total	\$254.33	\$122.50	\$102.50

* Np cost at \$15,000/kg of Np.

If the "near term" costs are modified to represent annual production rates of 30 and 60 kg Pu-238, respectively, the only component which

changes is the target fabrication costs. These costs are estimated to be \$100 and \$75 per gram of Pu-238 at these respective production rates (see Fig. 44).

D. Discussion

1. Recover Np

The estimate of neptunium recovery cost is based upon private discussions with General Electric, the probable producer of much of this material. A visit to their Morris, Illinois facility recently by SNE personnel revealed that all the recovery equipment is installed such that no sizable further investment is required by GE to recover Np nitrate.

Since the Np cost is one of the major contributors to the total cost of Pu-238, the sensitivity of results to this number has been investigated. Figure 45 shows the possible range of Pu-238 costs for both (1) a given Np cost and (2) a variation in Np recovery cost. At any given cost of Np, the uncertainty in the cost of Pu-238 is \$20/g and for each \$10/g change in Np cost, the Pu-238 cost changes by \$15/g in the same direction.

2. Fabricate Np Targets

In order to develop fabrication costs for the Np target rods, estimates of current costs of making UO₂ rods for power reactors were extrapolated to (1) the appropriate scales of production and (2) the different materials (Np oxide) involved.

First, the assumption was used that a $\text{PuO}_2\text{-UO}_2$ (mixed oxide) bearing fuel rod costs 20% more to manufacture than a UO_2 bearing rod at equal scales of production. This assumption is often quoted in studies by industry. A further multiplier of 1.2 was used to account for the possibility of even greater penalties incurred through handling Np because of its radioactivity.

The base cost obtained above was scaled upward utilizing the following equation. The equation represents a good approximation of the effect of throughput on the cost of making fuel rods:

$$C = C_o \left(\frac{T}{T_o} \right)^{-0.3}$$

where

T_o = reference throughput rate

C_o = reference cost

T = assumed throughput rate

C = cost at throughput, T

Figure 44 shows the behavior of such a curve based on a cost per UO_2 fuel rod of \$200 produced in a fuel fabrication facility operating at a throughput of one metric ton of uranium per day.

The possible savings available by adding a "Np line" to an existing fabrication facility was investigated. It was concluded that through sharing

of some equipment and overheads, a 20% cost reduction might be achieved. This reduction is reflected in the "long term" estimate.

3. Ship and Assemble Targets

After the target rods are built and welded shut, they will be sent to the fabricator to be inserted into the bundles during the final assembly stage.

Assuming that the shipping and assembly costs are comparable to the same steps in the commercial fuel market, these costs are minor and equal to about \$10/kg Np and \$250/kg Np, respectively. These figures imply a cost per gram of Pu-238 produced of roughly \$1.50.

4. Fuel Cost Penalty

The fuel cost penalty to the utility industry results from the fact that some neutrons which would normally produce energy or fissile plutonium are instead being used to produce Pu-238. Based on physics analyses performed previously by SNE, an optimum case was found and identified as Case PP4. The fuel cost penalty per year to produce 120 kg of Pu-238 annually turned out to be roughly \$5 million, or \$40/g Pu-238.

Although no optimization studies were performed beyond what had already been done, a few other cases were investigated. It was found that Case PP6 represented a possible savings in fuel cost of over \$1-1/4 million. This results in a savings of roughly \$10/g Pu-238, which is the basis for the "long term" forecast.

5. Ship Irradiated Targets

In the "near term," it is felt that chemical reprocessing of target rods would not be done commercially so that shipment would be done separately from the remainder of the fuel assembly containing the target rods. By 1980 and beyond, it is forecast that commercial reprocessors will recover the Pu-238 in separate campaigns after accumulating a sufficient inventory of rods. In the latter case, there is no special shipment required since the target rods are shipped with irradiated assemblies to a commercial reprocessor.

If a shipping cost in the near term of \$1000 per day is used, which includes rental of a shielded cask, freight, insurance, etc., and ten 8-day round trips from each reactor with target rods (each reactor will contain roughly 1200 rods and ship 120 rods at a time), the total cost of shipping 6000 rods containing 120 kg of Pu-238 from five reactors equals \$400,000, or roughly \$3.33 per gram of Pu-238.

6. Recover Pu-238 and Np

Chemical reprocessing of the target rods is required in order to purify and obtain the Pu-238. At the same time, the unburned Np can also be recovered for recycle.

In the near term, it is assumed that this can be done at government facilities. By 1980 and beyond, the assumption is that it will be done at

commercial facilities in separate campaigns. In the latter case, a processing charge of \$40,000 per day for "rental" of a commercial facility has been assumed. A recovery time, including clean-out time, of twelve days for a total cost of \$480,000 to recover 120 kg of Pu-238 has also been assumed. These assumptions yield a cost of \$4/g Pu-238.

Since the recovered Np can be refabricated and irradiated again, the Pu-238 production costs at \$15,000/kg for the remaining Np have been credited. A residual Np concentration of 70% of the initial concentration was assumed. This yields a net credit of \$53/g Pu-238 (i. e., $\$75/\text{g} \times 0.7 = \53).

7. Ship Pu-238 to Encapsulator

The final step analyzed in the study was the cost to ship the Pu-238 to government facilities to be encapsulated for a subsequent space mission. Because of its high neutron activity, Pu-238 must be shipped in small quantities in a shielded container.

Pu-238 is not unique in this respect. In fact, it is less troublesome than some other candidates for isotopic power sources. Specific neutron activities for californium and curium are 10^8 and 10^3 times that of Pu-238. Since the cost of this step in the process is almost proportional to neutron emission rates (for the same cask, the payload limit is reduced in direct proportion to the neutron activity), this cost for other isotopes could be significant.

There is in existence a cask licensed to ship about 350 grams of Pu-238. If it is assumed that an identical commercial cask would rent for \$350 per day, including freight, insurance, etc., and the round trip time is ten days, the cost of this step is \$10/g of Pu-238.

E. Future Areas for Optimization

The discussion up to this point has ignored any possible gains the future might bring which would result in cost reductions. There is considerable promise for future cost savings in the following areas:

- 1) Longer irradiation times;
- 2) more optimum Np loadings per reactor;
- 3) recovery of Pu-238 from completed missions; and
- 4) increased volumes above 120 kg of Pu-238 per year.

Items 1) and 2) will tend to reduce the fuel cost penalty to utilities, which is predicted to be one of the most significant cost factors. Item 4) will reduce the cost of fabricating the target rods, also a significant contributor to the total cost. Item 3) could greatly enhance the value of Pu-238 and, whereas it will increase the per gram cost, it may decrease the cost per watt-hour.

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Fig. 1 Isometric showing neptunium targets in fuel assembly E-08, loading position J-14 of the Connecticut Yankee Reactor.

Fig. 2 Flow diagram for destructive examination of target rods.

Fig. 3 Results of gamma-scan of neptunium target rod No. 2 and comparison with predictions.

Fig. 4 Core arrangement of different assembly combinations used in 2-D calculations through PP4.

Fig. 5 Calculated critical boron concentration as a function of average core burnup for the reference reactor and the fourth and fifth parametric problems.

17870	18100	17990	17980	17650	17570	15700	12800
	242.6		243.6		413.0		305.7
	146.5		146.1		239.9		112.8
	22.88		22.74		37.00		13.44
	5.364		5.309		8.540		2.389
	3.418		3.411		3.371		3.326
18100	18020	18550	17930	18100	17080	17050	12890
242.6		398.5		405.1		440.2	
146.5		246.0		243.2		229.8	
22.88		39.05		38.12		32.42	
5.364		9.326		8.973		6.753	
3.418		3.372		3.372		3.492	
17990	18550	18100	18380	17510	17180	14990	11790
	398.5		401.0		419.0		315.4
	246.0		244.9		237.2		106.6
	39.05		38.70		36.15		12.02
	9.326		9.194		8.232		1.393
	3.372		3.372		3.379		3.333
17980	17930	18380	17710	17420	16290	15190	10150
243.6		401.0		248.6		655.7	
146.1		244.9		144.0		300.2	
22.74		38.70		22.04		39.53	
5.309		9.194		5.027		7.651	
3.411		3.372		3.429		3.491	
17650	18100	17510	17420	18320	15560	13870	
	405.1		248.6		353.9		
	243.2		144.0		181.7		
	38.12		22.04		26.08		
	8.973		5.027		5.472		
	3.372		3.429		3.461		
17570	17080	17180	16290	15560	15580	10060	
413.0		419.0		353.9		333.9	
239.9		237.2		181.7		93.43	
37.00		36.15		26.08		9.493	
8.540		8.232		5.472		1.470	
3.371		3.379		3.461		3.222	
15700	17050	14990	15190	13870	10060	Assem. Burnup-Mwd/mtU	
	440.2		655.7		333.9	Np-237 mass gms	
	229.8		300.2		93.43	Pu-238 mass gms	
	32.42		39.53		9.493	Pu-239 mass gms	
	6.753		7.651		1.470	Pu-240 mass gms	
	3.492		3.491		3.222	Pu-236/Pu-238 ratio ppm	
12800	12890	11790	10150	Total masses in core at 16,000 Mwd/mtU			
305.7		315.4		Np-237 — 36.59 kg			
112.8		106.6		Pu-238 — 18.80 kg			
13.44		12.02		Pu-239 — 2.733 kg			
2.389		1.393		Pu-240 — .5943 kg			
3.326		3.333		Pu-236/Pu-238 ratio 3.403 ppm			

Fig. 6 Assembly-wise burnup and isotopic masses in neptunium target rods in PP5 at an average core burnup of 16,000 Mwd/mtU.

