NONPROLIFERATION ISSUES IN THE NUCLEAR ENERGY FUTURE

by

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Bachelor of Science in Mathematics

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ABSTRACT

The continuing increases in annual greenhouse gas emissions, in the absence of stringent mitigation measures, will produce a doubling of pre-industrial atmospheric concentrations in the second half of this century and a concomitant risk of serious disruption of the climate system, unless less carbon-intensive energy technologies are introduced. The nuclear power option is being discussed much more actively as part of this greenhouse gas challenge. Deployment on the necessary scale must entail establishment of nuclear power and a supporting infrastructure and workforce in many regions of the world, including developing nations. We shall be concerned here with the nonproliferation issues raised by such a nuclear power global growth scenario. In revisiting the issue of nonproliferation and the nuclear fuel cycle, we address two central questions:

1. If a robust nuclear growth scenario is realized, what might it look like, both geographically and technologically?
2. What are the relevant proliferation pathways in the context of this growth scenario, and what actions and studies might be taken to reduce the risk?

Our analysis has three components: development of a mid-century demand scenario; discussion of proliferation technology pathways; recommendations that derive from these results. Some of the key recommendations entail:

1. Strengthening of the international safeguards regime, for example by integration of safeguards surveillance and security functions with fuel cycle design and operation.
2. Enhanced focus on enrichment technologies.
3. Timely closure of the back end of the fuel cycle through geological isolation of spent fuel or high-level waste.
4. Focus on fuel cycles that do not yield separated plutonium during normal operation, and control over international cooperative R&D programs.
5. Implementation of suitable international fuel cycle architectures.

Thesis Supervisor: Ernest J. Moniz
Title: Professor of Physics

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Acronyms and Organizations

Acronyms

APEC	**Annual Per Capita Consumption**
BWR	**Boiler Water Reactor**
ENHS	**Encapsulated Nuclear Heat Source**
FSU	**Former Soviet Union**
GWD/t	**Gigawatt Days per Metric Ton of Heavy Metal**
GWe	**Gigawatts Electric**
HDI	**Human Development Index**
HEU	**High Enriched Uranium**
HTGR	**High Temperature Gas Reactor**
IFR	**Integral Fast Reactors**
INFCIRC	**Information Circular**
kWhrs (kWh)	**Kilowatt hours**
LEU	**Low Enriched Uranium**
LWR	**Light Water Reactor**
MOX	**Mixed Oxide**
MPBR	**Modular Pebble Bed Reactor**
MPC&A	**Material Protection, Control, and Accounting**
MT	**Metric Ton**
MUF	**Material Unaccounted For**
MWD/t	**Megawatt Days per Metric Ton of Heavy Metal**
MWe	**Megawatt Electric**
MWt	**Megawatt Thermal**
NDA	**Non-destructive Assay**
NPT	**Non-Proliferation Treaty**
psi	**Pounds Per Square Inch**
PUREX	**Plutonium Uranium Extraction**
PWR	**Pressurized Water Reactor**
RAR	**Reasonably Assured Resources**
SWU	**Separative Work Unit**
TBP	**Tri-n-butyl phosphate**
TEC	**Total Electricity Consumption**
W/MTHM	**Watts per Metric Ton of Heavy Metal**
w/o	**Weight Percent**
wt%	**Weight Percent**

Organizations

CIA	**Central Intelligence Agency**
DOE	**Department of Energy**
EIA	**Energy Information Administration**
IAEA	**International Atomic Energy Agency**
IISS	**International Institute for Strategic Studies**
INFCE	**International Nuclear Fuel Cycle Evaluation**
NAS	**National Academy of Sciences**
NASAP	**Nonproliferation Alternative Systems Assessment Program**
NERAC	**Nuclear Energy Research Advisory Committee**
NFS	**Nuclear Fuel Services**
NRC	**Nuclear Regulatory Commission**
TOPS	**Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems**
UN	**United Nations**
UNDP	**United Nations Development Program**
WISE	**World Information Service on Energy**
UNSCOM	**United Nations Security Commission**

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To My Grandparents, who have gone on, but
will never be forgotten…

1 INTRODUCTION

1.1 Introduction

Worldwide anthropogenic carbon emissions are more than six billion tonnes of carbon (equivalent) annually, and atmospheric carbon dioxide concentrations have now increased 30% above pre-industrial levels. This is shown in Figure 1-1. The continuing increases in annual greenhouse gas emissions, in the absence of stringent mitigation measures, will produce a doubling of pre-industrial concentrations in the second half of this century and a concomitant risk of serious disruption of the climate system.

Avoiding such an outcome requires an order of magnitude increase in non-carbon-emitting energy production and use. The four basic technology pathways for accomplishing this are much higher efficiency, renewables, carbon sequestration, and nuclear power. Non-hydro renewables have a very small market share because of costs and operational considerations, and hydropower is severely limited in terms of growth opportunities. Efficiency continues to improve slowly each year, a trend already incorporated in out-year projections of energy use per unit of economic activity. Sequestration remains unproved on a very large scale. Thus, although each of these pathways merits continuing research, development, and deployment, the uncertainties are such that the nuclear power option is being discussed much more actively as part of the greenhouse gas challenge for the decades ahead.

