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Greater-Than-Class C Low-Level Radioactive Waste Characterization

Appendix A-2: Timing of Greater-Than-Class C Low-Level Radioactive Waste from Nuclear Power Plants

Greater-Than-Class C Low-Level Waste Management Program

September 1994

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ABSTRACT

Planning for the storage or disposal of greater-than-Class C low-level radioactive waste (GTCC LLW) requires characterization of that waste. Timing, or the date the waste will require storage or disposal, is an integral aspect of that planning. The majority of GTCC LLW is generated by nuclear power plants, and the length of time a reactor remains operational directly affects the amount of GTCC waste expected from that reactor. This report uses data from existing literature to develop high, base, and low case estimates for the number of plants expected to experience (a) early shutdown, (b) 40-year operation, or (c) life extension to 60-year operation.

The discussion includes possible effects of advanced light water reactor technology on future GTCC LLW generation. However, the main focus of this study is timing for shutdown of current technology reactors that are under construction or operating.

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TABLES

ACRONYMS

BWR	boiling water reactor
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EIA	Energy Information Administration
GE	General Electric
GTCC	greater-than-Class C
GWe	gigawatt-electric
LLW	low-level radioactive waste
MWe	megawatt-electric
NRC	U.S. Nuclear Regulatory Commission
O&M	operating and maintenance
PWR	pressurized water reactor

Appendix A-2: Timing of Greater-Than-Class C Low-Level Radioactive Waste from Nuclear Power Plants

1. INTRODUCTION

1.1 Purpose

This appendix of DOE/LLW-114 Revision 1[1] describes various factors that influence the time at which commercial nuclear utility waste becomes available for disposal. This information is part of an overall effort sponsored by the U.S. Department of Energy (DOE) through the Greater-Than-Class C Low-Level Waste Program to estimate expected volumes and radionuclide activities for commercially generated greater-than-Class C (GTCC) low-level radioactive waste (LLW).

A significant portion GTCC LLW in the U.S. will be generated by commercial nuclear power plants. Each year, operation of a nuclear power plant produces a small amount of GTCC LLW. At decommissioning, however, components within the reactor system must be disposed of according to their activity level. Decommissioning will likely yield a larger volume of GTCC LLW than will reactor operation. The total volume of waste that could be classified as GTCC is directly related to the length of time that reactor structural components have been exposed to neutron flux during plant operations. During plant operations, the metal alloys in these components will become radioactive as a result of neutron absorption. The total volume of GTCC LLW produced by each power plant is the sum of the GTCC LLW operating waste and decommissioning waste volumes. Both of these waste volumes are influenced by the operating lifetime of the power plant. Therefore, to project the volume of GTCC LLW from nuclear utilities, it is necessary to estimate the expected total operating life of each plant.

1.2 Scope

This report presents estimates of the operating lifetime of both operating and planned nuclear power plants (from 1993 to 60 years in the future) to project when commercially generated GTCC LLW could become available for disposal. Forecasts of nuclear power plant capacity and generation over the long term have been selected as the principal tool for this analysis, and are consistent with efforts by DOE's Office of Civilian Radioactive Waste Management to estimate waste generation.[2] In this report, the most current projections by the DOE Energy Information Administration (EIA), as stated in the *Annual Energy Outlook 1993*,[3] have been used as the primary basis to develop timing assumptions through the year 2010. Information from the 1991 *National Energy Strategy*,[4] Reference 2, and EIA's *World Nuclear Capacity and Fuel Cycle Requirements 1992*[5] reports have been used to make projections through the year 2030.

The nuclear power plants studied include all operating commercial pressurized water reactor (PWR) and boiling water reactor (BWR) plants in the U.S. Projections of reactor operating lifetime extend until the last light water reactor built under the current technology is shut down. Some of these nuclear power plants are still under construction or have been delayed indefinitely.

Projected power demand beyond 2010 will require the addition of many power plants. Advanced technology nuclear power plants and new technology nuclear power plants (type yet to be determined) will be required to meet expected energy demands. This aspect is included in this study to address the potential impact on GTCC operational waste volume from these new waste generators.

This study identifies the number of nuclear power plant waste generators and projects lifetimes for the reactors. These probable reactor lifetimes are used in Reference 1 together with waste generation rates to estimate the volume of waste generated by reactor operations and at decommissioning.

Many uncertainties exist concerning the lifetime of operating and planned reactors. Some reactors have been shut down prematurely, and other reactor licenses may or may not be submitted for a 20-year operating life extension. In order to reasonably bound the range of possible operating lifetimes, this study evaluates all available information and then projects reactor operating lifetimes for high, base, and low cases.

Section 2 discusses background issues such as plant operating lifetime, current operating licenses, and possible plant life extension. Section 3 offers information on nuclear utility waste generators, including current and advanced light water reactor technology. Section 4 presents the uncertainties associated with predicting reactor lifetimes, such as operating and maintenance costs, decommissioning costs, plant extensions, and premature shutdown. Section 4 concludes by projecting high, base, and low case estimates for reactor lifetime. Section 5 summarizes the study and discusses several conclusions, and Section 6 lists the references used in this study.

2. BACKGROUND

2.1 Plant Operating Lifetime

Historically, the perception was that nuclear power generating plants were cheap to operate. Therefore, they were expected to operate cost-effectively until the end of their physical lives. The physical life for a nuclear power plant was thought to be limited only by failure of a prohibitively expensive component, such as the containment building or the reactor vessel (which has a design life of well over 40 years). In theory, then, conditions within the operating license should be the primary factor that limits the lifetime of a nuclear power plant. Nuclear units whose operational life has ended for reasons other than license expiration would be considered prematurely shut down. The following two sections discuss two ways that the term of an operating license could be extended: license renewal, which would typically provide 2 to 5 years of additional operations to compensate for construction time, and plant life extension, which extends licenses 20 years beyond the current expiration date.