.9990	.9961	1.059	1.046	1.106	1.130	1.060	.8913
1.260	1.276	1.236	1.210	1.132	1.094	.9247	.7424
1.113	1.161	1.101	1.145	1.076	1.094	.9414	.7785
.8061	.8550	.8279	.9207	.9255	1.040	.9998	.9575
.8501	.8967	.8596	.9389	.9297	1.031	.9916	.9752
.9961	1.046	1.094	1.094	1.120	1.110	1.152	.8935
1.276	1.254	1.281	1.189	1.172	1.047	1.021	.7485
1.161	1.105	1.159	1.093	1.136	1.039	1.052	.7874
.8550	.8122	.8785	.8769	.9879	.9956	1.128	.9744
.8967	.8497	.9072	.8921	.9876	.9859	1.114	.9907
1.059	1.094	1.104	1.112	1.086	1.081	.9873	.7932
1.236	1.281	1.216	1.218	1.110	1.061	.8817	.6849
1.101	1.159	1.097	1.157	1.084	1.089	.9160	.7338
.8279	.8785	.8566	.9595	.9735	1.084	1.016	.9464
.8596	.9072	.8758	.9643	.9655	1.064	1.003	.9621
1.046	1.094	1.112	1.076	1.024	1.018	.9956	.6490
1.210	1.189	1.218	1.136	1.097	.9841	.9017	.5912
1.145	1.093	1.157	1.105	1.142	1.025	.9588	.6541
.9207	.8769	.9595	.9714	1.099	1.071	1.121	.9202
.9389	.8921	.9643	.9636	1.075	1.045	1.102	.9501
1.106	1.120	1.086	1.024	1.159	.9367	.8933	
1.132	1.172	1.110	1.097	1.127	.9336	.8209	
1.076	1.136	1.084	1.142	1.166	1.021	.8924	
.9255	.9879	.9735	1.099	1.169	1.158	1.128	
.9297	.9876	.9655	1.075	1.132	1.123	1.123	
1.130	1.110	1.081	1.018	.9367	1.012	.6164	
1.094	1.047	1.061	.9841	.9336	.9232	.5881	
1.094	1.039	1.089	1.025	1.021	.9938	.6652	
1.040	.9956	1.084	1.071	1.158	1.180	.9496	
1.031	.9859	1.064	1.045	1.123	1.148	.9678	
1.060	1.152	.9873	.9956	.8933	.6164		
.9247	1.021	.8817	.9017	.8209	.5881		
.9414	1.052	.9160	.9588	.8924	.6652		
.9998	1.128	1.016	1.121	1.128	.9496		
.9916	1.114	1.003	1.102	1.123	.9678		
.8913	.8935	.7932	.6490	— 0.0 —	Burnup, Mwd/mtU		
.7424	.7485	.6849	.5912	— 5,000			
.7785	.7874	.7338	.6541	— 9,000			
.9575	.9744	.9464	.9202	— 16,000			
.9752	.9907	.9621	.9501	— 17,000			

Fig. 7 PP5 — Assembly-wise relative power distribution as a function of burnup.

17720	18030	17920	17980	17650	17680	15700	12790
	117.5		117.7		198.9		149.6
	75.19		75.10		123.7		58.67
	12.26		12.23		20.04		7.281
	2.893		2.881		4.694		1.315
	3.252		3.245		3.201		3.148
18030	17940	18610	17910	18200	17110	17140	12850
117.5		191.9		195.0		212.9	
75.19		126.4		125.2		119.0	
12.26		21.04		20.60		17.61	
2.893		5.092		4.919		3.714	
3.252		3.206		3.204		3.308	
17920	18610	18100	18460	17500	17280	15010	11810
	191.9		193.0		201.9		154.5
	126.4		126.0		122.4		55.58
	21.04		20.88		19.58		6.535
	5.092		5.031		4.523		1.110
	3.206		3.205		3.207		3.154
17980	17910	18460	17660	17390	16270	15330	10140
117.7		193.0		120.3		317.6	
75.10		126.0		74.07		156.3	
12.23		20.88		11.84		21.63	
2.881		5.031		2.722		4.255	
3.245		3.205		3.259		3.301	
17650	18200	17500	17390	18210	15550	13830	
	195.0		120.3		171.8		
	125.2		74.07		93.80		
	20.60		11.84		14.07		
	4.919		2.722		2.976		
	3.204		3.259		3.282		
17680	17110	17280	16270	15550	15470	10020	
198.9		201.9		171.8		164.4	
123.7		122.4		93.80		48.65	
20.04		19.58		14.07		5.127	
4.694		4.523		2.976		.7947	
3.201		3.207		3.282		3.046	
15700	17140	15010	15330	13830	10020	Assem.burnup - Mwd/mtU	
	212.9		317.6		164.4	Np-237 mass gms	
	119.0		156.3		48.65	Pu-238 mass gms	
	17.61		21.63		5.127	Pu-239 mass gms	
	3.714		4.255		.7947	Pu-240 mass gms	
	3.308		3.301		3.046	Pu-236/Pu-238 ratio ppm	
12790	12850	11810	10140	Total masses in core at 16,000 Mwd/mtU			
149.6		154.5		Np-237 - 17.72 kg			
58.67		55.58		Pu-238 - 9.710 kg			
7.281		6.535		Pu-239 - 1.478 kg			
1.315		1.110		Pu-240 - .3282 kg			
3.148		3.154		Pu-236/Pu-238 ratio 3.230 ppm			

Fig. 8 Assembly-wise burnup and isotopic masses in neptunium target rods in PP6 at an average core burnup of 16,000 Mwd/mtU.

	A	B	C	D	E	F	G	H
	.9864	.9889	1.053	1.046	1.107	1.139	1.061	.8910
	1.248	1.269	1.230	1.209	1.131	1.100	.9244	.7414
1	1.107	1.158	1.098	1.143	1.075	1.098	.9402	.7769
	.8026	.8522	.8251	.9174	.9229	1.039	.9975	.9553
	.8473	.8945	.8574	.9361	.9276	1.031	.9898	.9734
	.9889	1.039	1.097	1.093	1.128	1.113	1.160	.8904
2	1.269	1.247	1.284	1.188	1.178	1.048	1.025	.7456
	1.158	1.102	1.161	1.092	1.139	1.039	1.055	.7841
	.8522	.8097	.8773	.8745	.9871	.9944	1.129	.9705
	.8945	.8479	.9065	.8903	.9869	.9851	1.115	.9871
	1.053	1.097	1.103	1.117	1.085	1.088	.9896	.7942
3	1.230	1.284	1.215	1.223	1.109	1.067	.8828	.6852
	1.098	1.161	1.097	1.160	1.082	1.094	.9166	.7336
	.8251	.8773	.8552	.9589	.9721	1.085	1.016	.9462
	.8574	.9065	.8749	.9639	.9644	1.066	1.003	.9619
	1.046	1.093	1.117	1.072	1.020	1.016	1.005	.6480
4	1.209	1.188	1.223	1.133	1.094	.9829	.9098	.5903
	1.143	1.092	1.160	1.102	1.139	1.024	.9666	.6530
	.9174	.8745	.9589	.9695	1.098	1.072	1.129	.9191
	.9361	.8903	.9639	.9619	1.074	1.046	1.109	.9485
	1.107	1.128	1.085	1.020	1.148	.9326	.8876	
5	1.131	1.178	1.109	1.094	1.121	.9324	.8183	
	1.075	1.139	1.082	1.139	1.161	1.021	.8907	
	.9229	.9871	.9721	1.098	1.170	1.162	1.130	
	.9276	.9869	.9644	1.074	1.133	1.126	1.125	
	1.139	1.113	1.088	1.016	.9326	.9992	.6106	
6	1.100	1.048	1.067	.9829	.9324	.9173	.5858	
	1.098	1.039	1.094	1.024	1.021	.9897	.6639	
	1.039	.9944	1.085	1.072	1.162	1.183	.9539	
	1.031	.9851	1.066	1.046	1.126	1.150	.9718	
	1.061	1.160	.9896	1.005	.8876	.6106		
7	.9244	1.025	.8828	.9098	.8183	.5858		
	.9402	1.055	.9166	.9666	.8907	.6639		
	.9975	1.129	1.016	1.129	1.130	.9539		
	.9898	1.115	1.003	1.109	1.125	.9718		
	.8910	.8904	.7942	.6480	0.0	Burnup, Mwd/mtU		
8	.7414	.7456	.6852	.5903	5,000			
	.7769	.7841	.7336	.6530	9,000			
	.9553	.9705	.9462	.9191	16,000			
	.9734	.9871	.9619	.9485	17,000			

Fig. 9 PP6—Assembly-wise relative power distribution as a function of burnup.