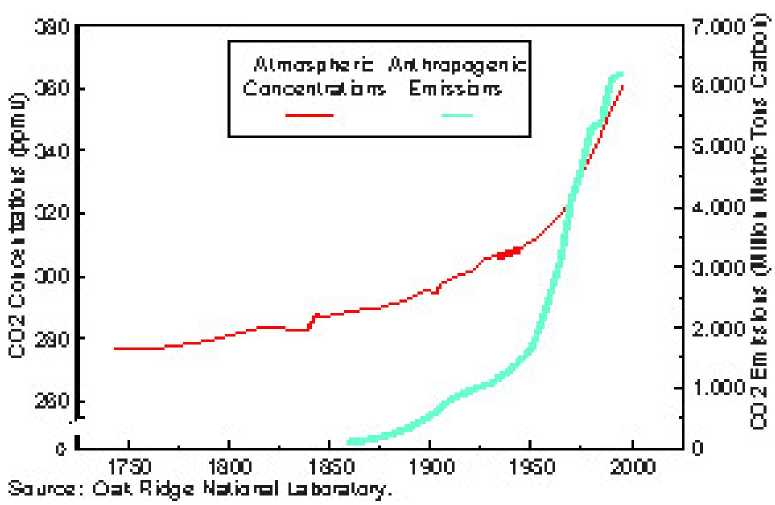

FIGURE 1-1: Trends in Atmospheric Concentrations and Anthropogenic Emissions

Nuclear power currently accounts for about 17% of global electricity production. To make a significant impact on the greenhouse gas challenge, it would need to maintain or increase its market share, with a deployment in the range of 1000 to 1500 GWe by mid-century (compared with about 360 GWe today). However, deployment on this scale raises significant issues, particularly since the deployment must entail establishment of nuclear power and a supporting infrastructure and workforce in many regions of the world, including developing nations. We shall be concerned here with the nonproliferation issues raised by such a nuclear power global growth scenario.

The importance of the developing world in such discussions is founded on their anticipated rapid growth in energy use and carbon emissions. Whereas electricity growth and carbon emissions are anticipated by the Energy Information Administration (EIA) to grow annually in the industrialized world by 1.8% and 1.2%, respectively, the comparable growth rates in the developing world are 4.2% and 3.7%, respectively. Thus, electricity supply needs will be immense in the developing world, and nuclear power may look attractive as a means to address those needs without significant atmospheric emissions. On the other hand, nonproliferation challenges would likely be significant if nuclear power is established in a multitude of new places. However, we should emphasize that proliferation risks are not limited to developing nations, as changing geopolitical imperatives (e.g., in the Far East) could lead industrialized non-nuclear-weapons states to change their security policies[1].

In revisiting the issue of nonproliferation and the nuclear fuel cycle, we address two central questions:

1. If a robust nuclear growth scenario is realized, what might it look like, both geographically and technologically?
2. What are the relevant proliferation pathways in the context of this growth scenario, and what actions and studies might be taken to reduce the risk?

1.2 Thesis Organization

We start in Chapter 2 by constructing a global electricity "demand map" for the year 2050. This demand map is not a forecast or an economic model. Rather it is a scenario organized around the expectation that nations will invest in their power infrastructures in order to lift their populations to a decent standard of living and economic activity. United Nations projections for mid-century population in each country are an important part of determining demand levels. With this overall determination of electricity production and use, the range of nuclear capacity is estimated based upon current use and a set of judgments about possible market share. We emphasize that the judgments are taken in the context of a world that has re-committed to nuclear power as an important part of environmentally-responsible energy supply, a context that does not represent today's reality in many parts of the world. This distribution of nuclear power has significant implications for our nonproliferation considerations.

We then turn to a representative set of technologies that may form the basis for the growth scenario. These include both fuel cycles in widespread use today (thermal light water reactors (LWR) with and without plutonium recycle) and technologies that need further development (including fast spectrum reactors with recycle of plutonium and other actinides). Chapter 3 emphasizes the structure and content of the assessment method used, derived from the national academy and DOE studies based upon material, technical, and institutional barriers to proliferation. Chapter 4 presents the results of assessing various nuclear fuel cycles, together with recommendations that flow from the consideration of proliferation pathways. Chapters 2 and 4 present the main results of the analysis. Chapter 5 provides a summary and revisits key results from chapters 2 and 4.

[1] These nations might decide that it is in their best interest to develop nuclear bombs to protect themselves.

2 GLOBAL DEMAND MAP: A SCENARIO FOR NUCLEAR POWER AT MID-CENTURY

In providing the context for assessing proliferation risks in a robust global growth scenario for nuclear power, we take a long-term view out to mid-century. By any means of modeling or projection, energy use – and especially electricity use – is expected to rise dramatically. For example, the EIA 2000 International Energy Outlook projections to 2020 are shown in Table 2-1 (EIA, 2000)[1]. Continuation of growth in global electricity use as shown in the table would lead to nearly 50 trillion kWh by 2050, a four-fold increase in half a century; while it is unlikely that this growth rate would be sustained for so long, the scale of the supply challenge is considerable. With the growth rates in Table 1, the developing world would use over 60% of the world's electricity, about double its share today.

TABLE 2-1: EIA 2000 Projections

EIA2000 KEY INDICATORS AND PROJECTIONS: 1997 to 2020

	WORLD	INDUSTRIALIZED COUNTRIES	EE/FSU	DEVELOPING COUNTRIES
TOTAL ENERGY CONSUMPTION/YR (QUADS)				
	380 to 608	204 to 260	53 to 76	123 to 272
	2.1%/yr	1.1%/yr	1.5%/yr	3.5%/yr
ELECTRICITY USE/YR (TRILLION KW-HRS)				
	12.3 to 21.6	7.3 to 10.3	1.5 to 2.1	3.5 to 9.2
	2.5%/yr	1.5%/yr	1.6%/yr	4.3%/yr
GROSS DOMESTIC PRODUCT (TRILLIONS OF U.S. $)				
	28.7 to 53.9	22.4 to 36.6	0.97 to2.4	5.3 to 14.9
	2.8%/yr	2.2%/yr	4.0%/yr	4.6%/yr
CARBON EMISSIONS/YR (BILLION TONS)				
	6.1 to 10.0	3.0 to 3.9	0.88 to 1.15	2.3 to 4.9
	2.1%/yr	1.1%/yr	1.2%/yr	3.5%/yr

The scale of capital investment needed to reach this global capacity is on the order of ten trillion dollars, not including associated infrastructure costs. Nevertheless, the central role of electricity in enhancing quality of life, because of its convenience and lack of pollution at the

[1] A more recent version of this table can be found in Moniz, E., Kenderdine, M. (2002) *Meeting Energy Challenges: Technology and Policy* Physics Today, April 2002.

point of end use, suggests that governments will assign high priority to such investments if at all possible, and conversely will gauge the significant investments called for to the level needed for serving citizens' needs. This provides the basic framework for our scenario construction and suggests the first task: associating levels of individual electricity use with well-being.

