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Special Nuclear Material Flow Projections for the Commercial Nuclear Industry

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E. H. Hasseltine, P. De Laquil III, P. L. Leary

Sandia Laboratories

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Issued by Sandia Laboratories, operated for the United States Energy Research and Development Administration by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy $4.50; Microfiche $3.00

SAND75-8276
NUREG 0210
Unlimited Release
Printed March 1977

NRC-13

SPECIAL NUCLEAR MATERIAL FLOW PROJECTIONS FOR THE COMMERCIAL NUCLEAR INDUSTRY

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ABSTRACT

Projections of the flows of special nuclear material within the commercial nuclear power industry are presented. Based on power levels and types of reactors, subject to assumptions regarding plant load factors and recycle of reactor products, total monthly material flows between operating fuel cycle facilities from 1976 to 2000 are examined. Nuclear power plant commitments as of July 1, 1976, are used to project industry growth through the early 1980s, and recent nuclear growth projections are assumed beyond 1985. The projected yearly flows of special nuclear material are presented, and for example purposes, the yearly numbers of single shipments are calculated assuming conventional truck carriers.

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under ERDA Contract No. AT(29-1)-789

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ABBREVIATIONS

BWR	boiling water reactor
DU	depleted uranium
ERDA	Energy Research and Development Administration
FBR	fast breeder reactor
HEU	highly enriched uranium
HTGR	high temperature gas reactor
LEU	low enriched uranium
LMFBR	liquid metal fast breeder reactor
LWR	light water reactor
MSWU	1000 separative work units
MT	metric tons
MW_e	megawatts of electrical power
MWD	megawatt days
NU	natural uranium
Pu	plutonium
PWR	pressurized water reactor
SNM	special nuclear material
Th	thorium
TPU	thirty percent enriched uranium
U	uranium
UR	uranium recycle

SPECIAL NUCLEAR MATERIAL FLOW PROJECTIONS FOR THE COMMERCIAL NUCLEAR INDUSTRY

Introduction

This document presents projections of the amounts of special nuclear material (SNM) required by the commercial nuclear power industry. The projections are based on assumptions concerning the growth of nuclear power plants, and the recycle of reactor products, specifically, plutonium recycle to light water reactors. Yearly values for the amounts of SNM flowing through the fuel cycle are shown, and the resulting numbers of single shipments for each transportation link in the fuel cycle are calculated assuming conventional truck shipments.

The work presented in this report was partially performed for the Nuclear Regulatory Commission project, "The Physical Protection of Nuclear Materials".[1] The purpose of these material flow predictions is to provide a basis for determining the requirements and costs of alternative commercial SNM transportation systems. The cost of the alternative transportation systems is one element in an overall benefit/cost analysis which also considers the safeguards effectiveness of the systems.

Commercial Nuclear Industry Growth

The status of the commercial nuclear industry as of July 1, 1976, was used as the basis for the reactor growth projections.[2] This consists of the presently operating reactors and those reactor projects under construction or on order. Table I presents the number of reactors of each type that are operating as of 1975 along with those scheduled to commence commercial operation through 1985. Also included in the table is the total nuclear generating capacity for each year. The list of current commitments for reactor projects by name, date, power level, and reactor type is given in the Appendix.

Table II details the reactor growth of Table I according to the generated power of each of the reactor types. Not listed in the table is the single high

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TABLE I

NEAR-TERM NUCLEAR POWER GROWTH

Year	Number Added	Cumulative Reactors	MW_e Added	Cumulative MW_e	Number of Reactors* PWR	BWR	HTGR
1975	8	53	7,109	36,244	30	23	0
1976	9	62	8,175	44,419	37	24	1
1977	7	69	6,411	50,830	43	25	1
1978	6	75	6,278	57,108	48	26	1
1979	11	86	10,974	68,082	54	31	1
1980	9	95	10,508	78,590	59	35	1
1981	14	111	16,514	95,104	72	38	1
1982	19	130	21,270	116,374	85	44	1
1983	14	144	15,780	132,154	94	49	1
1984	17	161	19,514	151,668	105	55	1
1985	14	175	16,307	167,975	115	59	1

*PWR - pressurized water reactor

BWR - boiling water reactor

HTGR - high temperature gas reactor

TABLE II

COMMITTED REACTOR POWER GROWTH IN MW_e

Year	PWR New	PWR Cumulative	BWR New	BWR Cumulative
1975	3,645	21,034	3,464	15,210
1976	6,778	27,812	1,067	16,277
1977	5,590	33,402	821	17,098
1978	5,200	38,602	1,078	18,176
1979	6,380	44,982	4,594	22,770
1980	5,910	50,892	4,598	27,368
1981	13,669	64,561	2,845	30,213
1982	14,613	79,174	6,657	36,870
1983	9,936	89,110	5,844	42,714
1984	12,548	101,658	6,966	49,680
1985	11,446	113,104	4,861	54,541

temperature gas reactor (HTGR) project, the 330 MW_e Fort St. Vrain plant, which is assumed to commence operation at the end of 1976.

The nuclear industry was characterized in this report by a combination of the reactor projects committed as of July 1, 1976, and the growth projections through the year 2000 given by the Energy Research and Development Administration (ERDA) at an Atomic Industrial Forum conference in Geneva.[3] Those reactors under construction and scheduled to commence operation by the end of 1980 were assumed to conform to their present schedule. From 1981 to 2000, the reported ERDA high, median, and low growth projections for 1985, 1990, and 2000 were fitted to the 1980 projection. Yearly values of the industry growth were obtained from a smooth curve fit of these point values. In Figure 1, the current reactor commitments are depicted as the dashed line. This line tails off after 1985 due to the small number of orders for reactors scheduled to start-up after this date. The solid lines are the fitted high, median, and low growth projections based on the point projections which were considered as mid-year values.

The amounts of nuclear capacity for the years 1976 to 2000 for the high, median, and low growth projection cases are given in Tables III, IV, and V, respectively. The light water reactor (LWR) generating capacity up to 1985 was apportioned according to the ratio of committed pressurized water reactor (PWR) capacity to boiling water reactor (BWR) capacity as given in Table II. Beyond 1985, the ratio of PWR to BWR generating capacity was maintained at 2 to 1. The liquid-metal fast breeder reactor (LMFBR) growth projection for the high case was obtained by scaling the LMFBR projection of Reference 4 by the total projected nuclear capacity in the year 2000. For the median growth case, commercial LMFBR introduction was delayed until 1995 and a breeder introduction schedule of one per year for the first three years, two per year for the subsequent two years, and three in the year 2000 was employed. For the low growth case, no commercial operation was assumed before the year 2000. With the exception of the Fort St. Vrain reactor, HTGRs are not included in any of the growth projections. An example of the impact of HTGRs on SNM transportation requirements can be seen in Reference 5.

In determining the material flows, the nuclear industry was characterized by individual reactor projects located at specific sites. Site selection allows the direct interface of the material flow projections with transportation system models. Through 1980 the set of committed reactors was used. From 1981 to 1990 sites were selected so as to conform to the growth projections by adding new reactors at previously established sites. After 1990, the yearly increments of nuclear capacity were sited regionally in proportion to an estimate of nuclear energy demand growth.[6]

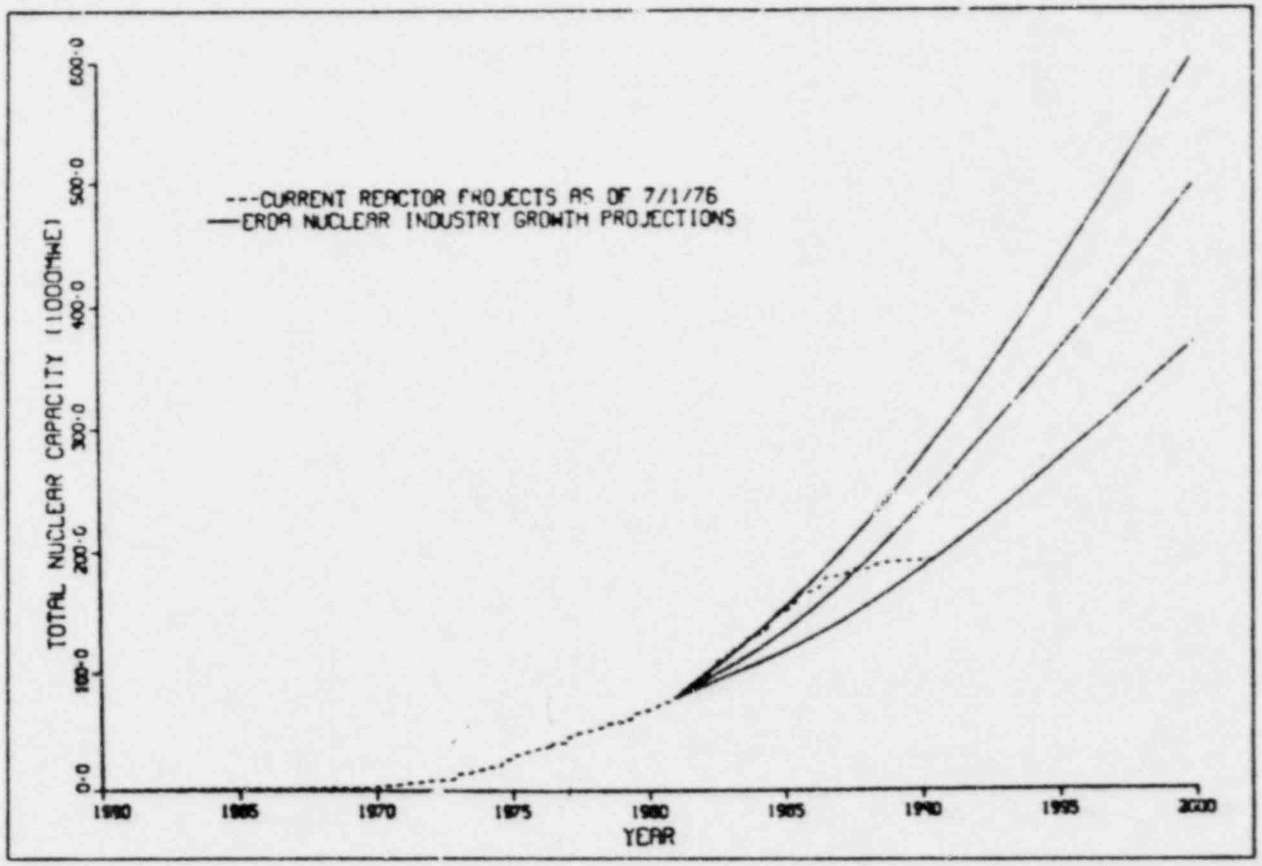


Figure 1. Nuclear Growth Projections

TABLE III

NUCLEAR POWER GROWTH PROJECTION - HIGH CASE

1000 MW_e

Year	PWR	BWR	LMFBR	Total*
1976	27.8	16.3	0.0	44.4
1977	33.4	17.1	0.0	50.8
1978	38.6	18.2	0.0	57.1
1979	45.0	22.8	0.0	68.1
1980	50.9	27.4	0.0	78.6
1981	65.9	30.9	0.0	97.1
1982	78.8	36.7	0.0	115.8
1983	91.4	43.8	0.0	135.5
1984	104.2	51.0	0.0	155.5
1985	119.2	57.4	0.0	176.9
1986	132.9	66.4	0.0	199.6
1987	148.9	74.5	0.0	223.7
1988	166.9	83.0	0.0	249.2
1989	183.8	91.9	0.0	276.0
1990	202.7	101.3	0.0	304.3
1991	222.4	111.2	0.0	333.9
1992	242.9	121.5	0.0	364.7
1993	263.7	131.9	0.7	396.6
1994	285.0	142.5	1.6	429.4
1995	306.3	153.1	3.3	463.0
1996	327.1	163.5	6.3	497.2
1997	346.9	173.4	11.4	532.0
1998	366.7	183.4	16.6	567.0
1999	385.8	192.9	23.3	602.3
2000	403.5	201.7	31.5	637.0

*Includes the 330 MW_e Fort St. Vrain HTGR. Through 1980 the committed reactor growth was used.