2.2 Current Operating Licenses

Before 1982, utilities were issued a license to operate for 40 years from the date the construction permit was issued. Depending on plant size, 2 to 5 years of that time span could have been spent in construction, leaving only 35 to 38 years of actual operation before the operating license expired. More than half of the 109 nuclear power generating units operating today were licensed in this manner.

In 1982, the U.S. Nuclear Regulatory Commission (NRC) began issuing operating licenses that defined the 40-year term as starting when construction activities were completed (10 CFR 50.51). With this revised process, the plants could operate commercially for a full 40 years with no loss of time for construction. A license renewal process was offered to the utility owners who had received their licenses before 1982. Renewal would adjust the expiration date of the existing license to allow 40 years of commercial operation after construction. Many plants in that category have submitted applications for renewal. Table 1 lists the projected licensed lifetimes of current operating plants (plus some that are under construction or delayed), based on 40 years of commercial operation, including license renewal.

2.3 Plant Life Extension

In 1991, the NRC established a rule (10 CFR 54) that allowed an applicant to extend the operating license of a nuclear power plant by 20 years. An extension would permit a nuclear power plant to operate commercially for up to 60 years before retirement and decommissioning. For example, Comanche Peak Unit 2, which achieved commercial status in 1993, will reach the 40-year license expiration in 2033. With an extension, operation could continue until 2053 before decommissioning.

Table 1. U.S. nuclear power plants operating, under construction, or on order as of December 1992.

No.	Reactor	State	MWt[a]	MWe[b]	Type	License start date[b]	Commercial operation start date[b]	License expiration date[b,c]
1	A W Vogtle 1	GA	3411	1100	PWR (W)	1987	6/87	2027
2	A W Vogtle 2	GA	3411	1097	PWR (W)	1989	5/89	2029
3	AK Nuclear 1	AK	2568	836	PWR (B&W)	1974	12/74	2014
4	AK Nuclear 2	AK	2815	858	PWR (CE)	1978	3/80	2018
5	Beaver Valley 1	PA	2653	810	PWR (W)	1976	10/76	2016
6	Beaver Valley 2	PA	2652	833	PWR (W)	1987	11/87	2027
7	Bellefonte 1	AL	3620	1213	PWR (B&W)	—[d]		—
8	Bellefonte 2	AL	3620	1213	PWR (B&W)	—[d]		—
9	Big Rock Pt	MI	240	67	BWR (GE)	1962	3/63	2002
10	Braidwood 1	IL	3411	1120	PWR (W)	1987	7/88	2027
11	Braidwood 2	IL	3411	1120	PWR (W)	1988	10/88	2028
12	Browns Ferry 1	AL	3293	1065	BWR (GE)	1973	8/74	2013
13	Browns Ferry 2	AL	3293	1065	BWR (GE)	1974	3/75	2014
14	Browns Ferry 3	AL	3293	1065	BWR (GE)	1976	3/77	2016
15	Brunswick 1	NC	2416	767	BWR (GE)	1976	3/77	2016
16	Brunswick 2	NC	2436	754	BWR (GE)	1975	11/75	2015
17	Byron 1	IL	3411	1105	PWR (W)	1985	9/85	2025
18	Byron 2	IL	3411	1105	PWR (W)	1987	8/87	2027
19	Callaway	MO	3565	1125	PWR (W)	1984	4/85	2024
20	Calvert Cliffs 1	MY	2700	825	PWR (CE)	1975	5/75	2015
21	Calvert Cliffs 2	MY	2700	825	PWR (CE)	1976	4/77	2016
22	Catawba 1	SC	3411	1129	PWR (W)	1985	6/85	2025
23	Catawba 2	SC	3411	1129	PWR (W)	1986	8/86	2026
24	Clinton 1	IL	2894	930	BWR (GE)	1987	4/87	2027
25	Comanche Peak 1	TX	3411	1150	PWR (W)	1990	8/90	2030
26	Comanche Peak 2	TX	3411	1150	PWR (W)	1993	8/93	2033
27	Cooper	NE	2381	764	BWR (GE)	1974	7/74	2014
28	Crystal River 3	FL	2544	821	PWR (B&W)	1977	3/77	2017
29	Davis-Besse 1	OH	2772	877	PWR (B&W)	1977	7/78	2017
30	Diablo Canyon 1	CA	3338	1073	PWR (W)	1984	5/85	2024
31	Diablo Canyon 2	CA	3411	1087	PWR (W)	1985	3/86	2025
32	Donald Cook 1	MI	3250	1020	PWR (W)	1975	8/75	2015

Table 1. (continued).