18490	18390	18250	17980	17630	17080	15710	12850
	1108.		1121.		1918.		1334.
	511.9		504.8		813.2		372.1
	64.41		62.81		98.93		36.11
	13.35		13.32		21.45		6.353
	4.319		4.324		4.317		4.308
18390	18350	18280	17980	17670	16960	16680	13100
1108.		1854.		1887.		2008.	
511.9		848.6		830.8		767.0	
64.41		106.8		102.8		85.93	
13.35		22.69		22.75		16.46	
4.319		4.293		4.305		4.511	
18250	18280	18090	18020	17560	16750	14910	11760
	1854.		1868.		1936.		1369.
	848.6		841.0		802.8		347.1
	106.8		105.1		96.69		31.86
	22.69		23.52		20.72		5.250
	4.293		4.298		4.331		4.336
17980	17980	18020	17940	17580	16390	14620	10230
1121.		1868.		1134.		2963.	
504.8		841.0		498.0		976.7	
62.81		105.1		61.26		101.5	
13.32		23.52		13.01		15.58	
4.324		4.298		4.351		4.566	
17630	17670	17560	17580	18810	15650	14110	
	1887.		1134.		1594.		
	830.8		498.0		617.5		
	102.8		61.26		71.46		
	22.75		13.01		14.50		
	4.305		4.351		4.444		
17080	16960	16750	16390	15650	16090	10260	
1918.		1936.		1594.		1422.	
813.2		802.8		617.5		307.1	
98.93		96.69		71.46		25.88	
21.45		20.72		14.50		3.990	
4.317		4.331		4.444		4.191	
15710	16680	14910	14620	14110	10260	Assem.burnup - Mwd/mtU	
	2008.		2963.		1422.	Np-237 mass gms	
	767.0		976.7		307.1	Pu-238 mass gms	
	85.93		101.5		25.88	Pu-239 mass gms	
	16.46		15.58		3.990	Pu-240 mass gms	
	4.511		4.566		4.191	Pu-236/Pu-238 ratio ppm	
12850	13100	11760	10230	Total masses in core at 16,000 Mwd/mtU			
1334.		1369.		Np-237 - 166.2 kg			
372.1		347.1		Pu-238 - 63.50 kg			
36.11		31.86		Pu-239 - 7.363 kg			
6.353		5.250		Pu-240 - 1.486 kg			
4.308		4.336		Pu-236/Pu-238 ratio 4.370 ppm			

Fig. 10 Assembly-wise burnup and isotopic masses in neptunium target rods in PP7 at an average core burnup of 16,000 Mwd/mtU.

1.052	1.024	1.082	1.045	1.099	1.087	1.055	.8912
1.314	1.307	1.260	1.215	1.134	1.065	.9268	.7469
1.137	1.172	1.111	1.147	1.080	1.074	.9481	.7868
.8250	.8691	.8415	.9334	.9356	1.037	1.011	.9688
.8658	.9078	.8701	.9494	.9378	1.028	1.000	.9849
1.024	1.076	1.081	1.097	1.086	1.094	1.120	.9067
1.307	1.284	1.268	1.196	1.146	1.041	1.001	.7622
1.172	1.116	1.143	1.096	1.117	1.037	1.038	.8044
.8691	.8251	.8811	.8866	.9865	.9999	1.123	.9946
.9078	.8594	.9073	.8995	.9854	.9889	1.108	1.010
1.082	1.081	1.105	1.089	1.088	1.048	.9784	.7886
1.260	1.268	1.217	1.195	1.114	1.036	.8781	.6843
1.111	1.143	1.095	1.139	1.089	1.069	.9154	.7361
.8415	.8811	.8621	.9575	.9786	1.072	1.015	.9490
.8701	.9073	.8789	.9614	.9697	1.054	1.002	.9649
1.045	1.097	1.089	1.096	1.039	1.029	.9560	.6546
1.215	1.196	1.195	1.151	1.108	.9902	.8680	.5966
1.147	1.096	1.139	1.118	1.152	1.031	.9268	.6618
.9334	.8866	.9575	.9795	1.110	1.065	1.084	.9292
.9494	.8995	.9614	.9707	1.078	1.040	1.070	.9616
1.099	1.086	1.088	1.039	1.209	.9551	.9206	
1.134	1.146	1.114	1.108	1.157	.9386	.8336	
1.080	1.117	1.089	1.152	1.189	1.023	.9036	
.9356	.9865	.9786	1.110	1.169	1.140	1.123	
.9378	.9854	.9697	1.078	1.134	1.109	1.121	
1.087	1.094	1.048	1.029	.9551	1.069	.6423	
1.065	1.041	1.036	.9902	.9386	.9499	.5982	
1.074	1.037	1.069	1.031	1.023	1.015	.6730	
1.037	.9999	1.072	1.065	1.140	1.171	.9343	
1.028	.9889	1.054	1.040	1.109	1.142	.9543	
1.055	1.120	.9784	.9560	.9206	.6423		
.9268	1.001	.8781	.8680	.8336	.5982		
.9481	1.038	.9154	.9268	.9036	.6730		
1.011	1.123	1.015	1.084	1.123	.9343		
1.000	1.108	1.002	1.070	1.121	.9543		
.8912	.9067	.7886	.6546	— 0.0 —	Burnup, Mwd/mtU		
.7469	.7622	.6843	.5966	— 5,000			
.7868	.8044	.7361	.6618	— 9,000			
.9688	.9946	.9490	.9292	— 16,000			
.9849	1.010	.9649	.9616	— 17,000			

Fig. 11 PP7- Assembly-wise relative power distribution as a function of burnup.

Fig. 12 Calculated critical boron concentration as a function of average core burnup for the reference reactor and the fourth through the seventh parametric problems.

21468 8724 30192	10855 10023 20878	21468 8782 30250	10855 10229 21084	21468 9241 30709	10855 11362 22217	21468 10649 32117	0.0 11499 11499
10855 10023 20878	21468 8748 30216	10855 10105 20960	21468 8959 30427	10855 10646 21501	21468 10043 31511	0.0 14301 14301	0.0 11621 11621
21468 8782 30250	10855 10105 20960	21468 8908 30376	10855 10468 21323	21468 9489 30957	10855 11460 22315	21468 10353 31821	0.0 10742 10742
10855 10229 21084	21468 8959 30427	10855 10468 21323	21468 9562 31030	10855 11645 22500	21468 10574 32042	0.0 13683 13683	0.0 9580 9580
21468 9241 30709	10855 10646 21501	21468 9489 30957	10855 11645 22500	10855 12797 23652	10855 13046 23901	0.0 12965 12965	
10855 11362 22217	21468 10043 31511	10855 11460 22315	21468 10574 32042	10855 13046 23901	0.0 14446 14446	0.0 10260 10260	
21468 10649 32117	0.0 14301 14301	21468 10353 31821	0.0 13683 13683	0.0 12965 12965	0.0 10260 10260		
0.0 11499 11499	0.0 11621 11621	0.0 10742 10742	0.0 9580 9580	Burnup, Mwd/mtU — Beginning of equilibrium cycle — Increment during cycle — End of equilibrium cycle			

Fig. 13 Assembly-wise burnup for the equilibrium cycle of the reference reactor.

.5543	.6574	.6056	.7762	.7616	1.029	1.008	1.040
.6491	.7592	.6810	.8367	.7927	1.038	1.007	1.068
.9828	1.119	.9508	1.059	.9055	1.054	.9497	1.007
.8475	.9630	.8503	.9717	.8718	1.032	.9554	1.067
.8652	.9768	.8617	.9723	.8681	1.014	.9408	1.082
.6574	.5807	.7198	.6876	.9035	.9149	1.365	1.063
.7592	.6651	.7980	.7354	.9283	.9182	1.358	1.085
1.119	.9655	1.083	.9172	1.033	.9242	1.252	1.012
.9630	.8487	.9662	.8570	.9897	.9175	1.243	1.074
.9768	.8631	.9729	.8601	.9798	.9052	1.214	1.089
.6056	.7198	.6679	.8634	.8406	1.090	1.001	.9734
.6810	.7980	.7206	.8928	.8433	1.070	.9862	.9931
.9508	1.083	.9254	1.039	.8947	1.032	.9060	.9309
.8503	.9662	.8539	.9779	.8787	1.031	.9358	1.019
.8617	.9729	.8594	.9723	.8714	1.013	.9278	1.046
.7762	.6876	.8634	.8514	1.138	1.062	1.370	.8569
.8367	.7354	.8928	.8483	1.092	1.014	1.324	.8777
1.059	.9172	1.039	.9050	1.047	.9174	1.151	.8223
.9717	.8570	.9779	.8803	1.029	.9366	1.197	.9490
.9723	.8601	.9723	.8727	1.009	.9231	1.186	1.004
.7616	.9035	.8406	1.138	1.353	1.422	1.319	
.7927	.9283	.8433	1.092	1.258	1.313	1.266	
.9055	1.033	.8947	1.047	1.096	1.083	1.069	
.8718	.9897	.8787	1.029	1.087	1.100	1.157	
.8681	.9798	.8714	1.009	1.058	1.076	1.173	
1.029	.9149	1.090	1.062	1.422	1.571	1.012	
1.038	.9182	1.070	1.014	1.313	1.453	.9841	
1.054	.9242	1.032	.9174	1.083	1.161	.8404	
1.032	.9175	1.031	.9366	1.100	1.206	.9669	
1.014	.9052	1.013	.9231	1.076	1.189	1.016	
1.008	1.365	1.001	1.370	1.319	1.012		
1.007	1.358	.9862	1.324	1.266	.9841		
.9497	1.252	.9060	1.151	1.069	.8404		
.9554	1.243	.9358	1.197	1.157	.9669		
.9408	1.214	.9278	1.186	1.173	1.016		
1.040	1.063	.9734	.8569	0.0	Burnup, Mwd/mtU		
1.068	1.085	.9931	.8777	1,000			
1.007	1.012	.9309	.8223	5,000			
1.067	1.074	1.019	.9490	9,000			
1.082	1.089	1.046	1.004	11,000			

Fig. 14 Assembly-wise relative power distribution as a function of burnup in the equilibrium cycle of the reference reactor.