TABLE IV

NUCLEAR POWER GROWTH PROJECTION - MEDIAN CASE

1000 MW_e

Year	PWR	BWR	LMFBR	Total*
1976	27.8	16.3	0.0	44.4
1977	33.4	17.1	0.0	50.8
1978	38.6	18.2	0.0	57.1
1979	45.0	22.8	0.0	68.1
1980	50.9	27.4	0.0	78.6
1981	62.6	29.2	0.0	92.1
1982	70.5	35.2	0.0	106.0
1983	81.3	39.0	0.0	120.6
1984	91.5	44.7	0.0	136.5
1985	103.6	50.0	0.0	153.9
1986	115.1	57.6	0.0	173.0
1987	128.9	64.4	0.0	193.6
1988	143.4	71.7	0.0	215.4
1989	158.7	79.3	0.0	238.3
1990	174.4	87.2	0.0	261.9
1991	190.6	95.3	0.0	286.2
1992	207.3	103.6	0.0	311.2
1993	224.2	112.1	0.0	336.6
1994	241.5	120.7	0.0	362.5
1995	258.5	129.3	0.7	388.8
1996	275.7	137.8	1.6	415.4
1997	292.9	146.5	2.6	442.3
1998	309.5	154.7	4.8	469.3
1999	326.1	163.0	7.0	496.4
2000	341.6	170.8	10.3	523.0

*Includes the 330 MW_e Fort St. Vrain HTGR. Through 1980 the committed reactor growth was used.

TABLE V

NUCLEAR POWER GROWTH PROJECTION - LOW CASE

1000 MW_e

Year	PWR	BWR	Total*
1976	27.8	16.3	44.4
1977	33.4	17.1	50.8
1978	38.6	18.2	57.1
1979	45.0	22.8	68.1
1980	50.9	27.4	78.6
1981	59.9	28.0	88.2
1982	66.7	31.1	98.1
1983	73.0	35.0	108.3
1984	79.9	39.0	119.2
1985	88.2	42.5	131.0
1986	95.6	47.8	143.7
1987	104.7	52.3	157.3
1988	114.3	57.2	171.8
1989	124.5	62.3	187.1
1990	135.2	67.6	203.1
1991	146.3	73.2	219.8
1992	157.9	79.0	237.2
1993	169.9	84.9	255.1
1994	182.1	91.1	273.5
1995	194.7	97.3	292.3
1996	207.5	103.7	311.5
1997	220.4	110.2	330.9
1998	233.4	116.7	350.4
1999	246.5	123.3	370.1
2000	259.8	129.9	390.0

*Includes the 330 MW_e Fort St. Vrain HTGR. Through 1980 the committed reactor growth was used.

Materials Requirements

Given the total power for each type reactor for any year, the amount of material needed for each refueling can be calculated. The calculations are subject to the scaling assumption and the assumption of the fraction of the core replaced. For PWR projects, loading and discharge values were taken in proportion to the proposed 1150 MW_e Jamesport reactor[7] with one-third of the core replaced at each refueling. For the BWR projects, one-fourth of the core was replaced at each refueling, and the loading and discharge values were taken in proportion to the proposed 820 MW_e Shoreham reactor.[7] The fuel cycle material requirements for individual reactor refuelings are given in Table VI. The data include material flows from reactors not on plutonium recycle and recycle flows at the self-generation recycle equilibrium level. The total materials required by reactors in any time period will be the sum of the refuelings and the initial core loading during that period. Initial core loading assumptions are presented in Table VII.

The scheduling of SNM shipments was determined according to representative cooling and lead times. These assumptions affect the timing of SNM shipments but not the overall material flows requirements. Following removal of irradiated fuel elements from the core, a five-month cooling period is assumed before shipment to a reprocessing plant. Shipment of appropriate amounts of recovered material to fuel element fabrication plants is assumed to take place three months before each light water reactor refueling date.[8] Plutonium for the refueling of an LMFBR is assumed to be shipped to the fabricator six months prior to refueling.[8] Shipments of fuel elements to operating reactors are assumed to occur during the assigned refueling month. For the light water reactors, initial core loadings are not of concern, since no highly enriched uranium or plutonium is involved. However, initial cores for LMFBR projects will be important. One-half the required plutonium for the new core is assumed to be required by the fabricator seven months in advance of the core loading date, and the other half is assumed to be required six months in advance.[8]

Reactor Refueling Schedules

The interrelated variables pertaining to reactor fuel include fuel enrichment, design burn-up level, plant load factor, fraction of core replaced during each refueling, and time between refuelings. The first two of these are normally predetermined design quantities. Of the latter three variables, specifying the value for two determines the value of the third. If fuel replacement is set according to a specific core fraction and a refueling frequency, it

TABLE VI

FUEL CYCLE REQUIREMENTS FOR INDIVIDUAL REACTOR REFUELINGS

1000 MW_e

PWR	Fabrication (MT)	Plant (MT)	Reprocessing (MT)	Enrichment (MSWU)
Recycle Pu	20.5 LEU	19.3 LEU	18.5 LEU*	89.9
(Equilibrium)	9.08 NU	9.04 NU	8.84 DU	
	0.468 Pu	0.46 Pu**	0.475 Pu	
No Recycle	30.5 LEU	28.8 LEU	27.5 LEU*	135.7
			0.26 Pu	
BWR				
Recycle Pu	27.9 LEU	26.3 LEU	25.2 LEU*	72.0
(Equilibrium)	9.42 NU	9.38 NU	9.17 DU	
	0.56 Pu	0.55 Pu**	0.61 Pu	
No Recycle	38.4 LEU	36.3 LEU	34.6 LEU*	99.1
			0.21 Pu	
HTGR				
Recycle U	7.07 Th	7.07 Th	6.55 Th	83.2
(Equilibrium)	0.053 HEU	0.353 HEU	0.086 TPU	
	0.31 UR	0.31 UR	0.319 UR	
	0.086 TPU	0.086 TPU		
No Recycle	7.07 Th	7.07 Th	6.55 Th	150.8
	0.64 HEU	0.64 HEU	0.155 TPU	
			0.216 UR	
LMFBR				
	6.77 NU†	21.4†† NU	20.3 DU	---
	2.22 Pu	2.4 Pu**	2.35 Pu	

* Approximately 0.8% U^{235}

** Fissile Pu into Plant is 63% for PWR, 57% for BWR, 71% for LMFBR

† Core Fabrication Only

†† Core F[illegible]ements and Blanket Elements

TABLE VII

INITIAL CORE LOADINGS FOR 1000 MW_e REACTOR

	PWR	BWR	HTGR	LMFBR*
LEU	86.5	145.0		
NU			1.48	42.4
Pu				3.98
Th			32.3	
Enrichment (MSWU)	331.7	373.0	349.4	
Fuel Elements	179.0	696.0	3400.0	

*Due to the lack of firm commercial-size LMFBR designs, no value for the number of fuel elements is given.

implies a load factor. If the load factor varies, as present experience indicates, either the fraction of core reloaded or the refueling frequency must change if the desired burn-up is to be attained. It appears that a policy of removing more or less than the design core fraction during a refueling is not as flexible an approach as prolonging or shortening the burn period. Therefore, for light water reactors, the plant load factors were varied and the refueling intervals were calculated which achieved the design burn-up. The LWR plant load factor was taken as 0.4 for each reactor in its initial year of operation, 0.65 in the second and third years, 0.75 in the fourth throughout the fifteenth, and a decrease of 0.02 each year following the fifteenth until the load factor reaches 0.25 which is maintained thereafter until retirement. Due to the lack of load factor data for LMFBRs, the refuelings were assumed to take place annually. This implies an 80 percent load factor.

Burn-up levels assumed in this report were 33,000 MWD/tonne for the PWR and 27,500 MWD/tonne for the BWR. Initial core burn-ups vary from these values due to the initial absence of nonfissile neutron absorbers. For the PWR, 42,000 MWD/tonne was used, and for the BWR, 56,000 MWD/tonne was used. A refueling schedule for each reactor was then determined from the refueling intervals and the reactor start-up date. Through 1980, the scheduled start-up dates were used. After 1980, reactor start-up dates were chosen so as to evenly distribute the new capacity over the year.

Plutonium Utilization

If plutonium is utilized within the nuclear power industry, the LWR will be the source of plutonium for either recycle to LWRs, or for the initial cores and early refuelings of LMFBRs. Refueling of the breeders will eventually use self-generated plutonium, but this is not foreseen before the year 2000. The median and high growth projections include LMFBR projects, and the associated plutonium demand must be served. Therefore, the amount of plutonium which could be recycled into the light water reactors would be less than the total plutonium produced, and there exists a maximum percentage of light water reactors which could initiate plutonium recycle. There are other factors affecting the ability of the light water reactors to recycle plutonium which may serve to lower this maximum percentage. These include plutonium oxide fuel fabrication capacity and existing reactor control and fuel-handling systems. It has been shown[5] that for projected nuclear power levels similar to the high growth case, 80 percent recycle is the maximum percentage recycle possible. By the end of 2000, all available plutonium has been used; however, it is important to note that significant quantities of plutonium through the 1980s and 1990s must be stored in order to meet the large demand of the late 1990s. Using this plutonium to increase the recycle percentage in the light water reactors would not allow for the refueling of LMFBRs on the schedule assumed.