No.	Reactor	State	MWt[a]	MWe[b]	Type	License start date[b]	Commercial operation start date[b]	License expiration date[b,c]
33	Donald Cook 2	MI	3411	1060	PWR (W)	1978	7/78	2018
34	Dresden 2	IL	2527	772	BWR (GE)	1970	6/70	2010
35	Dresden 3	IL	2527	773	BWR (GE)	1971	11/71	2011
36	Duane Arnold	IA	1658	538	BWR (GE)	1974	2/75	2014
37	Edwin Hatch 1	GA	2436	741	BWR (GE)	1974	12/75	2014
38	Edwin Hatch 2	GA	2436	761	BWR (GE)	1978	9/79	2018
39	Fermi 2	MI	3293	1075	BWR (GE)	1985	1/88	2025
40	Fort Calhoun 1	NE	1500	478	PWR (CE)	1973	9/73	2013
41	Grand Gulf 1	MS	3833	1142	BWR (GE)	1984	7/85	2024
42	Haddam Neck	CN	1825	590	PWR (W)	1967	1/68	2007
43	Hope Creek 1	NJ	3293	1031	BWR (GE)	1986	12/86	2026
44	Indian Pt 2	NY	2758	970	PWR (W)	1973	8/74	2013
45	Indian Pt 3	NY	3025	965	PWR (W)	1976	8/76	2016
46	J M Farley 1	AL	2652	814	PWR (W)	1977	12/77	2017
47	J M Farley 2	AL	2652	824	PWR (W)	1981	7/81	2021
48	James A Fitzpatrick	NY	2436	757	BWR (GE)	1975	7/75	2015
49	Kewaunee	WI	1650	503	PWR (W)	1974	6/74	2014
50	La Salle 1	IL	3323	1036	BWR (GE)	1982	1/84	2022
51	La Salle 2	IL	3323	1036	BWR (GE)	1984	10/84	2024
52	Limerick 1	PA	3293	1055	BWR (GE)	1985	2/86	2025
53	Limerick 2	PA	3293	1055	BWR (GE)	1989	1/90	2029
54	Maine Yankee	ME	2630	840	PWR (CE)	1972	12/72	2012
55	Millstone 1	CN	2011	660	BWR (GE)	1970	3/71	2010
56	Millstone 2	CN	2700	862	PWR (CE)	1975	12/75	2015
57	Millstone 3	CN	3579	1146	PWR (W)	1986	4/86	2026
58	Monticello	MN	1670	536	BWR (GE)	1971	6/71	2011
59	Nine Mile Pt 1	NY	1850	610	BWR (GE)	1969	12/69	2009
60	Nine Mile Pt 2	NY	3323	1080	BWR (GE)	1987	4/88	2027
61	North Anna 1	VA	2893	911	PWR (W)	1978	6/78	2018
62	North Anna 2	VA	2893	909	PWR (W)	1980	12/80	2020
63	Oconee 1	SC	2568	846	PWR (B&W)	1973	7/73	2013

Table 1. (continued).

No.	Reactor	State	MWt[a]	MWe[b]	Type	License start date[b]	Commercial operation start date[b]	License expiration date[b,c]
64	Oconee 2	SC	2566	846	PWR (B&W)	1973	9/74	2013
65	Oconee 3	SC	2568	846	PWR (B&W)	1974	12/74	2014
66	Oyster Cr 1	NJ	1930	610	BWR (GE)	1969	12/69	2009
67	Palisades	MI	2530	768	PWR (CE)	1971	12/71	2011
68	Palo Verde 1	AZ	3817	1221	PWR (CE)	1985	1/86	2025
69	Palo Verde 2	AZ	3817	1221	PWR (CE)	1986	9/86	2026
70	Palo Verde 3	AZ	3817	1221	PWR (CE)	1987	1/88	2027
71	Peach Bottom 2	PA	3293	1100	BWR (GE)	1974	7/74	2014
72	Peach Bottom 3	PA	3293	1100	BWR (GE)	1974	12/74	2014
73	Perry 1	OH	3579	1205	BWR (GE)	1986	11/87	2026
74	Perry 2	OH	3679	1205	BWR (GE)	—[d]	—	—
75	Pilgrim 1	MA	1998	670	BWR (GE)	1972	12/72	2012
76	Point Beach 1	WI	1518	485	PWR (W)	1970	12/70	2010
77	Point Beach 2	WI	1518	485	PWR (W)	1972	10/72	2012
78	Prairie Island 1	MN	1650	503	PWR (W)	1973	12/73	2013
79	Prairie Island 2	MN	1650	500	PWR (W)	1974	12/74	2014
80	Quad Cities 1	IL	2511	769	BWR (GE)	1972	2/73	2012
81	Quad Cities 2	IL	2511	769	BWR (GE)	1972	3/73	2012
82	River Bend 1	LA	2894	936	BWR (GE)	1985	6/86	2025
83	Robert E. Ginna	NY	1520	470	PWR (W)	1969	7/70	2009
84	Robinson 2	SC	2300	683	PWR (W)	1970	3/71	2010
85	Salem 1	NJ	3411	1106	PWR (W)	1976	6/77	2016
86	Salem 2	NJ	3411	1106	PWR (W)	1981	10/81	2021
87	San Onofre 2	CA	3390	1070	PWR (CE)	1982	8/83	2022
88	San Onofre 3	CA	3390	1080	PWR (CE)	1983	4/84	2023
89	Seabrook	NH	3411	1150	PWR (W)	1990	7/90	2030
90	Sequoyah 1	TN	3411	1148	PWR (W)	1980	7/81	2020
91	Sequoyah 2	TN	3411	1148	PWR (W)	1981	6/82	2021
92	Shearon Harris	NC	2775	860	PWR (W)	1987	5/87	2027
93	South Texas 1	TX	3817	1250	PWR (W)	1988	8/88	2028
94	South Texas 2	TX	3817	1250	PWR (W)	1989	6/89	2029

Table 1. (continued).

No.	Reactor	State	MWt[a]	MWe[b]	Type	License start date[b]	Commercial operation start date[b]	License expiration date[b,c]
95	St. Lucie 1	FL	2700	839	PWR (CE)	1976	12/76	2016
96	St. Lucie 2	FL	2700	839	PWR (CE)	1983	8/83	2023
97	Surry 1	VA	2441	781	PWR (W)	1972	12/72	2012
98	Surry 2	VA	2441	781	PWR (W)	1973	5/73	2013
99	Susquehanna 1	PA	3293	1032	BWR (GE)	1982	6/83	2022
100	Susquehanna 2	PA	3293	1038	BWR (GE)	1984	2/85	2024
101	Three Mile Island 1	PA	2535	786	PWR (B&W)	1974	9/74	2014
102	Turkey Pt. 3	FL	2200	666	PWR (W)	1972	12/72	2012
103	Turkey Pt. 4	FL	2200	666	PWR (W)	1973	9/73	2013
104	Vermont Yankee	VT	1593	504	BWR (GE)	1972	11/72	2012
105	Virgil C. Summer	SC	2775	885	PWR (W)	1982	1/84	2022
106	W B McGuire 1	NC	3411	1129	PWR (W)	1981	8/81	2021
107	W B McGuire 2	NC	3411	1129	PWR (W)	1983	3/84	2023
108	Waterford 3	LA	3410	1075	PWR (CE)	1985	9/85	2025
109	Watts Bar 1	TN	3411	1177	PWR (W)	—[e]	—	—
110	Watts Bar 2	TN	3411	1177	PWR (W)	—[d]	—	—
111	WNP 1	WA	3780	1259	PWR (B&W)	—[d]	—	—
112	WNP 2	WA	3323	1100	BWR (GE)	1984	12/84	2024
113	WNP 3	WA	3800	1240	PWR (B&W)	—[d]	—	—
114	Wolf Creek	KA	3411	1135	PWR (W)	1985	9/85	2025
115	Zion 1	IL	3250	1040	PWR (W)	1973	12/73	2013
116	Zion 2	IL	3250	1040	PWR (W)	1973	9/74	2013