The United Nations annually compiles statistics on the human development and environment of 175 countries. These statistics relate to energy use, life expectancy, nutrition and health, income and poverty, education, and other relevant factors. In particular, the United Nations Development Program (UNDP) uses three of these indicators to calculate the Human Development Index (HDI), which it defines as "a process of enlarging people's choices." They note that: "the three essential capabilities (indicators) for human development are for people to lead long and healthy lives, to be knowledgeable and to have a decent standard of living (UNDP, 2003)." They measure longevity by life expectancy, knowledge by educational attainment (a combination of adult literacy and collective primary, secondary, and tertiary enrollment), and standard of living by a discounted gross domestic product per capita[2].

The starting point for our scenario is the correlation between HDI and per capita electricity use. Benka (2002) adapted the results of Pasternak (2000) to produce Figure 2-1. The figure shows HDI and annual per capita electricity use for sixty countries accounting for 90% of the world's population.

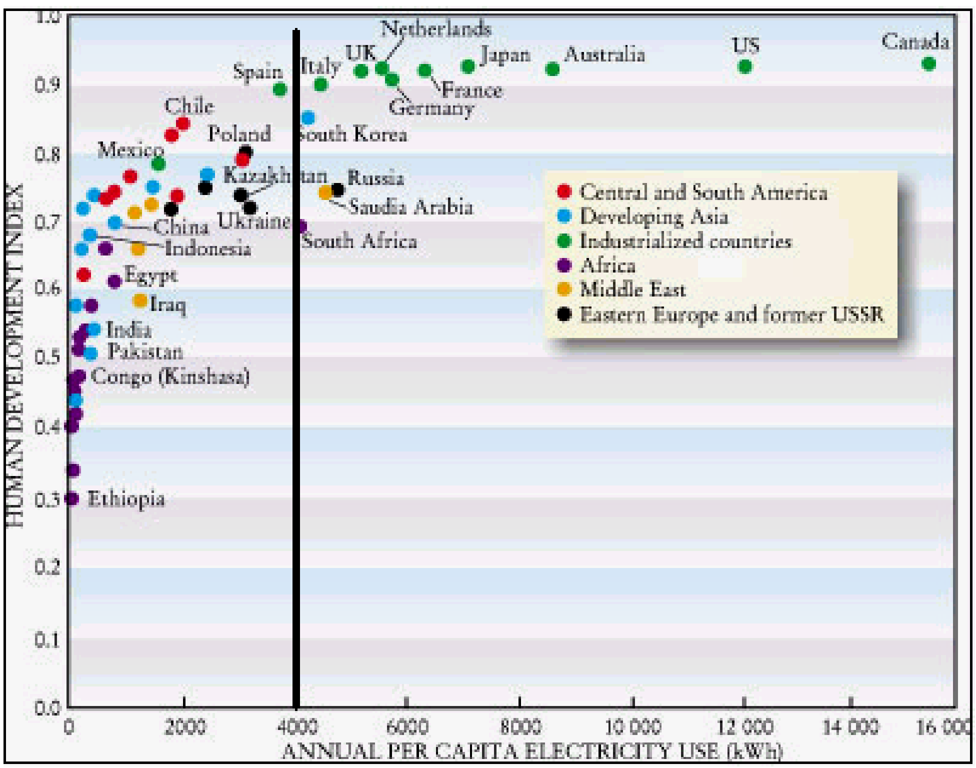

FIGURE 2-1: Correlation between HDI and Per Capita Electricity Consumption

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[2] Although specifics are neglected here, a great technical reference for understand the details of the Human Development Index can be found at the following website: http://hdr.undp.org/reports/global/2002/en/pdf/backtwo.pdf

The HDI reaches a high plateau (approximately 0.9 on a scale of 0 to 1) when a nation's annual per capita consumption of electricity is roughly 4000 kWhrs. All of the countries on this plateau are industrialized (developed) countries. The uniqueness of individual countries does bring about exceptions to this correlation: for example Russia, Saudi Arabia, and South Africa, for easily understood reasons, are at or above the benchmark of 4000 kWh despite the absence of highly developed economies. Developing countries are generally well below the 4000 kWhrs per capita electricity consumption level, although with an obvious gradation among former Soviet Union countries, emerging economies, and the least developed countries.

The underlying assumption in our scenario-building is that, while the developed countries continue with a small annual increase in per capita electricity use, the developing countries move to the 4000 kWh benchmark if at all practical. The indicator of practicality is total expansion of national electricity supply. These scenario guidelines will be presented quantitatively below. This approach clearly involves population projections to mid-century, and again we shall rely on the United Nations. We recognize that population changes may result from success in providing more energy and social progress. *Nevertheless, for our purposes, broad understanding of where people are expected to be and of what their needs are for satisfactory quality of life is sufficient to frame our discussion of nuclear power and nonproliferation*. Clearly the scenario is not based on economic modeling or forecasting, but we shall compare the outcome to those of the Energy Information Administration (EIA) over the next decades.

2.1 Methodology

The methodology consists of three basic steps that lead to the 2050 World Nuclear Electricity Demand Map and associated nuclear power deployments. These steps are detailed in the sections below and are captured graphically in the following flowchart.