Plutonium Recycle

The actual extent to which plutonium recycle will be practiced depends on as yet unresolved economic, environmental, and safeguards issues. For current analyses, two alternative recycle schedules have been postulated in which 25 percent or 80 percent of those reactors eligible for recycle in that year are actually on recycle. Eligibility is achieved at the end of initial core burn-up. In no case does plutonium recycle begin before 1982 due to the current lack of operational reprocessing plants. An additional assumption was that the plutonium recycle fraction applied equally to PWR and BWR projects. There may be a preference for the PWR in the recycle mode. However, as there are approximately twice as many PWRs as BWRs at any time, the number on recycle as calculated here results in a 2:1 ratio for PWR relative to BWR.

Plutonium charges to and discharges from reactors on self-generating plutonium recycle build up to equilibrium operation values over a period of time. Gradual increases in the amount of plutonium fed to the reactor are the established practice due to the different neutronic and thermal characteristics of plutonium and the control problems arising from its use. For the PWR projects, ten refuelings were assumed necessary with recycle beginning during the loading of the second core, i.e., three recycling periods after initial start-up.[7] For BWR projects, 24 refuelings were assumed to be required before equilibrium was attained.[7] Recycle begins with the loading of the second core, or four refuelings after initial start-up. The values for charges of plutonium to the reference 1000 MW_e reactors of the PWR and BWR type during the approach to equilibrium are given in Table VIII.

Materials Flow Analysis

The annual amounts of materials required in the total nuclear fuel cycle are summarized in Tables IX, X, and XI for the high, median, and low growth cases, respectively. Values for plutonium flowing to mixed oxide fabrication plants are given for 25 percent and 80 percent recycle levels. This is expected to be in the form of PuO_2. Approximately the same amount of plutonium will also be flowing from the fabrication plant to the uranium oxide fabrication plant, if separate, and then to the reactor in the form of mixed oxide fuel elements. For all reactors, plutonium will also flow from reactor to reprocessor within the spent fuel elements. Figures 2, 3, and 4 illustrate the total plutonium flow to fabrication plants for the high, median, and low growth cases, respectively. (Notice the changes in scale.)

TABLE VIII

RECYCLE PLUTONIUM CHARGE TO 1000 MW_e REACTOR

MT Pu

No. of Refuelings After Start-Up	PWR	BWR
3	0.180	-
4	0.262	0.107
5	0.299	0.140
6	0.307	0.174
7	0.310	0.208
8	0.379	0.242
9	0.434	0.276
10	0.454	0.309
11	0.459	0.343
12	0.460	0.361
13	0.460	0.380
14	0.460	0.400
15	0.460	0.420
16	0.460	0.440
17	0.460	0.465
18	0.460	0.490
19	0.460	0.514
20	0.460	0.520
21	0.460	0.522
22	0.460	0.522
23	0.460	0.524
24	0.460	0.536
25	0.460	0.542
26	0.460	0.548
27	0.460	0.550
28	0.460	0.550

TABLE IX

ANNUAL MATERIAL FLOW SUMMARY - HIGH GROWTH CASE

Metric Tons

Year	% Recycle	Pu to Reactors		Pu to Fabricators		To Reprocessors
		LWR	FBR	LWR	FBR	LWR Spent Fuel
1985	25	6.3	0	6.5	0	3,769
	80	17.0	0	18.0	0	3,769
1990	25	15.4	0	15.7	0	7 038
	80	44.7	0	47.3	0	7,038
1995	25	21.8	10.1	23.7	16.3	11,276
	80	71.6	10.1	72.9	16.3	11,276
2000	25	37.2	81.5	36.0	84.5	15,644
	80	112.5	81.5	110.3	84.5	15,644

TABLE X

ANNUAL MATERIAL FLOW SUMMARY - MEDIAN GROWTH CASE

Metric Tons

Year	% Recycle	Pu to Reactors		Pu to Fabricators		To Reprocessors
		LWR	FBR	LWR	FBR	LWR Spent Fuel
1985	25	5.3	0	5.3	0	3,397
	80	16.7	0	17.6	0	3,397
1990	25	10.2	0	13.3	0	6,237
	80	36.7	0	38.5	0	6,237
1995	25	17.9	2.8	20.4	5.0	9,437
	80	58.0	2.8	60.5	5.0	9,437
2000	25	29.9	27.8	27.2	23.2	13,106
	80	94.3	27.8	90.4	23.2	13,106

TABLE XI

ANNUAL MATERIAL FLOW SUMMARY - LOW GROWTH CASE

Metric Tons

Year	% Recycle	Pu to Reactors	Pu to Fabricators	To Reprocessors
		LWR	LWR	LWR Spent Fuels
1985	25	4.4	4.3	2,974
	80	16.2	16.6	2,974
1990	25	8.0	9.9	4,933
	80	31.4	35.0	4,933
1995	25	13.2	14.8	7,211
	80	46.5	48.9	7,211
2000	25	21.7	20.6	10,149
	80	66.7	67.5	10,149