a. See "Nuclear Engineering International, November 1989 Supplement," in the *World Nuclear Industry Handbook*.[6]

b. See "World List of Nuclear Power Plants," in *Nuclear News*.[7]

c. Assumes renewal of licenses that were issued before 1982, but does not reflect any license extension. Delivery of GTCC LLW would occur three years after this date.

d. Construction postponed indefinitely.

e. Watts Bar 1 has not started operation as of the publication of this report (September 1994), although the reference document estimated a commercial operation start date of June 1994, which would have resulted in a license expiration date of 2034.

The National Energy Strategy, published in 1991, projected that 70% of operating nuclear power generating units would be granted life extensions (Reference 4). Two utilities submitted applications in 1992 to begin the license extension process (for the Yankee-Rowe[a] and Monticello reactors) and later retracted them because of "the endless controversy over high- and low-level radioactive waste disposal, concern about controlling operating and maintenance (O&M) costs, and uncertainty over NRC regulation."[8] At this date, no applications are on file for license extension. In December 1992, the NRC began a review of the existing license extension process.[9]

A utility's decision to extend the life of an operating nuclear plant will depend heavily on refurbishment costs to prepare a unit for the extra years, in addition to the O&M costs. James Hewlett, a leading economic expert with the EIA, says "the ultimate economics of nuclear plant life-extension, therefore, will depend upon the extent of plant aging effects and future changes in NRC regulations."[10]

a. In fact, Yankee Atomic Electric Co. not only decided against life extension for the Yankee Rowe reactor, but opted to shut down the reactor prematurely (before its 40-year license expiration).

3. NUCLEAR UTILITY WASTE GENERATORS

3.1 Current Light Water Reactor Technology

No utility has placed an order for a new light water reactor, either a BWR or PWR, in the U.S. since 1978. Many units ordered since 1971 have been canceled. The most reasonable assumption is that no new nuclear generating units, using the current technology, will be added to the current operating list beyond those under construction.[11]

3.1.1 Operating Plants

There are currently 109 nuclear power plants, 37 BWRs and 72 PWRs, operating in this country. Forty-six units will reach the end of their 40-year life by 2015. Because many of these plants have an electrical generating capacity of less than 700 megawatts electric (MWe), it may not be economically feasible to extend their lives past the end of the operating licenses. They have a limited ability to produce revenue and may not be able to offset the refurbishment costs required for any extended operation. These nuclear power plants are assumed to comprise the majority of plants either experiencing early shutdown or achieving only a 40-year lifetime in the base and low cases discussed in Section 4.2.

3.1.2 Under Construction

Six plants, listed in Table 1 without "start" dates, are actively under construction or indefinitely delayed. Watts Bar Unit 1, still under construction, has been identified as the next most likely plant to achieve operating status. In 1993, Comanche Peak 2 was placed in service, which could extend the last date for reactor shutdown to 2053, assuming a 20-year life extension. When additional plants under construction (e.g., Watts Bar 1) are issued an operating license, the period for shutdown of the last current technology reactor will be extended beyond 2054, assuming life extension for the newest unit.

3.2 Advanced Light Water Reactor Technology

As a result of the Clinton Administration's energy goals and budget deficit reduction efforts, the review of advanced reactor designs has been narrowed to two designs. The Westinghouse AP600, a 600-MWe reactor with passive safety systems, represents the potential PWR technology for additional capacity beyond the year 2000. The General Electric (GE) 1,300-MWe advanced BWR, currently under construction in Japan, represents the other advanced design for further review by the NRC. Government funding for "first-of-a-kind engineering" has been identified in the FY 1993 budget to ensure that these designs are available within the next several years (Reference 3).

Significantly less radiological waste is expected from these new reactor designs. Potentially, fewer core components will be classified as GTCC LLW at decommissioning as a result of a much lower neutron leakage from the core. Westinghouse predicts that vessel fluence will be about 2×10^{19} n/cm^2 for a 60-year design life, compared with a typical 5×10^{19} n/cm^2 for a 40-year life using current technology.[12] Therefore, Westinghouse core barrels, which were estimated to be borderline GTCC LLW for the current technology, will probably be Class C in the advanced reactor, even with a 60-year life. Radiological waste from operating cycles will also decrease with advanced waste systems included in the GE design and similar improvements in the Westinghouse design (Reference 12).

3.3 Waste Generation Beyond 1993

The focus of this study is to identify the number of generators producing nuclear power plant waste and to project reactor lifetimes. Waste generation rates for currently operating reactors are estimated in Appendix A-3 of Reference 1.

3.3.1 Current Technology

Six PWR units, in addition to the Watts Bar Unit 1 discussed previously, are identified in Table 1 as potential future waste generators. The operational dates for these units are predicted in the Energy Information Administration's *Supplement to the Annual Energy Outlook 1993*.[13] Based on that prediction, only four or five of the seven units will be placed in service and are included in this study. Section 4 of this report further details the projected schedules for these units.