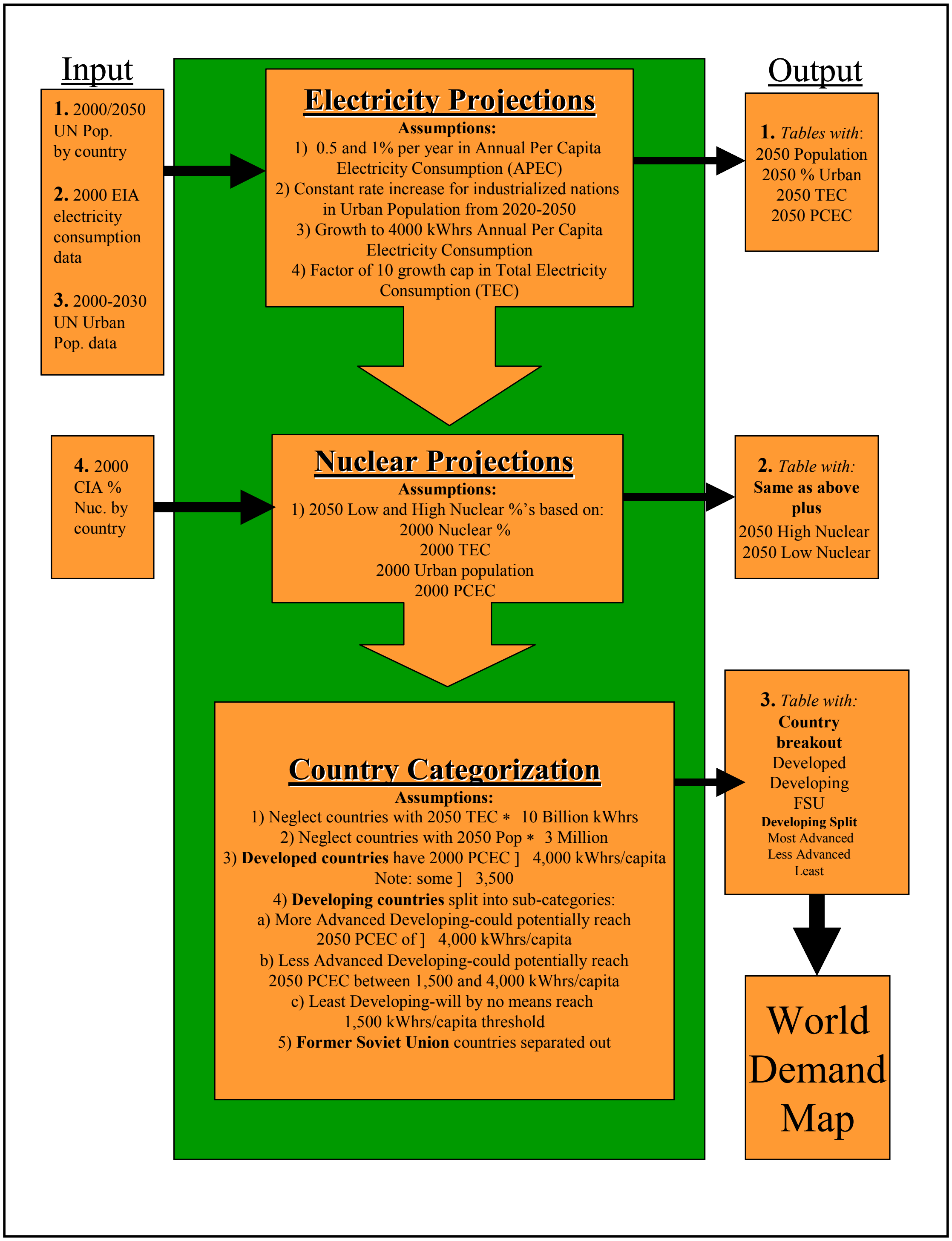

FIGURE 2-2: Electricity Demand Algorithm Flowchart

2.1.1 Electricity Projections

This step combined various data from the EIA and UN: the United Nations provides both estimates (2000 estimates were used) and projections (2050 medium variant projections were used) for individual country populations[3] based upon historical growth rates and other significant indicators; the Energy Information Agency provides estimates (2000 estimates used) on a county-by-country basis of individual electricity consumption numbers; the UN also provides estimates (2000 estimates used) and projections (up to 2030) of country-by-country urban population percentages. The 2050 urban populations were obtained from linear extrapolation of the 2000-2030 UN growth projections.

For countries with current annual per capita electricity consumption (APCEC) close to or above 4000 kWh, we take two cases: 0.5% and 1% growth in APCEC. These rates bracket the EIA expectations for the United States over the next twenty years (EIA, 2001). Over the last quarter century, this growth rate averaged about 2%, reaching 1.5% in 2000 and expected to decline further. For developing economies, we assume that (with some exceptions detailed below) they reach 4000 kWh APCEC in 2050. This yields total electricity use when combined with the population projection. Consequently, the growth rate in APCEC and in total electricity production are products of the calculation; for example, China needs a 2.9% annual growth in APCEC and 3.2% annual growth in total electricity production to reach the benchmark in 2050.

This algorithm would produce unreasonable rates of growth in electricity use for some of the least developed economies. Consequently, a cap was imposed on total electricity consumption (TEC) in any country. The EIA annual growth rate in electricity use in developing countries is collectively 4.2% (see Table 2-1). We have taken 4.7%/year as the maximum achievable sustained growth rate for any individual country. This is a formidable growth rate over a long period of time, but it should be remembered that countries for which this is an issue start from extremely low APCEC and generally end with a low APCEC. Consequently, relatively high growth rates are more easily achieved (for example, China achieved a 10% growth rate in electricity production last year). The 4.7% annual growth rate compounds to a factor of ten growth in TEC over fifty years. This completes the simple algorithm used to construct the following tables.