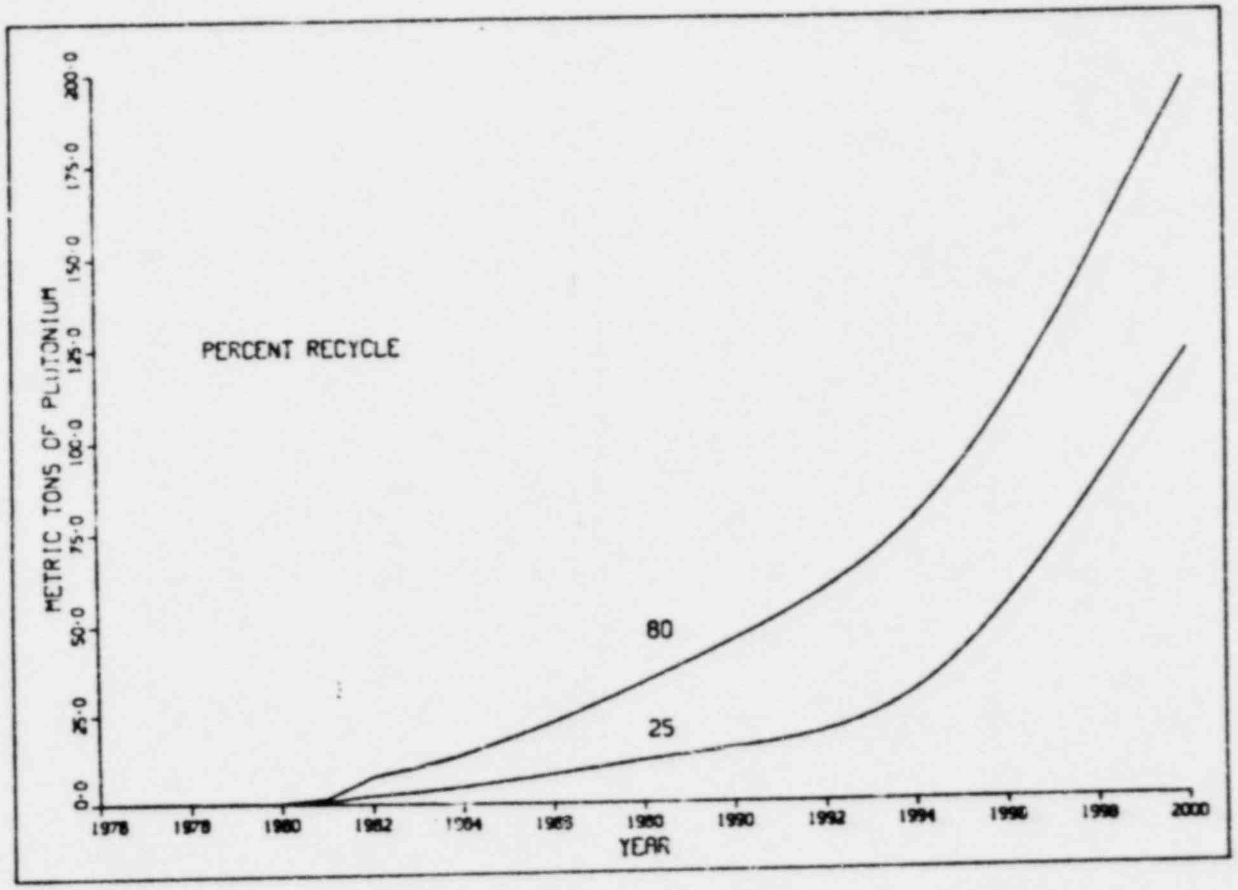


Figure 2. Plutonium Flow to Fabrication - High Growth Case

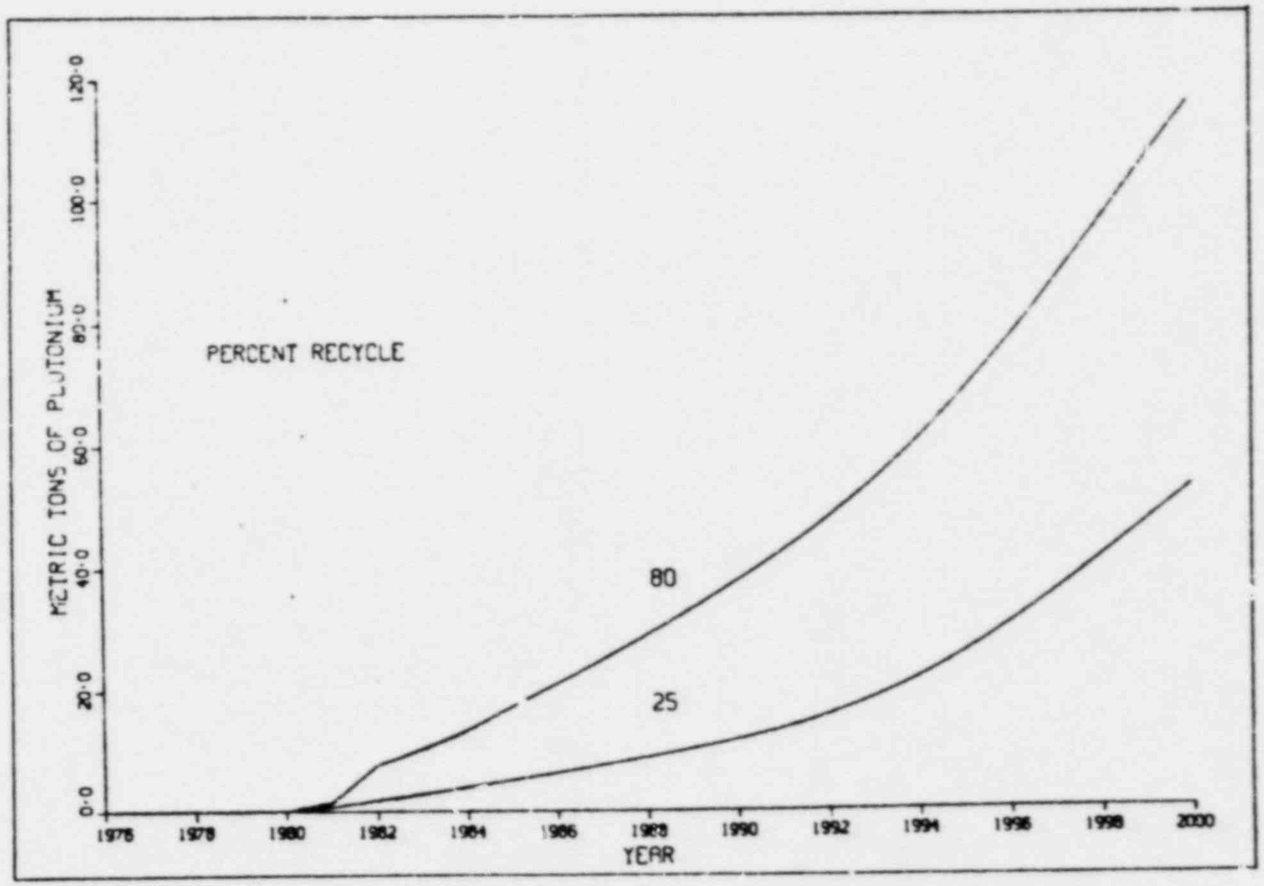


Figure 3. Plutonium Flow to Fabrication - Median Growth Case

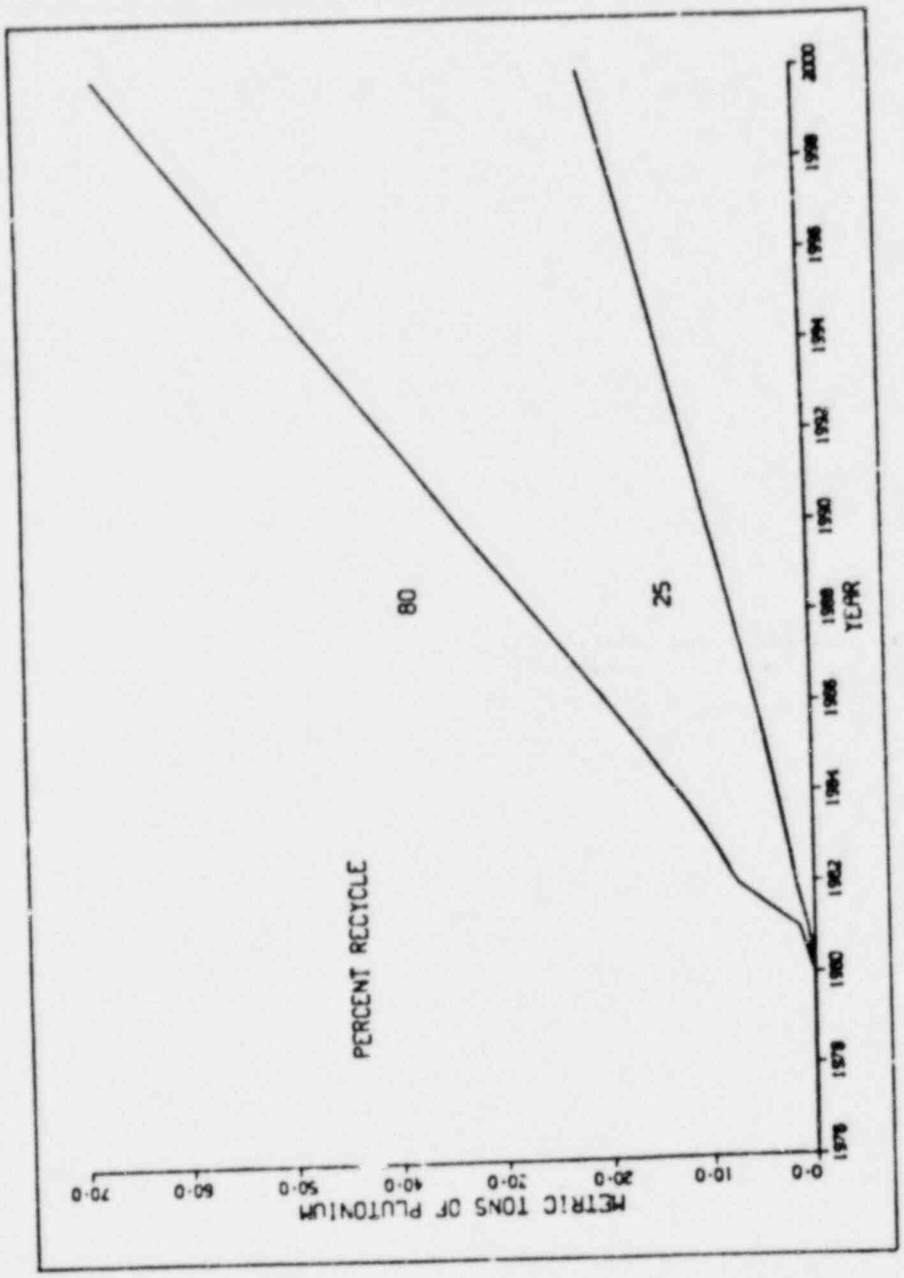


Figure 4. Plutonium Flow to Fabrication - Low Growth Case

While there were no projections made for future HTGR plants, there is a small material flow requirement for the single existing HTGR, the Fort St. Vrain plant. The yearly material flow requirements for this reactor would be 0.2 MT of highly enriched uranium (HEU) shipped to the fabrication plant and then to the reactor. The amount of spent fuel shipped each year is 2.3 MT. These amounts were calculated assuming annual refueling. No recycle mode was considered.

Shipment Requirements

Given the carrier capacity and the form of the special nuclear material (i.e., PuO_2 powder or fresh fuel elements), the number of shipments can be calculated. For example purposes, the mode of SNM transportation was assumed to be a conventional truck. The number of shipments associated with the material flow requirements is calculated using conventional shipment sizes. These shipment size assumptions are summarized in Table XII. Alternative SNM transportation modes can be investigated if the carrier capabilities are known. In the case of spent reactor fuel, rail shipment may be favored over truck. This reduces the required number of single shipments by about a factor of five.

For LWRs, the shipments of both fresh and spent fuel are determined under the assumption that the required numbers of fuel elements are proportional to reactor power levels, i.e., the ratio of fuel elements between any reactor and the reference reactor is equal to the ratio of power levels. The amount of special nuclear materials within the elements will vary according to whether or not the reactor is on recycle and the length of time on recycle as previously discussed. For the LMFBR, because of a lack of a firm commercial-size design, no value for the number of fuel elements in the core was used. Shipment size for the LMFBR fresh fuel elements was determined by the amount of plutonium in the fuel. A value of 200 kg of plutonium per shipment was used to calculate the number of LMFBR fuel shipments.

Using the data of Table XII, the material flows portrayed in Figures 2 through 4 have been converted to numbers of shipments. Tables XIII through XV summarize the number of required shipments for the high, median, and low growth cases, respectively.

Since total numbers of shipments at different stages of the fuel cycle are important in overall transportation safeguards analyses, the following figures are included:

1. Shipments of plutonium to fabrication plants, plotted in Figures 5, 6, and 7

TABLE XII

ASSUMED SHIPMENT DATA FOR A CONVENTIONAL ROAD VEHICLE

Fuel Elements*	
PWR[7]	193 @ 1085 MW_e
BWR[7]	764 @ 1093 MW_e
HTGR[9]	3944 @ 1160 MW_e
Shipment Capacities for Trucks	
PWR Fuel	
Fresh	14 elements
Spent	2 elements
BWR Fuel	
Fresh	32 elements
Spent	4 elements
HTGR Fuel	
Fresh	90 elements
Recycle	45 elements
LMFBR Fuel	
Fresh	200 kg Pu**
PuO_2	300 kg Pu[10]
UF_6 (93% enrichment)	1149 kg U^{235}

*Due to the lack of firm commercial-size LMFBR designs, no value for the number of fuel elements is given.

**LMFBR fresh fuel shipments were assumed to be determined by the amount of plutonium in the fuel.

TABLE XIII

ANNUAL SHIPMENT SUMMARY - HIGH GROWTH CASE

Number of Shipments

Year	% Recycle	Pu to Reactors		Pu to Fabricators		To Reprocessors
		LWR	FBR	LWR	FBR	LWR Spent Fuel
1985	25	93	0	33	0	4,350
	80	204	0	74	0	4,350
1990	25	165	0	68	0	8,160
	80	438	0	171	0	8,160
1995	25	171	53	97	55	13,080
	80	624	53	261	55	13,080
2000	25	329	420	144	270	18,150
	80	962	420	390	270	18,150

TABLE XIV

ANNUAL SHIPMENT SUMMARY - MEDIAN GROWTH CASE

Number of Shipments

Year	% Recycle	Pu to Reactors		Pu to Fabricators		To Reprocessors
		LWR	FBR	LWR	FBR	LWR Spent Fuel
1985	25	75	0	28	0	3,925
	80	200	0	67	0	3,925
1990	25	119	0	59	0	7,200
	80	365	0	145	0	7,200
1995	25	171	14	88	17	10,900
	80	492	14	288	17	10,900
2000	25	306	145	112	76	15,200
	80	815	145	326	76	15,200

TABLE XV

ANNUAL SHIPMENT SUMMARY - LOW GROWTH CASE

Number of Shipments

Year	% Recycle	Pu to Reactors LWR	Pu to Fabricators LWR	To Reprocessors LWR Spent Fuels
1985	25	65	23	3,440
	80	196	66	3,440
1990	25	96	47	5,710
	80	307	130	5,710
1995	25	116	66	8,335
	80	388	187	8,335
2000	25	191	89	11,800
	80	545	248	11,800