3.3.2 Advanced Technology

Looking ahead, a somewhat limited use of nuclear power is predicted between 1995 and 2010 to produce added electrical capacity. The *Annual Energy Outlook 1993* (Reference 3) estimated a maximum of three new advanced technology plants by year 2010, a relatively negligible number.

Reference 4 predicts that significant new electrical capacity from nuclear power plants will be added after the year 2010 if certain issues are resolved. The four major issues identified are (a) a high-level radioactive waste repository available, (b) the licensing process streamlined, (c) the timeframe for bringing a new plant online shortened to provide economic advantage, and (d) cooperative agreements created between states for disposal of low-level radioactive waste.

Nuclear power generation forecasts for 2010 to 2030, produced in Reference 4 and Reference 2 are very similar. The National Energy Strategy values are slightly higher (approximately 3%) and have been selected for the high-case predictions in this study to conservatively estimate maximum GTCC LLW generation. The high case presented in the National Energy Strategy predicts that generation demand for nuclear units will nearly double from 2010 to 2030. A summary of predictions in Table C-16 of Reference 4 includes a contribution of 123 gigawatts-electric (GWe) from advanced and new technology nuclear power plants.

The electrical demand forecasts in Reference 5 are used for this study's base-case prediction. Total demand for nuclear generated power in 2030 is projected to be 122 GWe, an increase of 19 GWe over today's nuclear-generated power level of 103 GWe.

Quantifying the number of new reactor power plants to be added is difficult because of different MWe ratings between designs. Assuming 1 GWe per plant, approximately 123 advanced or new-technology nuclear power plants would have to be added between the years of 2010 to 2030 to meet the high-case prediction, and about 80 such plants would have to be added to meet the base-case prediction. However, the volume of operational radiological waste from the advanced and new-technology nuclear power plants would be less as a result of advanced radioactive waste systems, lower neutron fluences, and more efficient maintenance activities (Reference 12).[b] The author estimates that reductions of 25 to 50% in GTCC LLW volume could be realized from a new plant when compared to a current technology nuclear power plant with the same megawatt output.

b. A description of Westinghouse's earlier AP1000 design (private communication, 1993) indicated that a 30% reduction in radioactive waste volume to be handled and disposed of would be realized because of (a) a lower number of fuel leaks, (b) advanced component materials, (c) lower corrosion rates, and (d) streamlined radioactive waste processing systems.

4. REACTOR SHUTDOWNS

The age at which a nuclear power plant is decommissioned determines the total amount of GTCC LLW generated by plant operations and decommissioning. This section discusses the uncertainties concerning the life span of a nuclear power plant and defines three cases with assumptions used to bound the range of predicted GTCC LLW volumes from decommissioning activities.

4.1 Uncertainties

An earlier theory that nuclear plants would be capital cost-effective to build and cheap to operate has long since been abandoned. Now, utility managers must decide whether to retire a nuclear unit early, run it to the end of its current operating license, or apply for a life extension. The decision is extremely sensitive to economic and political issues. For example, in 1992, utility management decided to retire several units early and retracted applications for life extension of two units.

Several factors influencing this decision process are discussed below, and their implications are recognized in this study:

- Operating and maintenance costs must remain at or near 1990 levels for a nuclear plant to maintain an economic advantage over alternative energy sources and, therefore, warrant a 40-year life.

- Uncertainties in cost of plant life extension cause significant uncertainty in predicting how often this option might be pursued in the future.

- Lack of availability of waste disposal facilities causes a significant increase in future O&M costs. Therefore, it is unlikely that life extension will be pursued by utilities that are already experiencing high O&M costs.

- DOE recognized that the 1991 National Energy Strategy projections (Reference 4) were too high regarding the frequency of plant life extension. A more accurate projection is presented in the 1993 Annual Energy Outlook (Reference 3).

4.1.1 Operating and Maintenance Costs

O&M costs have risen through the 1970s and 1980s to become one of the most important factors for determining the economic feasibility of continued operation of a nuclear power plant. Escalating O&M costs lend support to the argument for switching to alternative energy sources. The projected time at which decommissioning GTCC LLW becomes available changes significantly in reaction to this economic pressure.

James Hewlett of EIA described the concern caused by the uncertainties associated with escalating O&M costs by saying that if operating costs continue to escalate, even with accurate decommissioning cost estimates, it is possible that a situation may arise where nuclear units would be too costly to run and, simultaneously, too costly to close.[14] For a nuclear plant to maintain an economic advantage over alternative energy sources, O&M costs must remain at or near 1990 levels. This situation makes it increasingly difficult for utility executives to justify continued operation of nuclear power plants to state and local regulators. Many utilities are awaiting the outcome of economic studies on O&M and decommissioning costs to plan future operations.

4.1.2 Plant Life Extension

Industry experts disagree on the likelihood of future plant life extensions. In the July 1992 issue of *Energy Policy*, James Hewlett said, "The only time nuclear plant life extension has a clear and decisive economic advantage over any alternative is in the low cost, no escalation case."[15] Another source, the U.S. Council for Energy Awareness, estimates that 70% of the nuclear units "still running" when their operating license comes up for renewal will be life extended (Reference 8). In contrast, predictions made two years earlier in the 1991 National Energy Strategy were that 70% of all plants operating in 1990 would achieve life extension (Reference 4). However, a survey of nuclear utility executives by *Nucleonics Week* in early 1994 resulted in 46% responding that they would seek life extension for their commercial nuclear power plants.[16] This response was based on today's energy economics, which rely heavily on natural gas and oil imports. Volatility in this area, as was experienced in the 1970s, could quickly change the commercial nuclear outlook and increase the life extension preduction.

The availability of waste disposal facilities is an important part of the equation for nuclear plant life extension. The additional onsite waste storage costs will increase the O&M costs, making nuclear plant life extension much less attractive.