30730	21350	30660	21260	30750	21990	32170	11620
	652.3		654.1		1065.		655.2
	198.0		196.8		345.5		194.6
	20.29		20.06		36.84		20.24
	3.135		3.052		5.901		3.370
	4.127		4.123		4.116		3.794
21350	30690	21260	30590	21310	31460	14100	11890
652.3		654.1		1088.		1012.	
198.0		196.8		329.8		379.3	
20.29		20.05		33.70		44.33	
3.135		3.073		5.131		7.982	
4.127		4.125		4.133		3.978	
30660	21260	30560	21150	30870	22050	31900	10890
	654.1		1093.		1063.		668.7
	196.8		326.0		347.0		185.2
	20.05		32.97		37.14		18.44
	3.073		4.930		5.972		2.915
	4.125		4.138		4.112		3.802
21260	30590	21150	30920	22120	31900	13590	9874
654.1		1093.		1060.		822.2	
196.8		326.0		348.6		294.9	
20.06		32.97		37.46		33.72	
3.052		4.930		6.047		5.973	
4.123		4.138		4.111		3.950	
30750	21310	30870	22120	22340	23330	13040	
	1088.		1060.		1427.		
	329.8		348.6		525.4		
	33.70		37.46		60.34		
	5.131		6.047		10.48		
	4.133		4.111		4.079		
21990	31460	22050	31900	23330	14310	10210	
1065.		1063.		1427.		684.2	
345.5		347.0		525.4		173.3	
36.84		37.14		60.34		16.61	
5.901		5.972		10.48		2.615	
4.116		4.112		4.079		3.606	
32170	14100	31900	13590	13040	10210	Assem. burnup, Mwd/mtU	
	1012.		822.2		684.2	Np-237 mass gms	
	379.3		294.9		173.3	Pu-238 mass gms	
	44.33		33.72		16.61	Pu-239 mass gms	
	7.982		5.973		2.615	Pu-240 mass gms	
	3.978		3.950		3.606	Pu-236/Pu-238 ratio, ppm	
11620	11890	10890	9874	Total masses in core at 11,000 Mwd/mtU			
655.2		668.7		Np-237 — 88.68 kg			
194.6		185.2		Pu-238 — 28.59 kg			
20.24		18.44		Pu-239 — 3.068 kg			
3.370		2.915		Pu-240 — .5028 kg			
3.794		3.802		Pu-236/Pu-238 ratio 4.036 ppm			

Fig. 15 Assembly-wise burnup and isotopic masses in neptunium target rods added to the equilibrium cycle of the reference reactor. Average core burnup is 11,000 Mwd/mtU.

.6302	.7329	.6637	.8116	.7750	1.017	1.022	1.065
.7165	.8237	.7317	.8636	.8005	1.019	1.016	1.086
1.027	1.154	.9851	1.071	.9062	1.030	.9506	1.013
.8630	.9708	.8639	.9719	.8689	1.013	.9604	1.078
.8814	.9859	.8762	.9744	.8661	.9969	.9442	1.090
.7329	.6469	.7715	.7150	.8962	.9154	1.355	1.100
.8237	.7235	.8404	.7569	.9148	.9147	1.341	1.117
1.154	1.004	1.106	.9293	1.012	.9173	1.232	1.031
.9708	.8632	.9695	.8589	.9696	.9131	1.233	1.097
.9859	.8785	.9781	.8633	.9624	.9007	1.204	1.109
.6637	.7715	.6988	.8577	.8334	1.063	1.010	.9920
.7317	.8404	.7458	.8821	.8350	1.043	.9939	1.010
.9851	1.106	.9403	1.021	.8870	1.009	.9122	.9420
.8639	.9695	.8561	.9572	.8710	1.015	.9459	1.034
.8762	.9781	.8629	.9546	.8645	.9986	.9357	1.058
.8116	.7150	.8577	.8396	1.089	1.037	1.350	.8804
.8636	.7569	.8821	.8371	1.049	.9952	1.310	.9048
1.071	.9293	1.021	.8970	1.018	.9100	1.149	.8489
.9719	.8589	.9572	.8713	1.007	.9333	1.202	.9828
.9744	.8633	.9546	.8649	.9890	.9190	1.189	1.037
.7750	.8962	.8334	1.089	1.299	1.335	1.307	
.8005	.9148	.8350	1.049	1.216	1.243	1.266	
.9062	1.012	.8870	1.018	1.078	1.047	1.083	
.8689	.9696	.8710	1.007	1.074	1.074	1.177	
.8661	.9624	.8645	.9890	1.045	1.052	1.190	
1.017	.9154	1.063	1.037	1.335	1.528	.9897	
1.019	.9147	1.043	.9952	1.243	1.429	.9720	
1.030	.9173	1.009	.9100	1.047	1.162	.8440	
1.013	.9131	1.015	.9333	1.074	1.212	.9741	
.9969	.9007	.9986	.9190	1.052	1.192	1.021	
1.022	1.355	1.010	1.350	1.307	.9897		
1.016	1.341	.9939	1.310	1.266	.9720		
.9506	1.232	.9122	1.149	1.083	.8440		
.9604	1.233	.9459	1.202	1.177	.9741		
.9442	1.204	.9357	1.189	1.190	1.021		
1.065	1.100	.9920	.8804	0.0 — Burnup, Mwd/mtU			
1.086	1.117	1.010	.9048	1,000			
1.013	1.031	.9420	.8489	5,000			
1.078	1.097	1.034	.9828	9,000			
1.090	1.109	1.058	1.037	11,000			

Fig. 16 Assembly-wise relative power distribution as a function of burnup for the equilibrium cycle of the reference reactor with neptunium targets added.

18280	18290	18280	18080	17840	17440	15750	12640
	520.0		523.5		891.9		642.7
	276.6		274.9		447.6		204.6
	39.08		38.61		61.88		21.85
	8.720		8.558		13.41		3.708
	3.771		3.772		3.747		3.718
18290	18330	18550	18150	18040	17170	16790	12790
520.0		860.7		875.1		944.9	
276.6		463.0		456.0		423.3	
39.08		66.12		64.18		53.41	
8.720		14.90		14.22		10.45	
3.771		3.732		3.739		3.893	
18280	18550	18300	18340	17700	17040	14980	11600
	860.7		866.5		903.5		661.0
	463.0		460.1		441.6		191.9
	66.12		65.35		60.29		19.37
	14.90		14.63		12.87		3.080
	3.732		3.736		3.757		3.733
18080	18150	18340	17970	17500	16380	14790	9999
523.5		866.5		533.2		1402.	
274.9		460.1		270.1		544.7	
38.61		65.35		37.28		63.71	
8.558		14.63		8.070		11.47	
3.772		3.736		3.799		3.910	
17840	18040	17700	17500	18460	15460	13730	
	875.1		533.2		757.1		
	456.0		270.1		335.8		
	64.18		37.28		43.25		
	14.22		8.070		8.546		
	3.739		3.799		3.853		
17440	17170	17040	16380	15460	15520	9921	
891.9		903.5		757.1		693.8	
447.6		441.6		335.8		167.5	
61.88		60.29		43.25		15.25	
13.41		12.87		8.546		2.224	
3.747		3.757		3.853		3.608	
15750	16790	14980	14790	13730	9921	Assem. burnup, Mwd/mtU	
	944.9		1402.		693.8	Np-237 mass gms	
	423.3		544.7		167.5	Pu-238 mass gms	
	53.41		63.71		15.25	Pu-239 mass gms	
	10.45		11.47		2.224	Pu-240 mass gms	
	3.893		3.910		3.608	Pu-236/Pu-238 ratio, ppm	
12640	12790	11600	9999	Total masses in core at 16,000 Mwd/mtU			
642.7		661.0		Np-237 — 78.29 kg			
204.6		191.9		Pu-238 — 34.85 kg			
21.85		19.37		Pu-239 — 4.551 kg			
3.708		3.080		Pu-240 — .9413 kg			
3.718		3.733		Pu-236/Pu-238 ratio 3.785 ppm			

Fig. 17 Assembly-wise burnup and isotopic masses in neptunium target rods in PP8 at an average core burnup of 16,000 Mwd/mtU.