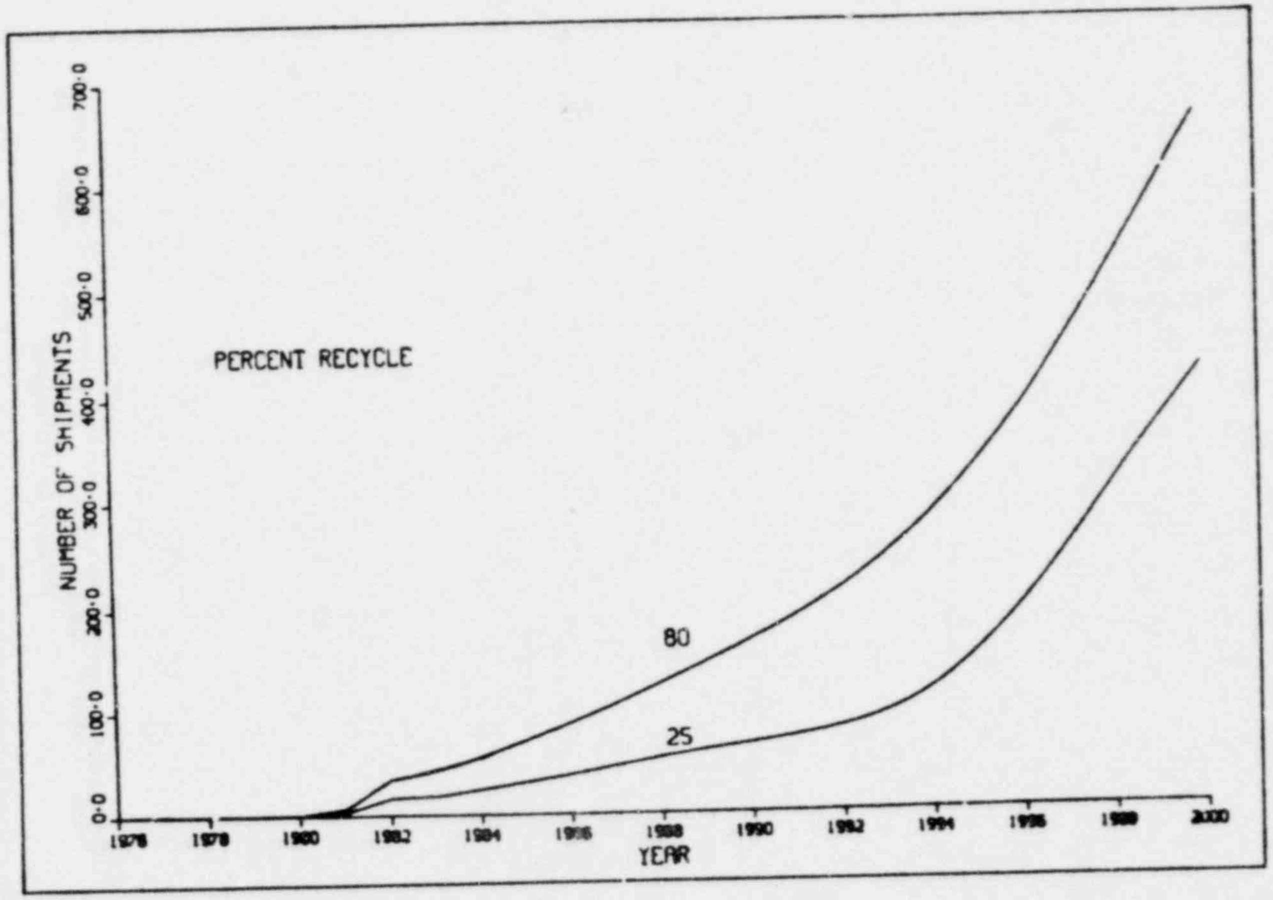


Figure 5. Plutonium Shipments to Fabrication · High Growth Case

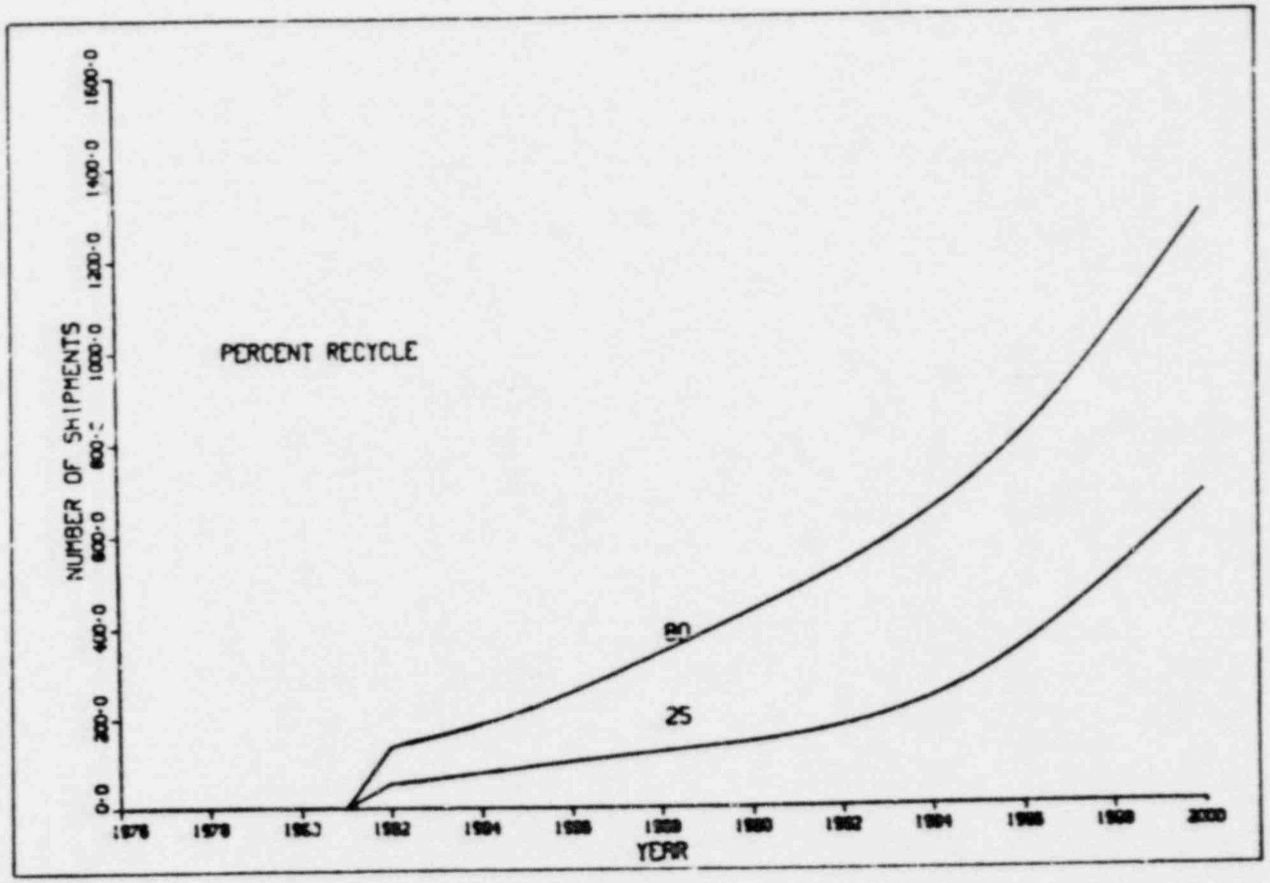


Figure 6. Plutonium Shipments to Reactors - High Growth Case

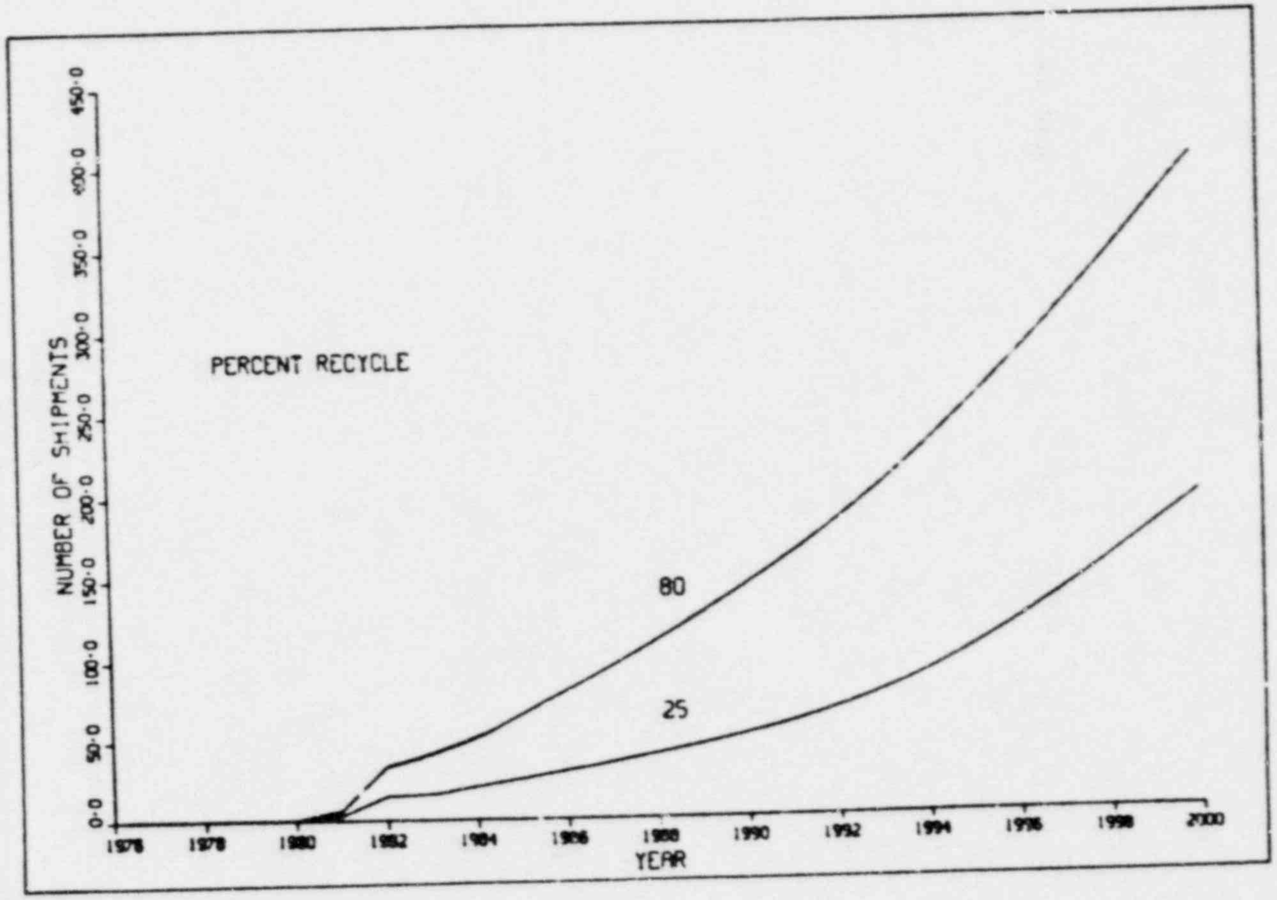


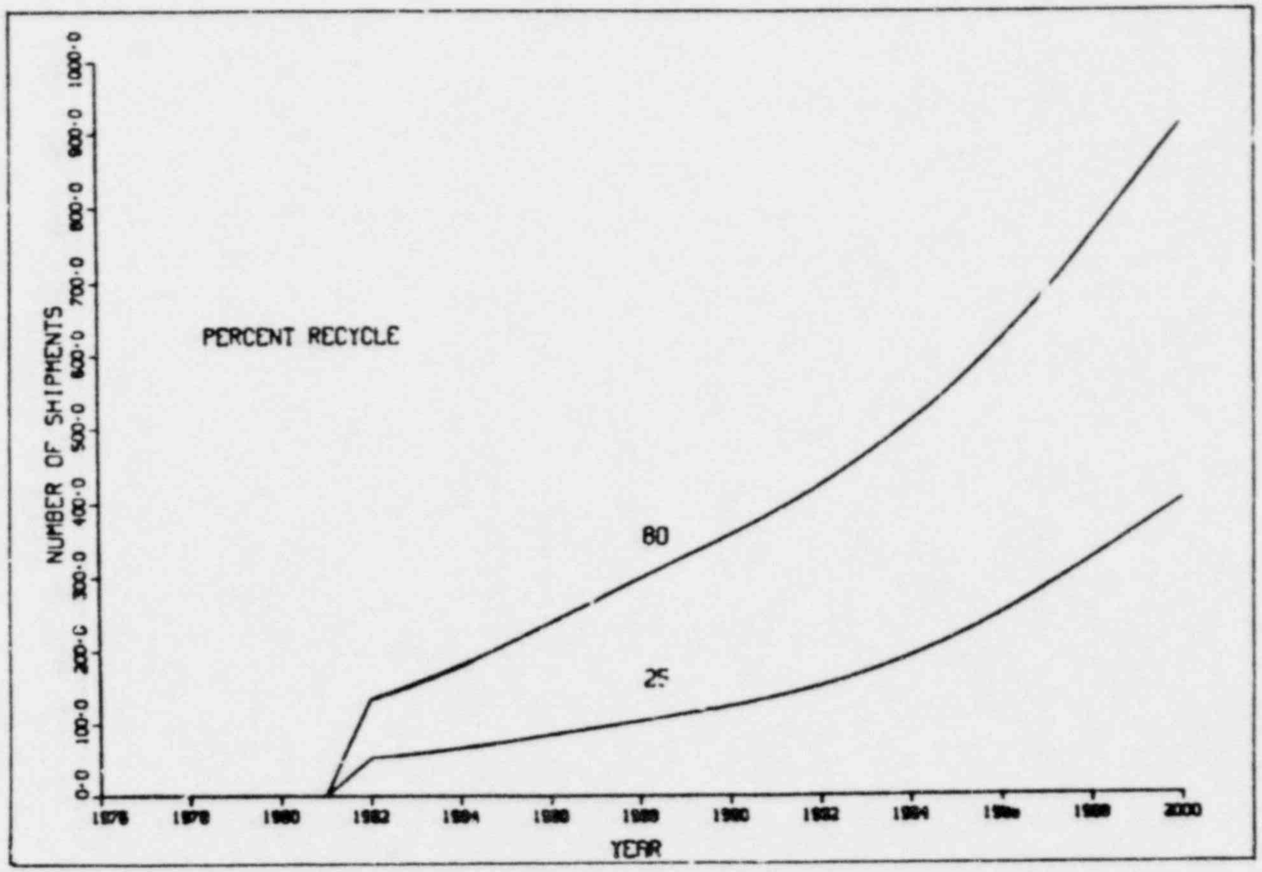
Figure 7. Plutonium Shipments to Fabrication · Median Growth Case

2. Shipments of plutonium fuel to reactors, plotted in Figures 8, 9, and 10

Potential shipments not detailed here are those of excess plutonium to storage sites, if different from the reprocessing location.

For the Fort St. Vrain HTGR, the annual number of shipments is one shipment of HEU to the fuel fabricator and four shipments of fresh fuel to the reactor. The number of spent fuel shipments each year is 47.

SNM shipment requirements depend on the size of the nuclear industry, the structure of the fuel cycle, and the specific transportation modes which are assumed. For example, requirements such that plutonium be shipped only in the form of mixed oxide (20 - 30 wt% Pu) would affect the number of shipments from reprocessors to fabrication depending on the container design and type of carrier. Co-location of reprocessing and fabrication facilities would eliminate this transportation leg within the fuel cycle and reduce the number of SNM shipments. These considerations affect the structure of the transportation network. Given such assumptions, a network simulation model, as described in Reference 11, can be used to predict capital and manpower requirements for a commercial SNM transportation industry. Such an analysis is to be performed at a future date in the physical protection analysis project.[1]