The two different values for industrialized country APCEC result in 11% difference in 2050 global electricity use. From here on, we will employ the 1% APCEC growth rate for industrialized countries as a baseline. Shown in Table Series 2-1 and 2-2, are the results of the application of the algorithm listing total population, urban population, current electricity consumption and the projected consumption for 2050 (with and without the growth cap).

[3]UN projections used here are from the 2000 publications, which projects World Total Population to be 9,326 Billion for 2050, although recently issued (2002) UN publications project the World Total Population for 2050 to be 8,919 Billion.

TABLE 2-2(a): Electricity Consumption Projections (0.5% growth rate base)

Country	Total Population (Millions)		Total Urban Population (%)		Total Urban Population (Millions)		Total Electricity Consumption (Billion kWhrs)		After growth cap	Per Capita Consumption (kWhrs/person)		After growth cap
	2000	2050	2000	2050	2000	2050	2000	2050	2050	2000	2050	2050
Afghanistan	21.76	72.27	21.9	61.2	4.77	44.20	0.45	289.07	4.54	21	4,000	63
Albania	3.13	3.90	66.3	50.4	2.08	1.97	5.38	15.62	15.62	1,716	4,000	4,000
Algeria	30.29	51.18	57.1	85.1	17.30	43.54	21.85	204.72	204.72	721	4,000	4,000
American Samoa	0.07	0.17	52.7	81.7	0.04	0.14	0.12	0.69	0.69	1,787	4,000	4,000
Angola	13.13	53.33	34.2	74.6	4.49	39.77	1.11	213.31	11.07	84	4,000	208
Antigua and Barbuda	0.06	0.07	36.8	67.1	0.02	0.05	0.09	0.29	0.29	1,434	4,000	4,000
Argentina	37.03	54.52	88.2	94.7	32.66	51.64	80.81	218.09	218.09	2,182	4,000	4,000
Armenia	3.79	3.15	67.2	80.0	2.54	2.52	4.89	12.60	12.60	1,291	4,000	4,000
Aruba	0.10	0.24	50.8	74.5	0.05	0.18	0.42	1.29	1.29	4,161	5,340	5,340
Australia	19.14	26.50	90.7	100.0	17.36	26.50	188.49	334.95	334.95	9,849	12,639	12,639
Austria	8.08	6.45	67.3	82.9	5.44	5.35	54.76	56.12	56.12	6,778	8,698	8,698
Azerbaijan	8.04	8.90	51.9	66.6	4.17	5.93	16.68	35.59	35.59	2,075	4,000	4,000
Bahamas	0.30	0.45	88.5	96.7	0.27	0.43	1.43	2.71	2.71	4,708	6,041	6,041
Bahrain	0.64	1.01	92.2	98.9	0.59	1.00	5.36	10.84	10.84	8,380	10,754	10,754
Bangladesh	137.44	265.43	25.0	67.2	34.36	178.48	12.55	1,061.73	125.48	91	4,000	473
Barbados	0.27	0.26	50.0	81.2	0.13	0.21	0.69	1.05	1.05	2,573	4,000	4,000
Belarus	10.19	8.30	69.4	83.0	7.07	6.89	26.78	33.22	33.22	2,629	4,000	4,000
Belgium	10.25	9.58	97.3	99.3	9.97	9.52	78.13	93.74	93.74	7,623	9,782	9,782
Belize	0.23	0.39	48.0	67.7	0.11	0.27	0.18	1.57	1.57	789	4,000	4,000
Benin	6.27	18.07	42.3	81.5	2.65	14.72	0.52	72.28	5.23	83	4,000	290
Bermuda	0.06	0.08	100.0	100.0	0.06	0.08	0.55	0.89	0.89	8,789	11,278	11,278
Bhutan	2.09	5.57	7.1	34.3	0.15	1.91	0.38	22.28	3.81	183	4,000	684
Bolivia	8.33	16.97	62.4	87.3	5.20	14.81	3.61	67.86	36.05	433	4,000	2,125
Bosnia and Herzegovina	3.98	3.46	43.0	74.8	1.71	2.59	2.58	13.83	13.83	648	4,000	4,000
Botswana	1.54	2.11	49.0	76.7	0.76	1.62	1.45	8.44	8.44	941	4,000	4,000
Brazil	170.41	247.24	81.2	99.3	138.37	245.54	360.64	988.98	988.98	2,116	4,000	4,000
Brunei Darussalam	0.33	0.56	72.2	91.8	0.24	0.52	2.06	4.56	4.56	6,289	8,070	8,070