1.109	1.085	1.146	1.100	1.145	1.119	1.041	.8396
1.231	1.235	1.209	1.185	1.132	1.090	.9481	.7530
1.115	1.150	1.101	1.136	1.081	1.087	.9546	.7847
.7931	.8365	.8156	.9066	.9197	1.031	1.006	.9688
.8532	.8952	.8609	.9375	.9318	1.028	.9966	.9743
1.085	1.142	1.157	1.156	1.137	1.114	1.105	.8448
1.235	1.222	1.235	1.176	1.155	1.061	1.024	.7632
1.150	1.104	1.142	1.094	1.125	1.046	1.045	.7973
.8365	.7985	.8588	.8673	.9750	.9948	1.122	.9912
.8952	.8507	.9020	.8931	.9836	.9888	1.107	.9940
1.146	1.157	1.172	1.147	1.117	1.064	.9607	.7410
1.209	1.235	1.193	1.192	1.118	1.062	.9036	.6932
1.101	1.142	1.095	1.144	1.090	1.082	.9266	.7375
.8156	.8588	.8447	.9445	.9707	1.077	1.023	.9587
.8609	.9020	.8752	.9599	.9688	1.061	1.006	.9598
1.100	1.156	1.147	1.120	1.038	1.013	.9332	.6021
1.185	1.176	1.192	1.143	1.104	1.007	.8987	.5985
1.136	1.094	1.144	1.112	1.140	1.034	.9453	.6597
.9066	.8673	.9445	.9691	1.096	1.076	1.113	.9462
.9375	.8931	.9599	.9679	1.077	1.050	1.090	.9542
1.145	1.137	1.117	1.038	1.161	.9129	.8442	
1.132	1.155	1.118	1.104	1.151	.9462	.8342	
1.081	1.125	1.090	1.140	1.173	1.019	.8976	
.9197	.9750	.9707	1.096	1.174	1.160	1.148	
.9318	.9836	.9688	1.077	1.138	1.124	1.127	
1.119	1.114	1.064	1.013	.9129	.9713	.5755	
1.090	1.061	1.062	1.007	.9462	.9442	.5959	
1.087	1.046	1.082	1.034	1.019	1.000	.6682	
1.031	.9948	1.077	1.076	1.160	1.193	.9706	
1.028	.9888	1.061	1.050	1.124	1.153	.9666	
1.041	1.105	.9607	.9332	.8442	.5755		
.9481	1.024	.9036	.8987	.8342	.5959		
.9546	1.045	.9266	.9453	.8976	.6682		
1.006	1.122	1.023	1.113	1.148	.9706		
.9966	1.107	1.006	1.090	1.127	.9666		
.8396	.8448	.7410	.6021	0.0 — Burnup, Mwd/mtU			
.7530	.7632	.6932	.5985	— 5,000			
.7847	.7973	.7375	.6597	— 9,000			
.9688	.9912	.9587	.9462	— 16,000			
.9743	.9940	.9598	.9542	— 17,000			

Fig. 18 PP8 — Assembly-wise relative power distribution as a function of burnup.

Fig. 19 Reference reactor and PP4.

Fig. 20 Equilibrium reactor, and equilibrium reactor containing neptunium.

17550	17940	17850	17970	17650	17810	15700	12780
17940	17850	18660	17890	18310	17140	17230	12800
17850	18660	18100	18550	17490	17390	15040	11820
17970	17890	18550	17600	17350	16260	15500	10130
17650	18310	17490	17350	18100	15530	13790	
17810	17140	17390	16260	15530	15360	9979	
15700	17230	15040	15500	13790	9979		
12780	12800	11820	10130	— Burnup, Mwd/mtU			

Fig. 21 Assembly-wise burnup in PP9 at an average core burnup of 16,000 Mwd/mtU.

.9724	.9810	1.047	1.045	1.109	1.150	1.063	.8903
1.234	1.261	1.224	1.207	1.131	1.107	.9239	.7402
1.099	1.153	1.094	1.141	1.073	1.102	.9390	.7754
.7995	.8496	.8225	.9137	.9200	1.038	.9950	.9531
.8453	.8930	.8558	.9332	.9254	1.030	.9878	.9715
.9810	1.031	1.010	1.092	1.136	1.117	1.168	.8867
1.261	1.239	1.287	1.186	1.184	1.050	1.030	.7423
1.153	1.097	1.163	1.090	1.142	1.039	1.059	.7808
.8496	.8075	.8761	.8720	.9857	.9929	1.129	.9665
.8930	.8467	.9061	.8886	.9858	.9840	1.115	.9833
1.047	1.010	1.103	1.123	1.085	1.097	.9922	.7952
1.224	1.287	1.215	1.228	1.108	1.073	.8840	.6854
1.094	1.163	1.097	1.163	1.081	1.099	.9176	.7339
.8225	.8761	.8538	.9579	.9704	1.087	1.017	.9463
.8558	.9061	.8744	.9632	.9631	1.067	1.004	.9617
1.045	1.092	1.123	1.067	1.016	1.014	1.016	.6470
1.207	1.186	1.228	1.129	1.091	.9816	.9189	.5893
1.141	1.090	1.163	1.099	1.137	1.024	.9758	.6523
.9137	.8720	.9579	.9673	1.097	1.074	1.138	.9181
.9332	.8886	.9632	.9601	1.072	1.048	1.117	.9468
1.109	1.136	1.085	1.016	1.135	.9280	.8813	
1.131	1.184	1.108	1.091	1.114	.9311	.8155	
1.073	1.142	1.081	1.137	1.156	1.021	.8895	
.9200	.9857	.9704	1.097	1.170	1.167	1.133	
.9254	.9858	.9631	1.072	1.133	1.129	1.126	
1.150	1.117	1.097	1.014	.9280	.9851	.6039	
1.107	1.050	1.073	.9816	.9311	.9107	.5832	
1.102	1.039	1.099	1.024	1.021	.9860	.6632	
1.038	.9929	1.087	1.074	1.167	1.186	.9589	
1.030	.9840	1.067	1.048	1.129	1.153	.9762	
1.063	1.168	.9922	1.016	.8813	.6039		
.9239	1.030	.8840	.9189	.8155	.5832		
.9390	1.059	.9176	.9758	.8895	.6632		
.9950	1.129	1.017	1.138	1.133	.9589		
.9878	1.115	1.004	1.117	1.126	.9762		
.8903	.8867	.7952	.6470	—	0.0 — Burnup, Mwd/mtU		
.7402	.7423	.6854	.5893	—	5,000		
.7754	.7808	.7339	.6523	—	9,000		
.9531	.9665	.9463	.9181	—	16,000		
.9715	.9833	.9617	.9468	—	17,000		

Fig. 22 PP9 — Assembly-wise relative power distribution as a function of burnup.

30248	20879	30323	21105	30779	22179	32085	11320
265.7	362.9	265.0	360.4	260.7	348.4	248.9	480.1
237.2	204.7	237.4	206.0	238.3	211.4	239.9	133.4
40.99	29.41	41.06	29.76	41.46	31.33	42.41	13.26
11.21	6.579	11.24	6.691	11.39	7.243	11.95	2.076
3.135	3.601	3.135	3.598	3.136	3.596	3.136	3.860
20879	30283	20977	30510	21508	31542	14123	11443
362.9	265.4	361.8	263.2	355.8	253.7	442.1	478.6
204.7	237.3	205.3	237.8	208.1	239.4	159.8	134.5
29.41	41.03	29.56	41.23	30.36	42.05	18.25	13.47
6.579	11.22	6.628	11.30	6.896	11.69	3.182	2.126
3.601	3.135	3.600	3.135	3.596	3.138	4.025	3.853
30323	20977	30549	21344	31024	22274	31790	10578
265.0	361.8	263.7	357.6	258.4	347.3	251.5	489.6
237.4	205.3	237.7	207.3	238.7	211.9	239.5	126.6
41.06	29.56	41.18	30.12	41.66	31.46	42.20	12.01
11.24	6.628	11.28	6.812	11.48	7.289	11.85	1.779
3.135	3.600	3.135	3.597	3.136	3.594	3.134	3.868
21105	30510	21344	31105	22490	32056	13509	9454
360.4	263.2	357.6	257.7	344.9	249.0	450.1	506.4
206.0	237.8	207.3	238.9	213.0	240.2	154.6	113.7
29.76	41.23	30.12	41.72	31.77	42.44	17.17	10.02
6.691	11.30	6.812	11.51	7.398	11.87	2.919	1.419
3.598	3.135	3.597	3.137	3.593	3.140	4.004	3.671
30779	21508	31024	22490	23613	23807	12808	
260.7	355.8	258.4	344.9	332.7	330.8	461.5	
238.3	208.1	238.7	213.0	218.0	218.5	146.1	
41.46	30.36	41.66	31.77	33.31	33.54	15.79	
11.39	6.896	11.48	7.398	7.974	8.105	2.736	
3.136	3.596	3.136	3.593	3.589	3.579	3.819	
22179	31542	22274	32056	23807	14260	10132	
348.4	253.7	347.3	249.0	330.8	440.7	497.6	
211.4	239.4	211.9	240.2	218.5	160.6	120.3	
31.33	42.05	31.46	42.44	33.54	18.46	11.14	
7.243	11.69	7.289	11.87	8.105	3.261	1.671	
3.596	3.138	3.594	3.140	3.597	3.987	3.664	
32085	14123	31790	13509	12808	10132	Assem. Burnup-Mwd/mtU	
248.9	442.1	251.5	450.1	461.5	497.6	Np-237 mass gms	
239.9	159.8	239.5	154.6	146.1	120.3	Pu-238 mass gms	
42.41	18.25	42.20	17.17	15.79	11.14	Pu-239 mass gms	
11.95	3.182	11.85	2.919	2.736	1.671	Pu-240 mass gms	
3.136	4.025	3.134	4.004	3.819	3.664	Pu-236/Pu-238 Ratio ppm	
11320	11443	10578	9454	Total masses in core at 11,000 Mwd/mtU			
480.1	478.6	489.6	506.4	Np-237 - 69.41 Kg			
133.4	134.5	126.6	113.7	Pu-238 - 37.81 Kg			
13.26	13.47	12.01	10.02	Pu-239 - 5.612 Kg			
2.076	2.126	1.779	1.419	Pu-240 - 1.358 Kg			
3.860	3.853	3.868	3.671	Pu-236/Pu-238 Ratio 3.470 ppm			

Fig. 23 Assembly-wise burnup and isotopic masses in neptunium target rods in PP10 at an average core burnup of 11,000 Mwd/mtU.