8. Plutonium Shipments to Reactors - Median Growth Case

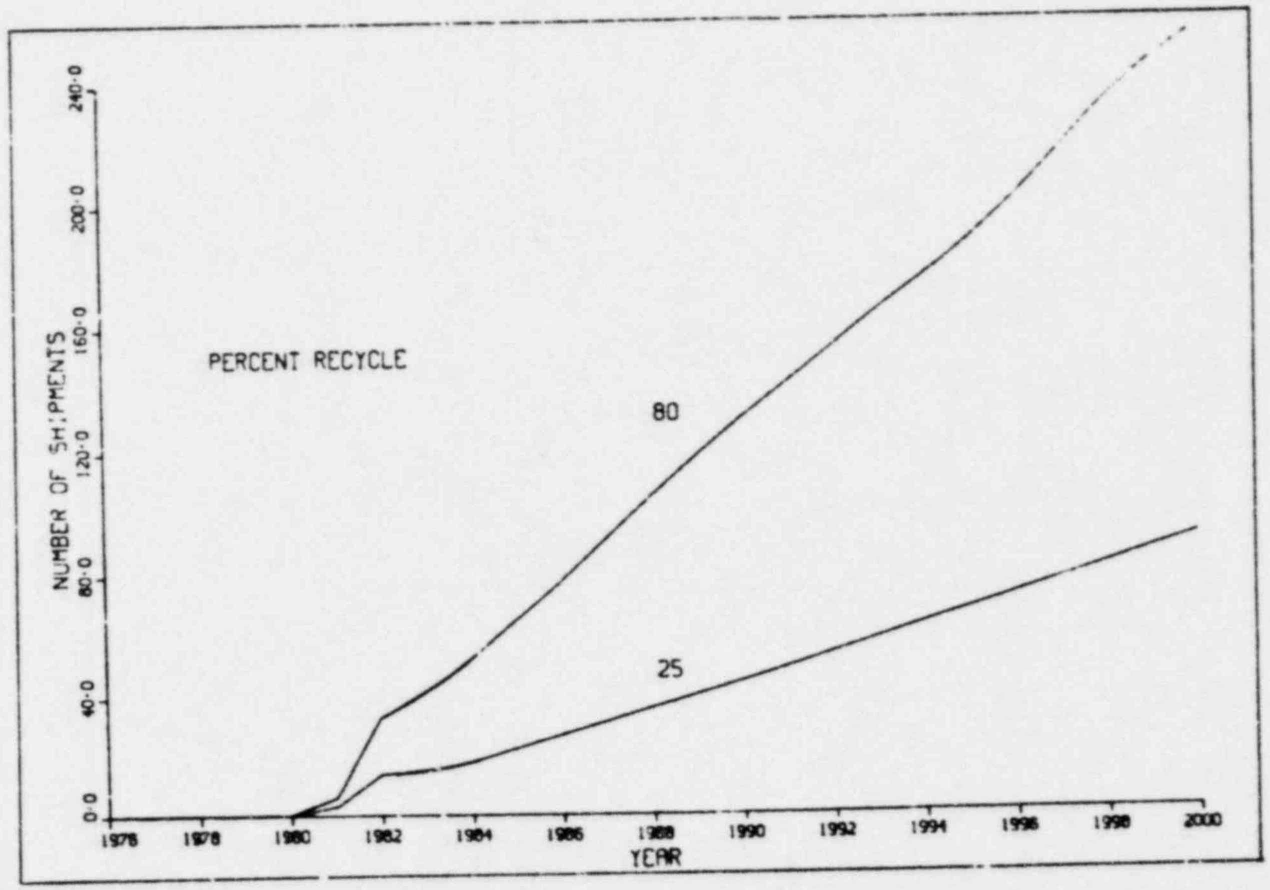


Figure 9. Plutonium Shipments to Fabrication - Low Growth Case

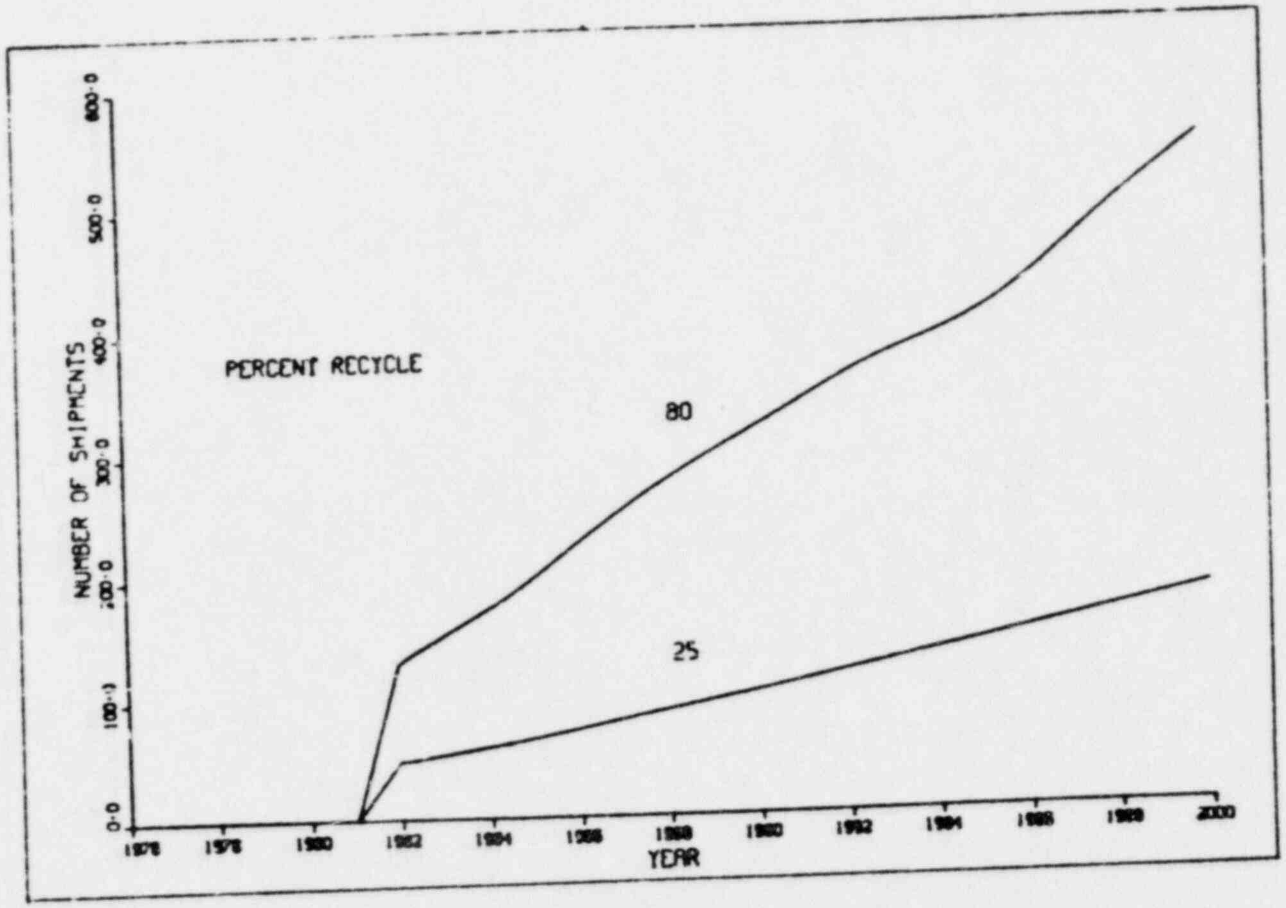


Figure 10. Plutonium Shipments to Reactors - Low Growth Case

APPENDIX

Reactor Commitments as of July 1, 1976

NO.	TYPE	MWE	INITIAL OPERATION	REACTOR NAME	NEAREST CITY	CODE
1	BWR	200	1960	DRESDEN 1	JOLIET, ILL.	DJI
2	PWR	175	1961	YANKEE	NORTH ADAMS, MASS.	NAM
3	PWR	265	1962	INDIAN POINT 1	PEEKSKILL, N.Y.	IPP
4	BWR	70	1962	BIG ROCK POINT	GAYLORD, MICH.	BRP
5	BWR	63	1963	HUMBOLDT BAY	EUREKA, CAL.	HBC
6	PWR	430	1968	SAN ONOFRE 1	OCEANSIDE, CAL.	SOC
7	PWR	575	1968	HADDAM NECK	MIDDLETOWN, CONN.	HCO
8	BWR	48	1969	LA CROSSE	LA CROSSE, WIS.	LCW
9	BWR	610	1969	NINE MILE POINT 1	OSWEGO, N.Y.	NMP
10	BWR	650	1969	OYSTER CREEK	TOMS RIVER, N.J.	TRN
11	PWR	490	1970	GINNA	ALTON, N.Y.	GNY
12	BWR	800	1970	DRESDEN 2	JOLIET, ILL.	DJI
13	PWR	497	1970	POINT BEACH 1	MANITOWOC, WIS.	PBW
14	BWR	652	1970	MILLSTONE 1	NEW LONDON, CONN.	MNL
15	PWR	665	1971	ROBINSON 2	FLORENCE, S.C.	FSC
16	BWR	548	1971	MONTICELLO	ST. CLOUD, MINN.	MSM
17	BWR	800	1971	DRESDEN 3	JOLIET, ILL.	DJI
18	PWR	700	1971	PALISADES	ST. JOSEPH, MICH.	CSJ
19	BWR	800	1972	QUAD CITIES 1	CLINTON, IA.	QCI
20	BWR	800	1972	QUAD CITIES 2	CLINTON, IA.	QCI
21	PWR	497	1972	POINT BEACH 2	MANITOWOC, WIS.	PBW
22	BWR	515	1972	VERMONT YANKEE	GREENFIELD, MASS.	VYV
23	PWR	790	1972	MAINE YANKEE	AUGUSTA, ME.	MYM
24	BWR	670	1972	PILGRIM 1	BOURNE, MASS.	PPM
25	PWR	788	1972	SURRY 1	WILLIAMSBURG, VA.	SWV
26	PWR	666	1972	TURKEY POINT 3	MIAMI, FLA.	TPF
27	PWR	788	1973	SURRY 2	WILLIAMSBURG, VA.	SWV
28	PWR	1100	1973	ZION 1	WAUKEGAN, ILL.	ZWI

NO.	TYPE	MWE	INITIAL OPERATION	REACTOR NAME	NEAREST CITY	CODE
29	PWR	871	1973	OCONEE 1	ANDERSON,S.C.	OAS
30	PWR	666	1973	TURKEY POINT 4	MIAMI,FLA.	TPF
31	PWR	457	1973	FORT CALHOUN 1	BLAIR,NEB.	FCN
32	PWR	530	1973	PRAIRIE ISLAND 1	RED WING,MINN.	PIM
33	PWR	1100	1973	ZION 2	WAUKEGAN,ILL.	ZWI
34	BWR	545	1974	ARNOLD 1	CEDAR RAPIDS,IA.	ACR
35	PWR	540	1974	KEWAUNEE	GREEN BAY,WIS.	KGB
36	PWR	873	1974	INDIAN POINT 2	PEEKSKILL,N.Y.	IPP
37	BWR	1065	1974	PEACH BOTTOM 2	LANCASTER,PA.	FLP
38	BWR	778	1974	COOPER	NEBRASKA CITY,NEB	CNB
39	BWR	1067	1974	BROWNS FERRY 1	DECATUR,ALA.	BFD
40	PWR	871	1974	OCONEE 2	ANDERSON,S.C.	OAS
41	PWR	818	1974	THREE MILE ISLAND 1	HARRISBURG,PA.	TMI
42	PWR	836	1974	ARKANSAS NUCLEAR 1	RUSSELLVILLE,ARK.	ARA