Bulgaria	7.95	4.53	67.5	78.5	5.37	3.56	34.42	25.17	25.17	4,330	5,556	5,556
Burkina Faso	11.54	46.30	16.5	51.3	1.90	23.76	0.26	185.21	2.62	23	4,000	57
Burundi	6.36	20.22	9.0	41.0	0.57	8.28	0.17	80.87	1.67	26	4,000	82
Cambodia	13.10	29.88	16.9	64.0	2.21	19.14	0.12	119.53	1.23	9	4,000	41
Cameroon	14.88	32.28	48.9	84.0	7.27	27.13	3.37	129.14	33.69	227	4,000	1,044
Canada	30.76	40.41	78.7	89.9	24.21	36.31	499.77	842.53	842.53	16,249	20,851	20,851
Cape Verde	0.43	0.81	62.2	95.1	0.27	0.77	0.04	3.23	0.38	89	4,000	472
Cayman Islands	0.04	0.09	100.0	100.0	0.04	0.09	0.33	0.99	0.99	8,636	11,082	11,082
Central African Republic	3.72	8.19	41.2	75.6	1.53	6.19	0.10	32.78	0.97	26	4,000	118
Chad	7.89	27.73	23.8	59.1	1.88	16.39	0.09	110.93	0.86	11	4,000	31
Chile	15.21	22.22	85.8	95.5	13.05	21.21	37.90	88.86	88.86	2,491	4,000	4,000
China	1,275.13	1,462.06	35.8	89.8	456.50	1,312.95	1,206.26	5,848.23	5,848.23	946	4,000	4,000
China, Hong Kong	7.12	7.76	100.0	100.0	7.12	7.76	35.40	49.52	49.52	4,975	6,384	6,384
Colombia	42.10	70.86	75.0	96.1	31.58	68.10	40.35	283.45	283.45	958	4,000	4,000
Comoros	0.71	1.90	33.2	72.6	0.23	1.38	0.02	7.60	0.18	25	4,000	93
Congo, DR	50.95	203.53	30.3	41.8	15.44	85.08	4.58	814.11	45.75	90	4,000	225
Congo, Rep. (Brazzaville)	3.02	10.74	65.4	73.4	1.97	7.88	0.43	42.97	4.29	142	4,000	400
Cook Islands	0.02	0.03	59.0	76.1	0.01	0.02	0.02	0.11	0.11	1,138	4,000	4,000
Costa Rica	4.02	7.20	59.0	85.2	2.37	6.13	5.89	28.78	28.78	1,465	4,000	4,000
IvoryCoast	16.01	32.19	43.6	73.5	6.98	23.65	3.55	128.74	35.50	222	4,000	1,103
Croatia	4.65	4.18	57.7	82.5	2.69	3.45	12.64	16.72	16.72	2,716	4,000	4,000
Cuba	11.20	10.76	75.3	87.3	8.43	9.40	13.83	43.06	43.06	1,235	4,000	4,000
Cyprus	0.78	0.91	69.9	86.6	0.55	0.79	2.91	4.34	4.34	3,714	4,766	4,766
Czech Republic	10.27	8.43	74.5	84.0	7.65	7.08	54.70	57.60	57.60	5,325	6,834	6,834
Denmark	5.32	5.08	85.1	88.7	4.53	4.51	33.93	41.57	41.57	6,377	8,183	8,183
Djibouti	0.63	1.07	84.0	93.2	0.53	1.00	0.17	4.27	1.67	265	4,000	1,567
Dominica	0.07	0.07	71.0	88.1	0.05	0.06	0.06	0.29	0.29	883	4,000	4,000
Dominican Republic	8.37	11.96	65.4	89.5	5.48	10.70	8.81	47.84	47.84	1,052	4,000	4,000
Ecuador	12.65	21.19	63.0	85.3	7.97	18.07	9.67	84.76	84.76	764	4,000	4,000
Egypt	67.88	113.84	42.7	61.9	28.99	70.44	64.72	455.36	455.36	953	4,000	4,000
El Salvador	6.28	10.86	60.3	98.8	3.79	10.73	4.07	43.42	40.70	648	4,000	3,749
Equatorial Guinea	0.46	1.38	48.2	91.2	0.22	1.26	0.02	5.51	0.20	45	4,000	148
Eritrea	3.66	10.03	18.7	56.5	0.68	5.66	0.20	40.11	1.95	53	4,000	195
Estonia	1.39	0.75	69.4	80.2	0.97	0.60	5.36	3.71	3.71	3,848	4,938	4,938
Ethiopia	62.91	186.45	15.5	50.2	9.75	93.64	1.52	745.81	15.16	24	4,000	81
Falkland Islands (Malvinas)	0.00	0.00	80.8	96.1	0.00	0.00	0.01	0.03	0.03	5,619	7,211	7,211
Fiji	0.81	0.92	49.4	86.1	0.40	0.79	0.48	3.66	3.66	589	4,000	4,000
Finland	5.17	4.69	59.0	66.2	3.05	3.11	81.96	95.44	95.44	15,848	20,336	20,336
France	59.24	61.83	75.4	87.0	44.67	53.80	408.51	547.18	547.18	6,896	8,849	8,849
French Guiana	0.16	0.50	75.1	85.4	0.12	0.43	0.42	2.01	2.01	2,539	4,000	4,000
French Polynesia	0.23	0.37	52.7	65.6	0.12	0.24	0.38	1.49	1.49	1,626	4,000	4,000