Another factor clouding the issue of life extension is nuclear plant aging. Concern from the NRC for plant aging and safety-related maintenance has resulted in increased costs, forcing many utilities to reconsider extending the life of the nuclear plant. As mentioned previously, no utility is actively pursuing a life extension at this time.

4.1.3 Premature Shutdowns

In the May 1991 edition of *Energy Journal*, EIA expert James Hewlett points out that "it is not valid to assume *a priori* that a nuclear power plant will continue to operate until the end of its licensed life" (Reference 14). For example, early shutdowns occurred for three nuclear units in 1991–1992. The 1991 National Energy Strategy assumption that "all" plants will operate until the end of their 40-year life did not account for these occurrences. A variety of issues, such as demand-side management, least-cost planning, and integrated resource planning, are influencing decisions by utility management today.

Utilities now face a serious economic question. Can a plant of relatively low power and relatively low earning ability pay back, in one or two decades, all of the costs required for a license extension? Many older nuclear plants have less than 700 MWe generating capability. Approximately 40% of nuclear plants that will reach the end of their 40-year life by 2015 fall into this category. Yankee Rowe's retirement last year is an excellent example of this situation. The utility decided that the 167-MWe generating capacity was not sufficient to pay back the refurbishment cost involved with the reactor vessel. However, the susceptibility is not limited to small nuclear power plants (i.e., 700 MWe or less). Last year Trojan, a 1,100-MWe PWR power plant, shut down after only 16 years of operation rather than spend $250 million replacing steam generators.

San Onofre Unit 1 is another example of the unpredictability of plant life. Special compensation for uncollected decommissioning costs was allowed by regulators, providing additional incentive to shut the unit down. Economic studies conducted for San Onofre Unit 1's "cost-effectiveness" concluded that it was profitable to operate in 27 of 32 scenarios analyzed. Still, the integrated resource planning process led to a decision to shut the unit down some 12 years before the end of its 40-year life. Currently, other nuclear power plants are carefully evaluating the benefit of continued operation (e.g., Nine Mile Point 1).

Early shutdown of nuclear power plants can have significant impact on the total volume of GTCC waste. Operational waste volume would be less than expected from a plant if fewer fuel cycles were completed. According to some industry experts, the number of nuclear power reactors experiencing early shutdown could reach 25 to 30 plants before the year 2000.[17]

4.1.4 Decommissioning Costs

High decommissioning costs may represent the greatest incentive to extend power plant life. Decommissioning cost estimates have increased rapidly in the past several years. In some cases, they have doubled. Studies conducted in the late 1970s did not consider storage of high-level radioactive waste a decommissioning cost. However, without a waste repository, SAFSTOR is the only option available to a plant in early retirement. In the SAFSTOR option, nonessential plant systems are removed from service. Essential systems, required for storage of spent fuel and other waste, security, and monitoring for radiation, are required to operate for 30 to 60 years or longer before the plant is dismantled. Maintaining these essential systems substantially increases the total cost of decommissioning. As a result, unrecovered costs for decommissioning may defer decisions to shut down early, adding further uncertainty to ultimate dates of decommissioning.[18]

4.2 Timing for Receipt of Low-Level Radioactive Waste

Reference 1 uses three cases to calculate a range of projections for the volume of GTCC LLW: high, base, and low. This report provides timing assumptions for use in these three cases. The high case uses the 1991 National Energy Strategy information to define the possibility of life extension, which could move shutdown and decommissioning dates 20 years farther into the future (Reference 4). Conditions described by the high case would create a larger total volume of GTCC LLW from operations and decommissioning. The base-case assumptions and calculations are intended to represent the most probable waste generation timing using the most current projections by the EIA, *Annual Energy Outlook 1993* (Reference 3). The low case establishes a lower bounding for waste volume calculations by assuming a 40-year life with no extension. The low case, which also includes the possibility of early shutdown to account for uncertainties of regulatory, political, and economic issues, presents a conservatively short projection for nuclear plant life.

Tables for timing of decommissioning waste generation are based on license expiration dates. Table 1 lists the expiration date for 40-year license periods, assuming that all licenses issued before 1982 are amended to recoup any lost construction time. The assumption for all three cases is that GTCC LLW from decommissioning will be available for disposal three years after a nuclear power plant is shut down. A summary of the projections for the three cases is provided in Table 2 of this report. The number of BWRs and PWRs in each category has been estimated by extrapolating from the ratio of operating BWRs to PWRs. This approach may slightly underestimate the early retirement number of BWRs, since, in general, BWRs have less generating power than PWRs. However, Table 2 represents the best estimates derived from all available resources to use in calculating waste generation from nuclear power plants.

If a nuclear power plant is retired early, it likely will be placed in a SAFSTOR condition until a repository is made available. However, if waste disposal sites are available, it is assumed that all utilities currently operating reactors will decontaminate the nuclear structures and systems promptly,[19] and that GTCC LLW will be available for disposal three years after reactor shutdown.

4.2.1 High Case

Using the *Supplement to the Annual Energy Outlook 1993*, the high case assumes that 114 current-technology reactors (37 BWRs and 77 PWRs) will be operating by 2005. This includes the 109 currently operating reactors, plus five out of seven reactors presently under construction and listed in Table 1. All 114 reactors are assumed to operate at least to the end of their 40-year license to satisfy a high-growth energy demand scenario (Reference 13). The shutdown date for the last operating reactor (with life extension) is 2065, with delivery of waste in 2068. The 60-year life expectancy of most reactors is based on high availability and production rates (i.e., capacity factors) of newer units.[20] Economically, these nuclear power plants are most likely to apply for life extension.

The National Energy Strategy estimate of 70% (approximately 80 plants) operating for a full 60 years (Reference 4) has been adopted to adequately bound waste volume and timing predictions in the high case. Individual shutdown dates for these plants would occur 20 years later than the dates established in Table 1. An analysis of plants with projected shutdown dates after 2015 shows approximately 75% have generating capacities greater than 1,000 MWe, which indicates good support for the 70% estimate. It is reasonable to assume that most of the 80 plants with life extension will generate 1,000 MWe or greater.