.5999	.7015	.6478	.8106	.7909	1.037	1.007	1.011
.6856	.7921	.7148	.8620	.8161	1.042	1.006	1.040
.9578	1.082	.9349	1.039	.9058	1.051	.9594	1.005
.8623	.9701	.8633	.9747	.8804	1.030	.9630	1.060
.8700	.9731	.8669	.9693	.8745	1.014	.9529	1.082
.7015	.6246	.7593	.7239	.9259	.9299	1.339	1.032
.7921	.7003	.8273	.7645	.9443	.9301	1.332	1.056
1.082	.9454	1.056	.9116	1.024	.9317	1.248	1.011
.9701	.8625	.9709	.8674	.9892	.9248	1.235	1.067
.9731	.8681	.9694	.8657	.9775	.9137	1.211	1.089
.6478	.7593	.7064	.8918	.8649	1.092	.9968	.9439
.7148	.8273	.7515	.9139	.8636	1.071	.9833	.9661
.9349	1.056	.9173	1.027	.9002	1.034	.9187	.9309
.8633	.9709	.8649	.9780	.8852	1.028	.9420	1.011
.8669	.9694	.8645	.9683	.8765	1.012	.9375	1.043
.8106	.7239	.8918	.8780	1.144	1.065	1.332	.8297
.8620	.7645	.9139	.8708	1.099	1.019	1.294	.8547
1.039	.9116	1.027	.9101	1.050	.9333	1.156	.8262
.9747	.8674	.9780	.8865	1.026	.9418	1.187	.9424
.9693	.8657	.9683	.8765	1.004	.9292	1.179	1.001
.7909	.9259	.8649	1.144	1.344	1.394	1.275	
.8161	.9443	.8636	1.099	1.254	1.296	1.235	
.9058	1.024	.9002	1.050	1.108	1.098	1.080	
.8804	.9892	.8852	1.026	1.083	1.096	1.148	
.8745	.9775	.8765	1.004	1.053	1.073	1.167	
1.037	.9299	1.092	1.065	1.394	1.515	.9741	
1.042	.9301	1.071	1.019	1.296	1.417	.9572	
1.051	.9317	1.034	.9333	1.098	1.175	.8510	
1.030	.9248	1.028	.9418	1.096	1.196	.9595	
1.014	.9137	1.012	.9292	1.073	1.181	1.011	
1.007	1.339	.9968	1.332	1.275	.9741		
1.006	1.332	.9833	1.294	1.235	.9572		
.9594	1.248	.9187	1.156	1.080	.8510		
.9630	1.235	.9420	1.187	1.148	.9595		
.9529	1.211	.9375	1.179	1.167	1.011		
1.011	1.032	.9439	.8297	0.0	Burnup, Mwd/mtU		
1.040	1.056	.9661	.8547	1,000			
1.005	1.011	.9309	.8262	5,000			
1.060	1.067	1.011	.9424	9,000			
1.082	1.089	1.043	1.001	11,000			

Fig. 24 PP10 — Assembly-wise relative power distribution as a function of burnup.

Fig. 25 Revised 24-plane three-dimensional geometric model of the Connecticut Yankee reactor containing experimental neptunium targets.

.5788	.7444	.6523	.8638	.7990	.9537	.8498	.6837
.7484	.7099	.8535	.8360	.9566	.9270	1.129	.8979
.6647	.8641	.8864	.8712	1.024	.9361	1.180	Np Targets
.9010	.8646	.8832	.9102	1.127	1.279	1.097	
.8799	1.023	1.067	1.150	1.223	1.237		
.8799	1.033	1.003	1.334	1.263			
.9723	1.283	1.302	1.169				
.9322	1.018						

Fig. 26 Connecticut Yankee Core 3, 24-plane model — x, y power distribution, BOL, no Xe, equilibrium Sm.

.4995	.6438	.5683	.7737	.7451	.9530	.9169	.8321
.6445	.6087	.7423	.7439	.8969	.9257	1.264	1.132
.5707	.7440	.7717	.7802	.9629	.9395	1.385	Np Targets
.7838	.7503	.7790	.8275	1.072	1.335	1.351	
.7867	.9218	.9735	1.077	1.211	1.398		
.8427	.9755	.9615	1.349	1.404			
.9657	1.333	1.436	1.376				
1.019	1.174						

Fig. 27 Connecticut Yankee Core 3, 24-plane model - x, y power distribution, July-August, 1971, 843.9 Mwd/mtU.

.5744	.7326	.6260	.8254	.7624	.9558	.8988	.8455
.7324	.6780	.8102	.7792	.9157	.9135	1.258	1.147
.6258	.8094	.8192	.7986	.9576	.9087	1.377	Np Targets
.8276	.7792	.7937	.8184	1.034	1.292	1.347	
.7917	.9287	.9595	1.034	1.144	1.361		
.8370	.9466	.9183	1.295	1.361			
.9270	1.301	1.404	1.356				
1.005	1.164						

Fig. 28 Connecticut Yankee Core 3, 24-plane model — x, y power distribution, September-October, 1971, 2,492 Mwd/mtU.

.5591	.7124	.6053	.7992	.7367	.9357	.8891	.8870
.7124	.6537	.7833	.7494	.8894	.8905	1.272	1.221
.6055	.7830	.7903	.7694	.9284	.8879	1.429	Np Targets
.8023	.7502	.7652	.7902	1.003	1.291	1.446	
.7667	.9038	.9313	1.004	1.126	1.421		
.8281	.9253	.8988	1.295	1.422			
.9176	1.317	1.458	1.456				
1.044	1.237						

Fig. 29 Connecticut Yankee Core 3, 24-plane model - x, y power distribution, November-December, 1971, 4, 118 Mwd/mtU.

.5631	.7149	.6007	.7854	.7142	.9059	.8610	.9009
.7153	.6501	.7755	.7317	.8655	.8601	1.256	1.260
.6023	.7765	.7779	.7502	.9014	.8622	1.451	Np Targets
.7925	.7356	.7480	.7687	.9745	1.281	1.523	
.7502	.8869	.9098	.9783	1.108	1.473		
.8184	.9061	.8819	1.294	1.479			
.9041	1.324	1.502	1.549				
1.073	1.298						

Fig. 30 Connecticut Yankee Core 3, 24-plane model - x, y power distribution, January-February, 1972, 5,788 Mwd/mtU.

.5157	.6553	.5516	.7268	.6667	.8620	.8369	.9318
.6564	.5943	.7136	.6767	.8143	.8229	1.253	1.339
.5550	.7163	.7205	.7016	.8580	.8411	1.515	Np Targets
.7390	.6848	.7022	.7313	.9450	1.299	1.680	
.7104	.8447	.8731	.9525	1.112	1.595		
.7988	.8832	.8721	1.322	1.607			
.8993	1.354	1.596	1.728				
1.130	1.411						

Fig. 31 Connecticut Yankee Core 3, 24-plane model - x, y power distribution, March-April, 1972, 7,409 Mwd/mtU.

.4506	.5737	.4857	.6480	.6042	.8021	.8029	.9599
.5753	.5202	.6306	.6050	.7458	.7743	1.241	1.430
.4908	.6349	.6441	.6381	.8019	.8164	1.593	Np Targets
.6655	.6173	.6417	.6832	.9104	1.330	1.890	
.6557	.7856	.8244	.9221	1.126	1.771		
.7662	.8514	.8613	1.367	1.793			
.8897	1.386	1.717	1.974				
1.198	1.552						

Fig. 32 Connecticut Yankee Core 3, 24-plane model - x, y power distribution, May-June, 1972, 9, 102 Mwd/mtU.