43	PWR	871	1974	OCONEE 3	ANDERSON,S.C.	OAS
44	BWR	1065	1974	PEACH BOTTOM 3	LANCASTER,PA.	FLP
45	PWR	530	1974	PRAIRIE ISLAND 2	RED WING,MINN.	PIM
46	BWR	1067	1975	BROWNS FERRY 2	DECATUR,ALA.	BFD
47	PWR	913	1975	RANCHO SECO 1	LODI,CAL.	RSC
48	PWR	850	1975	CALVERT CLIFFS 1	ANNAPOLIS,MD.	CAM
49	BWR	821	1975	FITZPATRICK	OSWEGO,N.Y.	NMP
50	PWR	1054	1975	COOK 1	ST. JOSEPH,MICH.	CSJ
51	BWR	790	1975	BRUNSWICK 2	WILMINGTON,N.C.	BNC
52	BWR	786	1975	HATCH 1	MC RAE,GA.	HMG
53	PWR	828	1975	MILLSTONE 2	NEW LONDON,CONN.	MNL
54	PWR	852	1976	BEAVER VALLEY 1	ROCHESTER,PA.	BVP
55	PWR	1130	1976	TROJAN	KELSO,WASH.	TPO
56	PWR	965	1976	INDIAN POINT 3	PEEKSKILL,N.Y.	IPP
57	PWR	802	1976	ST. LUCIE 1	OKEECHOBEE,FLA.	SLF
58	HTGR	330	1976	FORT ST. VRAIN	GREELEY,COL.	FSV
59	BWR	1067	1976	BROWNS FERRY 3	DECATUR,ALA.	BFD
60	PWR	855	1976	CRYSTAL RIVER 3	OCALA,FLA.	CRF

NO.	TYPE	MWE	INITIAL OPERATION	REACTOR NAME	NEAREST CITY	CODE
61	PWR	1084	1976	DIABLO CANYON 1	SAN LUIS OBISPO,C	DCC
62	PWR	1090	1976	SALEM 1	DEEPWATER,N.J.	SNJ
63	PWR	850	1977	CALVERT CLIFFS 2	ANNAPOLIS,MD.	CAM
64	BWR	821	1977	BRUNSWICK 1	WILMINGTON,N.C.	BNC
65	PWR	906	1977	DAVIS BESSE 1	FREMONT,OHIO	DBO
66	PWR	934	1977	NORTH ANNA 1	CHARLOTTESVILLE,V	NCV
67	PWR	860	1977	FARLEY 1	DOTHAN,ALA.	FDA
68	PWR	1106	1977	DIABLO CANYON 2	SAN LUIS OBISPO,C	DCC
69	PWR	934	1977	NORTH ANNA 2	CHARLOTTESVILLE,V	NCV
70	PWR	1180	1978	MC GUIRE 1	CHARLOTTE,N.C.	CNC
71	PWR	912	1978	ARKANSAS NUCLEAR 2	RUSSELLVILLE,ARK.	ARA
72	PWR	1054	1978	COOK 2	ST. JOSEPH,MICH.	CSJ
73	PWR	1148	1978	SEQUOYAH 1	CHATTANOOGA,TENN.	SCT
74	PWR	906	1978	THREE MILE ISLAND 2	HARRISBURG,PA.	TMI
75	BWR	1078	1978	LA SALLE 1	LA SALLE,ILL.	LSI
76	PWR	1148	1979	SEQUOYAH 2	CHATTANOOGA,TENN.	SCT
77	PWR	1180	1979	MC GUIRE 2	CHARLOTTE,N.C.	CNC
78	BWR	786	1979	HATCH 2	MC RAE,GA.	HMG
79	PWR	860	1979	FARLEY 2	DOTHAN,ALA.	FDA
80	BWR	820	1979	SHOREHAM 1	PATCHOQUE,N.Y.	SNY
81	PWR	900	1979	SUMMER 1	SUMTER,S.C.	SSS
82	PWR	1115	1979	SALEM 2	DEEPWATER,N.J.	SNJ
83	PWR	1177	1979	WATTS BAR 1	CROSSVILLE,TENN.	WBT
84	BWR	810	1979	ZIMMER 1	CINCINNATI,OHIO	ZCO
85	BWR	1078	1979	LA SALLE 2	LA SALLE,ILL.	LSI
86	BWR	1100	1979	WPPSS 2	PASCO,WASH.	WPW
87	PWR	1150	1980	COMANCHE PEAK 1	HILLSBORO,TEX.	CPT
88	PWR	1177	1980	WATTS BAR 2	CROSSVILLE,TENN.	WBT
89	BWR	1205	1980	PERRY 1	ASHTABULA,OHIO	PAO
90	PWR	1213	1980	BELLEFONTE 1	HUNTSVILLE,ALA.	BHA
91	BWR	1250	1980	GRAND GULF 1	VICKSBURG,MISS.	GGM
92	BWR	1093	1980	FERMI 2	WILLOW RUN,MICH.	FWR