For the high case, the 30% (approximately 34 plants) that will not extend life are expected to operate until the end of their 40-year life. The Trojan, San Onofre-1, and Yankee-Rowe plants are not included in this category (see Table 3), since they are already shut down. No other plants are assumed to shut down before completion of their 40-year life (see Table 2).

Table 2. High-, base-, and low-case predictions of numbers of current technology nuclear plants at assumed time of shut down.

	High case[a]			Base case[b]			Low case[c]		
Time of shut down	Percent of 114 (%)	Number of BWRs	Number of PWRs	Percent of 113 (%)	Number of BWRs	Number of PWRs	Percent of 113 (%)	Number of BWRs	Number of PWRs
Early shut down	0	0	0	25	11	17	25	11	17
40-year lifetime	30	11	23	38	13	30	75	26	59
60-year lifetime (life extension)	70	26	54	37	13	29	0	0	0

a. The high case assumes 114 operating reactors (37 BWRs and 77 PWRs; includes five in addition to the 109 currently operating).

b. The base case assumes 113 operating reactors (37 BWRs and 76 PWRs; includes four in addition to the 109 currently operating).

c. The low case assumes 113 operating reactors (37 BWRs and 76 PWRs)—same as for the base case.

Table 3. U.S. nuclear power plants no longer in service as of December 1992.[a]

Number	Reactor	State	MWe	Type	License start date	Shutdown date[b]
1	BONUS	PR	72	BWR	1964	1968
2	Dresden 1	IL	200	BWR	1960	1978
3	Fermi 1	MI	61	LMFBR	1966	1972
4	Fort St. Vrain	CO	330	HTGR	1979	1989
5	Hallam	NE	75	LMGMR	1963	1964
6	Hanford-N	WA	860	LGR	1966	1988
7	Humboldt Bay 3	CA	63	BWR	1963	1976
8	Indian Point 1	NY	257	PWR	1963	1974
9	La Crosse	WI	50	BWR	1969	1987
10	Pathfinder	SD	59	BWR	1966	1967
11	Peach Bottom 1	PA	40	HTGR	1967	1974
12	Rancho Seco	CA	913	PWR	1975	1989
13	San Onofre 1	CA	436	PWR	1968	1992
14	Shippingport	PA	60	PWR	1957	1982
15	Shoreham	NY	809	BWR	—[c]	1989
16	Three Mile Island 2	PA	792	PWR	1978	1979
17	Trojan	OR	1095	PWR	1976	1992
18	Yankee-Rowe	MA	167	PWR	1961	1991

a. See *Spent Fuel Storage Requirements 1991-2040.*[21]

b. Date the reactor was shut down. Generation of GTCC LLW is assumed to occur three years after this date.

c. Only low-power physics testing was performed. Full-power status was not licensed or achieved.

Advanced and new technology reactor power plants must be considered in order to adequately bound the high-case projections of GTCC LLW for the years beyond 2010. Future energy demand may require as many as 123 new or advanced technology reactor power plants to be placed in operation from 2010 to 2030 (Reference 4). Thirty-four of these would be considered as replacement power for those current technology units shutting down by 2030, at the end of their 40-year license period.

GTCC LLW generated by new or advanced technology units coming on line would more than offset the decrease in operating GTCC waste volume from shutdown of the current technology units. It is assumed here that newer reactor power plant designs will produce 25% less operational waste per megawatt than current technology plants. Thus, the addition of 123 new or advanced units would add an operational waste volume equivalent to 92 of the current technology units. The operational waste volume produced in 2030 would be about 150% of the volume produced in 2010.

Considering all of the above factors, the high case estimates future waste generation from advanced or new technology reactors by assuming the total operational GTCC LLW volume will increase 50% between 2010 and 2030.

4.2.2 Base Case

Using the *Supplement to the Annual Energy Outlook 1993* (Reference 13), the base case assumes that 113 current-technology reactors (37 BWRs and 76 PWRs) will be operating by 2001 to satisfy a moderate growth in energy demand. This includes the 109 currently operating reactors, plus four out of seven reactors presently under construction and listed in Table 1. The shutdown date for the last operating reactor will be 2061, with delivery of waste in 2064. As in the high case, a 60-year life expectancy is based on high capacity factors of newer units. This represents the highest economic probability that utilities will apply for a life extension option.

The base-case assumption for life expectancy is that 25% (approximately 28 plants) of the currently operating plants will shut down before their 40-year licenses expire. This number is higher than predictions cited in References 2 and 4 (both 1991), which assume that all existing plants will operate for their 40-year licensed period. However, an evaluation of nuclear power plants by O&M costs in an economic study by James Hewlett determined that nuclear plants with O&M costs at the 90th percentile could be replaced today with coal plants and save money (Reference 15). Additionally, those plants with O&M costs in the 75th percentile were marginally cost-effective to operate, even assuming no escalation of future costs. Currently, there are approximately 29 nuclear power plants with O&M costs above the 75th percentile.[22] Many of those plants are predicted to shut down by the year 2000 (Reference 17).

Reference 3 predicts "5 of the 12 units eligible for license renewal during the forecast period (to 2010) are projected to have their operating license renewed (2.8 gigawatts) and to be life-extended for 20 years." This renewal rate of 42% may be skewed (low) by the number of smaller units (i.e., less than 800 MWe). However, in the economic study by Hewlett, an optimistic presumption of constant O&M costs for the future was assumed. Given that set of conditions, only plants below the 10th percentile for operating costs would have an economic advantage for pursuing life extension. Additionally, the ability of nuclear units to earn back costs incurred from refurbishment (e.g., economy of scale, 1,000 MWe versus 700 MWe) will be an important factor for a life-extension decision. Taking all this into account, the base case assumes 50% (42 plants) of the approximate 85 reaching the end of their 40-year life will have their lives extended (see Table 2). This corresponds to about 37% of all the reactors.