.5367	.6904	.6056	.8033	.7453	.8937	.7996	.6438
.8397	1.080	.9464	1.254	1.160	1.386	1.236	.9967
.7797	1.003	.8777	1.161	1.070	1.270	1.126	.9071
.6351	.8167	.7145	.9440	.8692	1.028	.9078	.7316
.3404	.4372	.3828	.5058	.4674	.5579	.4968	.3956
.6938	.6583	.7922	.7772	.8917	.8681	1.061	.8452
1.086	1.030	1.239	1.213	1.389	1.347	1.644	1.311
1.008	.9562	1.149	1.124	1.283	1.235	1.497	1.193
.8215	.7788	.9355	.9140	1.042	.9993	1.206	.9613
.4397	.4170	.5004	.4897	.5589	.5427	.6585	.5184
.6160	.8010	.8222	.8093	.9528	.8740	1.106	Np Targets
.9646	1.254	1.287	1.265	1.487	1.361	1.721	
.8958	1.165	1.194	1.172	1.375	1.253	1.576	
.7297	.9486	.9720	.9536	1.118	1.016	1.274	
.3907	.5072	.5199	.5104	.5975	.5456	.6822	
.8346	.8011	.8187	.8446	1.047	1.191	1.023	
1.308	1.255	1.282	1.322	1.639	1.864	1.602	
1.215	1.166	1.190	1.226	1.518	1.723	1.477	
.9899	.9495	.9692	.9977	1.234	1.399	1.198	
.5290	.5076	.5181	.5327	.6563	.7401	.6292	
.8147	.9472	.9886	1.066	1.135	1.149		
1.278	1.486	1.551	1.673	1.782	1.805		
1.187	1.381	1.440	1.553	1.652	1.672		
.9670	1.124	1.172	1.263	1.344	1.359		
.5163	.5995	.6245	.6710	.7096	.7114		
.8206	.9561	.9291	1.236	1.170			
1.289	1.502	1.460	1.944	1.844			
1.198	1.395	1.356	1.805	1.711			
.9754	1.136	1.104	1.469	1.391			
.5187	.6041	.5858	.7740	.7275			
.8997	1.187	1.205	1.082				
1.415	1.869	1.900	1.708				
1.315	1.737	1.765	1.586				
1.070	1.414	1.436	1.291				
.5673	.7450	.7530	.6730				
.8623	.9416	2 — Plane groupings					
1.359	1.486	3					
1.263	1.381	4					
1.028	1.124	5					
.5403	.5873	6					

Fig. 33 Connecticut Yankee Core 3, 24-plane model — June, 1971 assembly-wise relative power distribution, BOL, no Xe, equilibrium Sm.

.4732	.6100	.5390	.7347	.7092	.9098	.8780	.7963
.6364	.8202	.7222	.9832	.9449	1.211	1.163	1.064
.6206	.7997	.7043	.9576	.9184	1.169	1.118	1.022
.5635	.7264	.6407	.8712	.8361	1.061	1.015	.9245
.3561	.4587	.4063	.5526	.5340	.6831	.6597	.5885
.6106	.5770	.7040	.7066	.8532	.8837	1.209	1.083
.8209	.7732	.9432	.9429	1.139	1.173	1.610	1.447
.8007	.7546	.9201	.9194	1.107	1.134	1.547	1.390
.7275	.6868	.8374	.8380	1.008	1.031	1.400	1.258
.4594	.4354	.5303	.5333	.6412	.6661	.9036	.7994
.5409	.7052	.7320	.7408	.9154	.8955	1.322	Np Targets
.7247	.9449	.9788	.9878	1.219	1.188	1.766	
.7076	.9226	.9557	.9642	1.189	1.155	1.706	
.6444	.8402	.8711	.8798	1.085	1.054	1.550	
.4085	.5320	.5528	.5598	.6897	.6747	.9803	
.7429	.7115	.7390	.7856	1.019	1.269	1.283	
.9943	.9496	.9856	1.046	1.355	1.694	1.725	
.9716	.9284	.9635	1.022	1.324	1.652	1.677	
.8859	.8478	.8801	.9349	1.212	1.510	1.529	
.5613	.5390	.5597	.5947	.7692	.9485	.9474	
.7460	.8739	.9234	1.022	1.151	1.327		
.9951	1.168	1.231	1.360	1.529	1.777		
.9736	1.142	1.205	1.331	1.497	1.737		
.8897	1.043	1.102	1.220	1.374	1.589		
.5652	.6605	.6985	.7734	.8676	.9857		
.7985	.9251	.9123	1.280	1.331			
1.070	1.233	1.214	1.710	1.784			
1.046	1.207	1.189	1.674	1.746			
.9544	1.105	1.090	1.533	1.599			
.6013	.6999	.6905	.9602	.9912			
.9158	1.263	1.361	1.304				
1.222	1.695	1.827	1.754				
1.196	1.658	1.788	1.717				
1.095	1.515	1.635	1.570				
.6915	.9458	1.014	.9669				
.9651	1.112	Plane Groupings					
1.297	1.496						
1.269	1.464						
1.158	1.337						
.7204	.8260						

Fig. 34 Connecticut Yankee Core 3, 24-plane model —
 July-August, 1971 assembly-wise relative power distribution,
 843.9 Mwd/mtU.

.5519	.7041	.6025	.7954	.7366	.9261	.8736	.8208
.7015	.8933	.7590	.9959	.9121	1.139	1.063	1.008
.6906	.8798	.7485	.9832	.9010	1.121	1.044	.9903
.6453	.8233	.7032	.9273	.8546	1.066	.9968	.9435
.4291	.5479	.4717	.6252	.5842	.7381	.7026	.6494
.7040	.6523	.7799	.7515	.8845	.8858	1.222	1.114
.8929	.8225	.9808	.9357	1.096	1.083	1.492	1.365
.8795	.8111	.9679	.9249	1.083	1.068	1.465	1.341
.8232	.7616	.9108	.8751	1.028	1.018	1.397	1.280
.5479	.5105	.6111	.5939	.7005	.7102	.9775	.8825
.6023	.7793	.7894	.7708	.9258	.8810	1.336	Np Targets
.7579	.9793	.9866	.9551	1.139	1.072	1.632	
.7479	.9664	.9752	.9456	1.129	1.062	1.611	
.7033	.9102	.9211	.8976	1.077	1.018	1.544	
.4719	.6109	.6218	.6112	.7373	.7078	1.063	
.7976	.7517	.7661	.7910	1.001	1.251	1.305	
.9963	.9339	.9482	.9719	1.220	1.524	1.596	
.9853	.9245	.9395	.9648	1.214	1.516	1.585	
.9311	.8761	.8926	.9209	1.165	1.459	1.525	
.6279	.5947	.6079	.6310	.8024	.9988	1.032	
.7647	.8968	.9275	1.001	1.109	1.318		
.9435	1.108	1.138	1.219	1.342	1.605		
.9358	1.099	1.131	1.213	1.338	1.600		
.8907	1.046	1.081	1.166	1.292	1.544		
.6078	.7112	.7395	.8029	.8921	1.047		
.8086	.9160	.8895	1.254	1.318			
.9969	1.119	1.080	1.525	1.604			
.9898	1.112	1.076	1.519	1.600			
.9442	1.067	1.035	1.465	1.545			
.6411	.7326	.7142	1.002	1.048			
.8978	1.259	1.359	1.313				
1.092	1.539	1.659	1.602				
1.087	1.532	1.652	1.597				
1.045	1.472	1.592	1.540				
.7191	1.001	1.079	1.039				
.9724	1.126	2 — Plane Groupings					
1.192	1.380	3					
1.186	1.374	4					
1.138	1.321	5					
.7700	.8896	6					

Fig. 35 Connecticut Yankee Core 3, 24-plane model —
September-October, 1971 assembly-wise relative power
distribution, 2,492 Mwd/mtU.

.5417	.6905	.5874	.7765	.7175	.9136	.8706	.8672
.6514	.8281	.6988	.9156	.8338	1.049	.9850	.9902
.6497	.8265	.6987	.9172	.8368	1.052	.9869	.9928
.6267	.7988	.6784	.8959	.8240	1.042	.9850	.9908
.4436	.5666	.4856	.6469	.6058	.7806	.7552	.7418
.7906	.6344	.7604	.7289	.8663	.8703	1.245	1.194
.8280	.7555	.9022	.8541	1.006	.9933	1.412	1.359
.8265	.7550	.9027	.8566	1.011	.9967	1.414	1.363
.7988	.7323	.8783	.8392	.9961	.9902	1.411	1.363
.5666	.5239	.6297	.6107	.7308	.7482	1.076	1.023
.5878	.7603	.7682	.7491	.9054	.8681	1.398	Np Targets
.6988	.9017	.9048	.8727	1.043	.9855	1.587	
.6988	.9023	.9068	.8766	1.050	.9929	1.596	
.6786	.8779	.8858	.8619	1.040	.9914	1.599	
.4856	.6293	.6398	.6300	.7686	.7471	1.199	
.7801	.7301	.7452	.7706	.9803	1.262	1.413	
.9185	.8545	.8676	.8886	1.117	1.432	1.608	
.9207	.8573	.8717	.8948	1.127	1.448	1.625	
.8995	.8401	.8571	.8854	1.125	1.451	1.631	
.6488	.6107	.6231	.6528	.8383	1.080	1.202	
.7474	.8809	.9088	.9813	1.102	1.389		
.8668	1.022	1.046	1.117	1.244	1.576		
.8716	1.028	1.054	1.128	1.259	1.596		
.8587	1.014	1.044	1.126	1.263	1.603		
.6290	.7405	.7694	.8380	.9467	1.183		
.8076	.9041	.8792	1.267	1.391			
.9333	1.033	.9981	1.436	1.577			
.9400	1.042	1.008	1.453	1.597			
.9300	1.037	1.007	1.456	1.604			
.6799	.7689	.7514	1.081	1.183			
.8974	1.288	1.427	1.424				
1.020	1.469	1.622	1.620				
1.030	1.483	1.640	1.639				
1.028	1.482	1.643	1.644				
.7658	1.093	1.210	1.205				
1.020	1.029	2 — Plane Groupings					
1.167	1.381	3					
1.179	1.396	4					
1.176	1.395	5					
.8620	1.020	6					

Fig. 36 Connecticut Yankee Core 3, 24-plane model —
November-December, 1971 assembly-wise relative power
distribution, 4, 118 Mwd/mtU.