NO.	TYPE	MWE	INITIAL OPERATION	REACTOR NAME	NEAREST CITY	CODE
93	PWR	1120	1980	BYRON 1	ROCKFORD, ILL.	BRI
94	PWR	1250	1980	SOUTH TEXAS 1	VICTORIA, TEX.	STX
95	BWR	1050	1980	SUSQUEHANNA 1	HAZLETON, PA.	SHP
96	PWR	1153	1981	CATAWBA 1	CHARLOTTE, N.C.	CNC
97	BWR	1055	1981	LIMERICK 1	POTTSTOWN, PA.	LPP
98	PWR	1213	1981	BELLEFONTE 2	HUNTSVILLE, ALA.	BHA
99	PWR	1220	1981	WPPSS 1	PASCO, WASH.	WPW
100	PWR	818	1981	MIDLAND 2	MIDLAND, MICH.	MDM
101	PWR	1165	1981	WATERFORD 3	NEW ORLEANS, LA.	WNO
102	PWR	938	1981	NORTH ANNA 3	CHARLOTTESVILLE, V	NCV
103	PWR	852	1981	BEAVER VALLEY 2	ROCHESTER, PA.	BVP
104	PWR	1200	1981	SEABROOK 1	PORTSMOUTH, N.H.	SNH
105	BWR	950	1981	CLINTON 1	CLINTON, IA.	QCI
106	PWR	802	1981	ST. LUCIE 2	OKEECHOBEE, FLA.	SLF
107	PWR	1120	1981	BRAIDWOOD 1	JOLIET, ILL.	DJI
108	BWR	840	1981	RIVER BEND 1	BATON ROUGE, LA.	BRL
109	PWR	1150	1981	CALLAWAY 1	COLUMBIA, MO.	CMO
110	PWR	1100	1981	SAN ONOFRE 2	OCEANSIDE, CAL.	SOC
111	PWR	938	1981	NORTH ANNA 4	CHARLOTTESVILLE, V	NCV
112	PWR	1150	1982	COMANCHE PEAK 2	HILLSBORO, TEX.	CPT
113	PWR	1153	1982	CATAWBA 2	CHARLOTTE, N.C.	CNC
114	PWR	1240	1982	WPPSS 3	ABERDEEN, WASH.	WAW
115	PWR	1250	1982	SOUTH TEXAS 2	VICTORIA, TEX.	STX
116	PWR	492	1982	MIDLAND 1	MIDLAND, MICH.	MDM
117	PWR	1220	1982	WPPSS 4	PASCO, WASH.	WPW
118	PWR	1150	1982	WOLF CREEK 1	EMPORIA, KAN.	WCK
119	BWR	1205	1982	PERRY 2	ASHTABULA, OHIO	PAO
120	PWR	1150	1982	MILLSTONE 3	NEW LONDON, CONN.	MNL
121	PWR	1270	1982	PALO VERDE 1	PHOENIX, ARIZ.	PVA
122	BWR	1050	1982	SUSQUEHANNA 2	HAZLETON, PA.	SHP
123	PWR	1168	1982	FORKED RIVER 1	TOMS RIVER, N.J.	TRN
124	BWR	1055	1982	LIMERICK 2	POTTSTOWN, PA.	LPP

NO.	TYPE	MWE	INITIAL OPERATION	REACTOR NAME	NEAREST CITY	CODE
125	PWR	1130	1982	MARBLE HILL 1	MADISON,IND.	MHT
126	BWR	1100	1982	NINE MILE POINT 2	OSWEGO,N.Y.	NMP
127	PWR	1120	1982	BYRON 2	ROCKFORD,ILL.	BRI
128	PWR	1120	1982	BRAIDWOOD 2	JOLIET,ILL.	DJI
129	BWR	1180	1982	PILGRIM 2	BOURNE,MASS.	PPM
130	BWR	1067	1982	HOPE CREEK 1	DEEPWATER,N.J.	SNJ
131	PWR	1100	1983	SAN ONOFRE 3	OCEANSIDE,CAL.	SOC
132	PWR	1150	1983	FORT CALHOUN 2	BLAIR,NEB.	FCN
133	PWR	1280	1983	PERKINS 1	STATESVILLE,N.C.	PSN
134	BWR	1233	1983	HARTSVILLE A1	NASHVILLE,TENN.	HNT
135	PWR	1100	1983	VOGTLE 1	AUGUSTA, GA.	AUG
136	PWR	1150	1983	CALLAWAY 2	COLUMBIA,MO.	CMO
137	PWR	900	1983	KOSHKONONG 1	JANESVILLE,WIS.	KKW
138	PWR	906	1983	DAVIS BESSE 2	FREMONT,OHIO	DBO
139	PWR	1150	1983	JAMESPORT 1	RIVERHEAD,N.Y.	JNY
140	BWR	1288	1983	SKAGIT 1	BELLINGHAM,WASH.	SBW
141	BWR	1150	1983	BLACK FOX 1	TULSA,OK.	BFO
142	BWR	1233	1983	HARTSVILLE B1	NASHVILLE,TENN.	HNT
143	BWR	940	1983	RIVER BEND 2	BATON ROUGE,LA.	BRL
144	PWR	1200	1983	SEABROOK 2	PORTSMOUTH,N.H.	SNH
145	PWR	1280	1984	CHEROKEE 1	SPARTANBURG,S.C.	CHE
146	BWR	1233	1984	HARTSVILLE A2	NASHVILLE,TENN.	HNT
147	PWR	1288	1984	GREENWOOD 2	PORT HURON,MICH.	GPH
148	PWR	900	1984	HARRIS 1	RALEIGH,N.C.	HNC
149	PWR	1150	1984	STERLING	OSWEGO,N.Y.	NMP
150	PWR	1240	1984	WPPSS 5	ABERDEEN,WASH.	WAW
151	PWR	1100	1984	VOGTLE 2	AUGUSTA, GA.	AUG
152	BWR	1233	1984	PHIPPS BEND 1	KINGSPORT,TENN.	PBT
153	PWR	1270	1984	PALO VERDE 2	PHOENIX,ARIZ.	PVA
154	BWR	1067	1984	HOPE CREEK 2	DEEPWATER,N.J.	SNJ
155	BWR	950	1984	CLINTON 2	CLINTON,IA.	QCI
156	BWR	1233	1984	HARTSVILLE B2	NASHVILLE,TENN.	HNT

NO.	TYPE	MWE	INITIAL OPERATION	REACTOR NAME	NEAREST CITY	CODE
157	PWR	1150	1984	MARBLE HILL 2	MADISON,IND.	MHI
158	PWR	900	1984	KOSHKONONG 2	JANESVILLE,WIS.	KKW
159	BWR	1250	1984	GRAND GULF 2	VICKSBURG,MISS.	GGM
160	PWR	1150	1984	CHARLESTOWN 1	NEWPORT,R.I.	CRI
161	PWR	1200	1984	GREENE COUNTY	CATSKILL,N.Y.	GCC
162	PWR	1280	1985	PERKINS 2	STATESVILLE,N.C.	PSN
163	PWR	906	1985	DAVIS BESSE 3	FREMONT,OHIO	DBO
164	PWR	1150	1985	SOUTH DADE 1	MIAMI,FLA.	TPF
165	BWR	1300	1985	YELLOW CREEK 1	CORINTH,MISS.	YCM
166	BWR	1178	1985	DOUGLAS POINT 1	FREDERICKSBURG,MD	FDP
167	PWR	950	1985	SUNDESERT 1	BLYTHE,CA.	ARZ
168	BWR	1233	1985	PHIPPS BEND 2	KINGSPORT,TENN.	PBT
169	PWR	1150	1985	TYRONE 1	NELSON,WIS.	TNW
170	PWR	1150	1985	ATLANTIC 1	ATLANTIC CITY,N.J	ANJ
171	PWR	1150	1985	JAMESPORT 2	RIVERHEAD,N.Y.	JNY
172	PWR	1150	1985	SOUTH DADE 2	MIAMI,FLA.	TPF
173	PWR	1300	1985	CENTRAL IOWA	DES MOINES, IOWA	DSM
174	PWR	1260	1985	PEBBLE SPRINGS 1	PASCO,WASH.	WPW
175	BWR	1150	1985	BLACK FOX 2	TULSA,OK.	BFO
176	PWR	1280	1986	CHEROKEE 2	SPARTANBURG,S.C.	CHE
177	BWR	1150	1986	ZIMMER 2	CINCINNATI,OHIO	ZCO
178	BWR	1300	1986	YELLOW CREEK 2	CORINTH,MISS.	YCM
179	PWR	1208	1986	GREENWOOD 3	PORT HURON,MICH.	GPH
180	PWR	900	1986	HARRIS 2	RALEIGH,N.C.	HN3
181	BWR	1150	1986	MONTAGUE 1	GREENFIELD,MASS.	VYV
182	PWR	900	1986	SURRY 3	WILLIAMSBURG,VA.	SWV
183	PWR	1270	1986	PALO VERDE 3	PHOENIX,ARIZ.	PVA
184	PWR	1150	1986	CHARLESTOWN 2	NEWPORT,R.I.	CRI
185	BWR	1288	1986	SKAGIT 2	BELLINGHAM,WASH.	SBW
186	PWR	1280	1987	PERKINS 3	STATESVILLE,N.C.	PSN
187	PWR	1150	1987	SR 1	LUMBERTON,N.C.	CLN
188	BWR	1178	1987	DOUGLAS POINT 2	FREDERICKSBURG,MD	FDP

NO.	TYPE	MWE	INITIAL OPERATION	REACTOR NAME	NEAREST CITY	CODE
189	PWR	900	1987	SURRY 4	WILLIAMSBURG,VA.	SWV
190	PWR	1150	1987	ATLANTIC 2	ATLANTIC CITY,N.J	ANJ
191	PWR	1280	1988	CHEROKEE 3	SPARTANBURG,S.C.	CHE
192	BWR	1150	1988	MONTAGUE 2	GREENFIELD,MASS.	VYV
193	PWR	900	1988	HARRIS 4	RALEIGH,N.C.	HNC
194	PWR	950	1988	SUNDESERT 2	BLYTHE,CA.	ARZ
195	PWR	1260	1988	PEBBLE SPRINGS 2	PASCO,WASH.	WPW
196	PWR	1150	1989	SR 2	LUMBERTON,N.C.	CLN
197	PWR	900	1990	HARRIS 3	RALEIGH,N.C.	HNC

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6 / 27 / 77