In the base case, demand for additional power capacity between 2010 and 2030 would also require advanced or new technology units to come on line. Reference 5 predicts a total demand of 122 GWe by the year 2030. Using a 1 GWe per plant assumption, the total number of nuclear power plants operating in the year 2030 would therefore be about 122. About 80 new technology units would be needed to supplement the 42 current technology plants assumed to be still operating in 2030 (see Table 4). The 80 new units would effectively produce the same amount of operational GTCC waste as 60 units of the current technology, assuming a 25% reduction in waste volume. The estimated operational GTCC waste volume from all 122 operating plants in 2030 would be approximately 90% of the volume produced in 2010.

4.2.3 Low Case

Like the base case, the low case also assumes that 113 current-technology reactors (37 BWRs and 76 PWRs) will be operating by 2001, including the 109 currently operating reactors, plus four out of seven reactors presently under construction and listed in Table 1. However, prospects for life-extension are unclear. No applicants are actively engaged in the process at this time. The fact that the NRC is reviewing the life-extension rule leaves many unanswered questions. To account for this uncertainty, the low-case timing assumes no extension for any of the identified 113 base-case nuclear power reactors.

The low-case assumption for early shutdown is the same as for the base case, that is, 25% of reactors will shut down before the end of their 40-year license. In the low case, 40 years is the maximum expected lifetime for the remaining 75% of the plants. The last nuclear power plant will shut down in 2041, with delivery of waste expected in 2044 (see Table 2). No advanced or new-technology reactors are included in the low case.

DOE's *Integrated Data Base for 1992: U.S. Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics*[23] compiled a table (7.1) that chronologically lists plants by their 40-year shutdown dates. It correlates well with Table 1 of this report, and with the exception of early shutdown and current technology plants placed in operation after 1991, it closely predicts the GTCC waste timing schedule for the low case.

Table 4. Estimated number of nuclear reactors needed in 2030.

	High case	Base case	Low case
Number of current technology reactors	80	42	8
Number of advanced and new-technology reactors	123[a]	80[b]	0

a. Derived from electrical demand estimates reported in Reference 4.

b. Derived from electrical demand estimates reported in Reference 5.

5. SUMMARY AND CONCLUSIONS

Under public law, DOE is responsible for disposal of all GTCC LLW. To plan waste strategy and formulate policy, the volume of GTCC LLW must be projected. The first section of this report recaps the major issues causing utilities to consider options that will affect the total volume of GTCC LLW produced. Next, advanced technology light water reactors' contribution to the waste volume is discussed. Finally, the operating lifetimes for the current technology light water reactors years are projected for the high, base, and low cases. These cases are used elsewhere in Reference 1 to estimate the total GTCC LLW volume from nuclear power plant waste generators.

The uncertainties created by state and federal regulations, costs for decommissioning, the life-extension process, O&M, and plant aging make it difficult to predict dates for receipt of decommissioning waste and how much of the waste will exceed Class C limits. Current regulatory and economic pressures on operating nuclear plants clearly do not support the concept of nuclear power plants as national assets, as stated by James Hewlett, a leading economic export with the EIA (Reference 15). No utilities are currently pursuing operating license extension because life extension presents such an unknown economic factor. Early shutdowns are increasing as demonstrated in 1992 by the unexpected closing of two nuclear power plants. O&M costs resulting from additional required onsite waste storage may promote early retirement (SAFSTOR) for many marginally economic nuclear units. The lack of waste disposal sites is a primary factor adding to the overall uncertainty.

Advanced technology light water reactors are not predicted to be placed into service until some time around 2010 or later. Design efforts on advanced technology plants should decrease the operational waste volumes by 25–50% and eliminate major structural components from the decommissioning GTCC LLW category. The major impact of advanced or new technology power plants over the next 40 years will be in operating waste volumes. For the high and base cases, increases in electrical power demand between 2010 to 2030 will require the addition of many more of these plants. The new technology plants are assumed to either offset the decrease in operating GTCC waste volume from shutdown of current technology plants, as discussed in the base case, or increase the total volume as in the high case. The low case assumes no generation of GTCC LLW by new technology reactors.

Shutdown dates for current technology light water reactors fall into one of three categories: early shutdown, 40-year, or life extended up to 20 years beyond the 40-year date. Based on projections in Reference 3 and in other references, best estimates for each of these categories have been made to provide input assumptions for GTCC LLW volume calculations.

Eighteen nuclear plants have already been shut down. An additional 25 to 30 nuclear power plants may shut down by 2010, before the expiration of their 40-year licenses (Reference 17). Waste volumes from units experiencing early shutdown will be lower because of less operational waste and possibly fewer decommissioned reactor structural components activated to GTCC levels. The GTCC LLW volume associated with reactor decommissioning is assumed to be available for disposal three years after reactor shutdown.

Yankee Atomic Electric Company's attempt to extend the life of the Yankee-Rowe Unit revealed many unanswered questions. If their application for life extension is a typical example of the effect of aging on refurbishment costs, then any nuclear plant generating less than 700 MWe will have a difficult time justifying life extension from an economic standpoint. Most reactor decommissioning GTCC LLW ready for disposal in the next 15 years will probably come from smaller nuclear units.

Plants able to control O&M costs are likely candidates for extended operation. Those plants with 70% or higher capacity factors, low O&M costs, and high generating capacity (e.g., 1,000 MWe or greater) are most likely to achieve a 60-year life. Approximately 50 to 55 units, currently in operation, fall into this category.

The base case projects that out of 113 units currently or expected to be operating, 28 units will experience early shutdown, 43 units will shut down with a 40-year life, and 42 will shut down with a 60-year life (including license extension).

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