.5500	.6986	.5875	.7690	.7006	.8901	.8477	.8856
.6355	.8045	.6716	.8704	.7814	.9796	.9186	.9673
.6373	.8073	.6751	.8768	.7887	.9880	.9264	.9769
.6258	.7945	.6672	.8721	.7910	.9984	.9437	.9962
.4644	.5917	.5011	.6627	.6130	.7924	.7684	.7937
.6991	.6360	.7590	.7172	.8491	.8459	1.236	1.240
.8050	.7275	.8646	.8069	.9464	.9260	1.342	1.352
.8078	.7308	.8697	.8135	.9557	.9345	1.353	1.365
.7949	.7214	.8614	.8113	.9594	.9461	1.378	1.392
.5919	.5419	.6491	.6211	.7426	.7565	1.118	1.111
.5894	.7602	.7622	.7360	.8856	.8484	1.428	Np Targets
.6736	.8659	.8622	.8237	.9795	.9260	1.556	
.6768	.8708	.8684	.8314	.9906	.9371	1.573	
.6686	.8621	.8631	.8315	.9986	.9513	1.604	
.5018	.6493	.6554	.6395	.7784	.7570	1.277	
.7768	.7217	.7343	.7555	.9591	1.261	1.499	
.8790	.8119	.8218	.8376	1.050	1.376	1.639	
.8850	.8181	.8292	.8468	1.064	1.396	1.663	
.8793	.8150	.8287	.8513	1.078	1.421	1.696	
.6665	.6226	.6364	.6606	.8480	1.119	1.324	
.7371	.8713	.8948	.9635	1.092	1.451		
.8225	.9721	.9903	1.055	1.187	1.584		
.8300	.9814	1.001	1.069	1.204	1.607		
.8305	.9829	1.007	1.082	1.225	1.638		
.6395	.7558	.7818	.8495	.9697	1.279		
.8044	.8921	.8690	1.275	1.458			
.8945	.9820	.9514	1.393	1.591			
.9037	.9932	.9633	1.412	1.614			
.9077	1.002	.9748	1.434	1.643			
.6989	.7824	.7652	1.124	1.281			
.8909	1.304	1.480	1.527				
.9760	1.433	1.622	1.673				
.9877	1.450	1.643	1.696				
.9990	1.468	1.667	1.723				
.7841	1.143	1.296	1.335				
1.056	1.278	2 — Plane Groupings					
1.164	1.408	3					
1.178	1.426	4					
1.191	1.443	5					
.9214	1.113	6					

Fig. 37 Connecticut Yankee Core 3, 24-plane model—January-February, 1972 assembly-wise relative power distribution, 5,788 Mwd/mtU.

.5072	.6448	.5430	.7159	.6573	.8502	.8262	.9183
.5654	.7159	.5996	.7827	.7099	.9069	.8704	.9754
.5693	.7213	.6048	.7911	.7187	.9172	.8798	.9875
.5670	.7201	.6059	.7974	.7295	.9379	.9060	1.018
.4414	.5634	.4774	.6368	.5937	.7842	.7760	.8535
.6459	.5853	.7029	.6672	.8030	.8122	1.236	1.320
.7172	.6461	.7729	.7259	.8666	.8638	1.306	1.404
.7225	.6514	.7802	.7341	.8774	.8735	1.319	1.420
.7211	.6519	.7832	.7412	.8913	.8937	1.357	1.462
.5640	.5140	.6200	.5957	.7252	.7509	1.160	1.124
.5467	.7059	.7104	.6922	.8471	.8307	1.495	Np Targets
.6038	.7764	.7768	.7505	.9095	.8846	1.592	
.6088	.7833	.7846	.7592	.9214	.8960	1.611	
.6091	.7857	.7895	.7678	.9379	.9164	1.653	
.4791	.6212	.6293	.6193	.7669	.7621	1.377	
.7290	.6760	.6933	.7225	.9344	1.284	1.658	
.7981	.7364	.7523	.7783	.9971	1.371	1.777	
.8056	.7437	.7605	.7879	1.011	1.390	1.802	
.8097	.7491	.7679	.7991	1.031	1.421	1.848	
.6438	.5998	.6178	.6490	.8482	1.167	1.502	
.7019	.8345	.8633	.9426	1.101	1.577		
.7608	.9040	.9292	1.007	1.170	1.688		
.7688	.9137	.9401	1.020	1.187	1.711		
.7761	.9235	.9532	1.038	1.213	1.749		
.6251	.7437	.7743	.8519	1.000	1.421		
.7891	.8737	.8630	1.308	1.590			
.8550	.9392	.9253	1.401	1.704			
.8641	.9497	.9362	1.419	1.726			
.8738	.9630	.9511	1.447	1.761			
.7031	.7844	.7763	1.178	1.427			
.8898	1.338	1.579	1.709				
.9553	1.442	1.701	1.843				
.9658	1.458	1.720	1.864				
.9800	1.479	1.746	1.895				
.7999	1.198	1.411	1.525				
1.116	1.394	2 — Plane Groupings					
1.209	1.510	3					
1.221	1.526	4					
1.237	1.547	5					
.9946	1.239	6					

Fig. 38 Connecticut Yankee Core 3, 24-plane model —
March-April, 1972 assembly-wise relative power
distribution, 7,409 Mwd/mtU.

.4456	.5676	.4804	.6409	.5972	.7919	.7920	.9452
.4814	.6106	.5153	.6819	.6308	.8287	.8237	.9926
.4858	.6166	.5208	.6900	.6387	.8378	.8315	1.004
.4888	.6216	.5263	.7008	.6521	.8607	.8585	1.036
.3994	.5113	.4347	.5875	.5554	.7540	.7665	.9041
.5693	.5150	.6242	.5988	.7374	.7648	1.222	1.407
.6126	.5516	.6666	.6352	.7787	.8008	1.278	1.487
.6184	.5572	.6739	.6428	.7883	.8089	1.288	1.501
.6233	.5627	.6822	.6533	.8046	.8300	1.327	1.544
.5122	.4656	.5671	.5500	.6856	.7273	1.183	1.338
.4859	.6288	.6380	.6319	.7936	.8066	1.570	Np Targets
.5218	.6722	.6794	.6699	.8373	.8511	1.666	
.5268	.6790	.6867	.6776	.8471	.8600	1.681	
.5313	.6864	.6957	.6884	.8641	.8787	1.719	
.4377	.5694	.5810	.5801	.7364	.7554	1.474	
.6594	.6119	.6360	.6770	.9019	1.314	1.864	
.7039	.6510	.6755	.7167	.9510	1.398	1.997	
.7107	.6575	.6824	.7245	.9615	1.413	2.017	
.7183	.6656	.6917	.7359	.9796	1.437	2.051	
.5977	.5568	.5806	.6216	.8345	1.211	1.713	
.6500	.7788	.8174	.9144	1.116	1.751		
.6917	.8281	.8665	.9663	1.180	1.874		
.6980	.8358	.8747	.9758	1.192	1.891		
.7061	.8462	.8870	.9911	1.211	1.918		
.5916	.7098	.7483	.8408	1.027	1.595		
.7589	.8439	.8532	1.353	1.774			
.8116	.8986	.9104	1.447	1.903			
.8180	.9058	.9176	1.459	1.918			
.8261	.9156	.9275	1.474	1.940			
.6888	.7697	.7771	1.230	1.607			
.8813	1.371	1.698	1.952				
.9422	1.476	1.835	2.110				
.9487	1.485	1.845	2.123				
.9569	1.495	1.856	2.137				
.8018	1.240	1.529	1.754				
1.184	1.534	2 — Plane Groupings					
1.281	1.665	3					
1.289	1.674	4					
1.296	1.681	5					
1.065	1.375	6					

Fig. 39 Connecticut Yankee Core 3, 24-plane model —
May-June, 1972 assembly-wise relative power distribution,
9, 102 Mwd/mtU.

Fig. 40 Pointwise average power as a function of burnup for point (2,6) in the target assembly.

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Fig. 41 Projected neptunium production rate.

Fig. 42 Microscopic absorption cross-sections of Np-237 and U-238.

Fig. 43 Process flow diagram.

Fig. 44 Target rod fabrication costs.

Fig. 45 Pu-238 Cost vs. Np Cost