TABLE 2-2(b): Electricity Consumption Projections (0.5% cont.)

Gabon	1.23	3.16	81.4	100.0	1.00	3.16	0.79	12.66	7.91	643	4,000	2,498
Gambia	1.30	2.60	30.7	72.0	0.40	1.87	0.07	10.42	0.70	54	4,000	268
Georgia	5.26	3.22	56.3	78.1	2.96	2.51	7.89	12.88	12.88	1,499	4,000	4,000
Germany	82.02	70.80	87.5	94.8	71.76	67.16	501.72	555.80	555.80	6,117	7,850	7,850
Ghana	19.31	40.06	36.1	65.2	6.97	26.10	5.48	160.23	54.84	284	4,000	1,369
Gibraltar	0.03	0.02	100.0	100.0	0.03	0.02	0.09	0.09	0.09	3,392	4,352	4,352
Greece	10.61	8.98	60.1	80.6	6.38	7.24	46.10	50.09	50.09	4,345	5,575	5,575
Greenland	0.06	0.06	82.0	92.5	0.05	0.06	0.23	0.33	0.33	4,136	5,307	5,307
Grenada	0.09	0.10	37.9	75.2	0.04	0.08	0.10	0.42	0.42	1,094	4,000	4,000
Guadeloupe	0.43	0.48	99.6	100.2	0.43	0.48	1.29	1.92	1.92	3,021	4,000	4,000
Guam	0.16	0.31	39.2	71.4	0.06	0.22	0.77	1.95	1.95	4,944	6,345	6,345
Guatemala	11.39	26.55	39.7	69.2	4.52	18.36	4.80	106.20	47.97	421	4,000	1,807
Guinea	8.15	20.71	27.5	63.8	2.24	13.22	0.72	82.84	7.16	88	4,000	346
Guinea-Bissau	1.20	3.28	31.5	77.8	0.38	2.55	0.06	13.10	0.56	47	4,000	170
Guyana	0.76	0.50	36.3	70.0	0.28	0.35	0.47	2.02	2.02	618	4,000	4,000
Haiti	8.14	13.98	35.7	75.5	2.91	10.55	0.49	55.93	4.85	60	4,000	347
Honduras	6.42	12.84	52.7	90.1	3.38	11.57	3.59	51.38	35.93	560	4,000	2,797
Hungary	9.97	7.49	64.5	83.1	6.43	6.22	35.10	33.82	33.82	3,521	4,518	4,518
Iceland	0.28	0.33	92.5	97.6	0.26	0.32	7.02	10.73	10.73	25,136	32,255	32,255
India	1,008.94	1,572.05	27.7	50.8	279.48	798.09	509.89	6,288.22	5,098.86	505	4,000	3,243
Indonesia	212.09	311.33	41.0	91.1	86.96	283.48	86.09	1,245.34	860.95	406	4,000	2,765
Iran	70.33	121.42	64.0	93.4	45.01	113.37	111.91	485.70	485.70	1,591	4,000	4,000
Iraq	22.95	53.57	67.5	77.0	15.49	41.26	25.39	214.30	214.30	1,106	4,000	4,000
Ireland	3.80	5.37	59.0	79.3	2.24	4.26	20.82	37.70	37.70	5,475	7,026	7,026
Israel	6.04	10.06	91.6	97.1	5.53	9.77	34.90	74.61	74.61	5,777	7,413	7,413
Italy	57.53	42.96	66.9	82.7	38.49	35.55	283.74	271.90	271.90	4,932	6,329	6,329
Jamaica	2.58	3.82	56.1	82.9	1.45	3.16	6.27	15.26	15.26	2,433	4,000	4,000
Japan	127.10	109.22	78.8	88.9	100.15	97.10	943.71	1,040.67	1,040.67	7,425	9,528	9,528
Jordan	4.91	11.71	78.7	88.2	3.87	10.32	7.09	46.84	46.84	1,443	4,000	4,000
Kazakhstan	16.17	15.30	55.8	70.7	9.02	10.81	48.34	61.21	61.21	2,989	4,000	4,000
Kenya	30.67	55.37	33.4	87.0	10.24	48.16	4.43	221.47	44.33	145	4,000	801
Kiribati	0.08	0.14	38.2	69.7	0.03	0.10	0.01	0.55	0.07	79	4,000	471
Korea, North (DROK)	22.27	28.04	60.2	67.8	13.41	19.02	31.06	112.15	112.15	1,395	4,000	4,000
Korea, South (ROK)	46.74	51.56	81.9	87.5	38.28	45.13	254.08	359.89	359.89	5,436	6,980	6,980
Kuwait	1.91	4.00	96.0	98.6	1.84	3.95	29.02	77.82	77.82	15,157	19,449	19,449
Kyrgyzstan	4.92	7.54	34.4	50.3	1.69	3.79	9.82	30.15	30.15	1,995	4,000	4,000
Lao People's Dem. Republic	5.28	11.44	19.3	58.1	1.02	6.65	0.69	45.75	6.91	131	4,000	604
Latvia	2.42	1.74	60.4	66.3	1.46	1.16	5.16	6.98	6.98	2,132	4,000	4,000
Lebanon	3.50	5.02	89.7	97.5	3.14	4.89	8.64	20.07	20.07	2,472	4,000	4,000
Lesotho	2.03	2.48	28.0	73.9	0.57	1.83	0.10	9.91	1.00	49	4,000	404
Liberia	2.91	14.37	44.9	79.1	1.31	11.37	0.42	57.48	4.19	144	4,000	291
Libya	5.29	9.97	87.6	95.6	4.63	9.53	18.04	43.63	43.63	3,411	4,377	4,377
Lithuania	3.70	2.99	68.5	81.9	2.53	2.45	6.90	11.95	11.95	1,866	4,000	4,000
Luxembourg	0.44	0.71	91.5	100.0	0.40	0.72	6.16	12.93	12.93	14,097	18,090	18,090
Madagascar	15.97	47.03	29.5	71.7	4.71	33.73	0.76	188.12	7.63	48	4,000	162
Malawi	11.31	31.11	14.7	49.6	1.66	15.43	0.77	124.45	7.67	68	4,000	247
Malaysia	22.22	37.85	57.4	87.1	12.75	32.96	58.59	151.40	151.40	2,637	4,000	4,000
Maldives	0.29	0.87	27.6	62.7	0.08	0.54	0.10	3.47	1.02	352	4,000	1,179
Mali	11.35	41.72	30.2	74.4	3.43	31.04	0.43	166.90	4.30	38	4,000	103
Malta	0.39	0.40	90.9	98.5	0.35	0.39	1.63	2.14	2.14	4,174	5,356	5,356
Martinique	0.38	0.41	94.9	100.0	0.36	0.41	1.05	1.65	1.65	2,729	4,000	4,000
Mauritania	2.66	8.45	57.7	100.0	1.54	8.45	0.14	33.81	1.43	54	4,000	169
Mauritius	1.16	1.43	41.3	72.4	0.48	1.03	1.20	5.70	5.70	1,029	4,000	4,000
Mexico	98.87	146.65	74.4	87.3	73.56	128.05	182.83	586.61	586.61	1,849	4,000	4,000
Moldova	4.30	3.58	41.6	62.3	1.79	2.23	3.65	14.31	14.31	851	4,000	4,000
Mongolia	2.53	4.15	56.6	72.6	1.43	3.01	2.73	16.58	16.58	1,078	4,000	4,000
Montserrat	0.00	0.01	13.0	37.2	0.00	0.00	0.00	0.04	0.04	1,240	4,000	4,000
Morocco	29.88	50.36	55.5	85.5	16.58	43.08	14.35	201.44	143.46	480	4,000	2,849
Mozambique	18.29	38.84	32.1	94.6	5.87	36.73	0.93	155.35	9.26	51	4,000	238
Myanmar	47.75	68.55	27.7	39.2	13.23	26.85	4.50	274.18	45.00	94	4,000	656
Namibia	1.76	3.66	30.9	68.5	0.54	2.51	0.89	14.65	8.91	507	4,000	2,433
Nauru	0.01	0.03	100.0	100.0	0.01	0.03	0.03	0.10	0.10	2,283	4,000	4,000
Nepal	23.04	52.41	11.8	45.6	2.72	23.91	1.43	209.66	14.31	62	4,000	273
Netherlands	15.86	15.85	89.5	94.8	14.20	15.02	100.71	129.09	129.09	6,349	8,147	8,147
Netherlands Antilles	0.22	0.26	69.2	84.3	0.15	0.22	1.09	1.69	1.69	5,076	6,514	6,514
New Caledonia	0.22	0.40	78.9	100.0	0.17	0.40	1.46	3.44	3.44	6,760	8,675	8,675
New Zealand	3.78	4.44	85.8	91.9	3.24	4.08	33.32	50.23	50.23	8,818	11,316	11,316
Nicaragua	5.07	11.48	56.1	81.0	2.85	9.29	2.18	45.91	21.76	429	4,000	1,896
Niger	10.83	51.87	20.6	61.5	2.23	31.91	0.40	207.49	4.05	37	4,000	78
Nigeria	113.86	278.79	44.1	84.4	50.21	235.23	14.77	1,115.15	147.68	130	4,000	530
Niue	0.00	0.00	32.8	62.8	0.00	0.00	0.00	0.01	0.01	1,394	4,000	4,000
Norway	4.47	4.88	74.7	88.9	3.34	4.34	112.50	157.63	157.63	25,172	32,302	32,302
Oman	2.54	8.75	76.0	95.1	1.93	8.32	7.53	35.01	35.01	2,968	4,000	4,000

TABLE 2-2(c): Electricity Consumption Projections (0.5% cont.)

Pakistan	141.26	344.17	33.1	63.1	46.76	217.16	58.30	1,376.68	582.99	413	4,000	1,694
Panama	2.86	4.26	56.3	78.1	1.61	3.33	4.65	17.05	17.05	1,629	4,000	4,000
Papua New Guinea	4.81	10.98	17.4	43.1	0.84	4.74	1.53	43.92	15.35	319	4,000	1,397
Paraguay	5.50	12.56	56.0	86.3	3.08	10.84	1.95	50.26	19.50	355	4,000	1,552
Peru	25.66	42.12	72.8	89.5	18.68	37.68	18.30	168.49	168.49	713	4,000	4,000
Philippines	75.65	128.38	58.6	91.7	44.33	117.71	37.82	513.53	378.20	500	4,000	2,946
Poland	38.61	33.37	62.3	80.0	24.05	26.70	119.33	133.48	133.48	3,091	4,000	4,000
Portugal	10.02	9.01	64.4	100.0	6.45	9.04	41.15	47.48	47.48	4,108	5,272	5,272
Puerto Rico	3.91	4.83	75.2	90.5	2.94	4.38	19.06	30.21	30.21	4,869	6,249	6,249
Qatar	0.57	0.83	92.7	98.8	0.52	0.82	8.56	16.13	16.13	15,132	19,417	19,417
Reunion	0.72	1.00	71.4	94.4	0.51	0.95	1.01	4.01	4.01	1,406	4,000	4,000
Romania	22.44	18.15	55.1	74.3	12.36	13.49	45.68	72.60	72.60	2,036	4,000	4,000
Russia	145.49	104.26	72.9	80.1	106.06	83.48	767.08	705.37	705.37	5,272	6,766	6,766
Rwanda	7.61	18.52	8.2	18.2	0.62	3.36	0.17	74.09	1.74	23	4,000	94
Saint Helena	0.01	0.01	70.6	97.3	0.00	0.01	0.00	0.04	0.04	739	4,000	4,000
Saint Kitts and Nevis	0.04	0.03	34.1	61.8	0.01	0.02	0.09	0.14	0.14	2,296	4,000	4,000
Saint Lucia	0.15	0.19	37.8	66.4	0.06	0.13	0.11	0.75	0.75	724	4,000	4,000
Saint Pierre and Miquelon	0.01	0.01	92.1	96.6	0.01	0.01	0.04	0.06	0.06	5,564	7,140	7,140
Saint Vincent and Grenadines	0.11	0.14	54.8	94.9	0.06	0.13	0.08	0.55	0.55	714	4,000	4,000
Samoa	0.16	0.22	22.1	100.0	0.04	0.71	0.10	0.89	0.89	604	4,000	4,000
Sao Tome and Principe	0.14	0.29	47.0	81.5	0.06	0.24	0.02	1.18	0.16	115	4,000	538
Saudi Arabia	20.35	59.68	86.2	98.4	17.54	58.73	114.86	432.33	432.33	5,645	7,244	7,244
Senegal	9.42	22.71	47.4	83.2	4.47	18.90	1.23	90.85	12.28	130	4,000	541
Seychelles	0.08	0.15	63.8	90.3	0.05	0.13	0.15	0.58	0.58	1,850	4,000	4,000
Sierra Leone	4.40	14.35	36.6	76.7	1.61	11.01	0.23	57.41	2.28	52	4,000	159
Singapore	4.02	4.62	100.0	100.0	4.02	4.62	25.95	38.28	38.28	6,458	8,286	8,286
Slovakia	5.40	4.67	57.4	78.0	3.10	3.64	25.20	28.00	28.00	4,668	5,991	5,991
Slovenia	1.99	1.53	49.2	65.6	0.98	1.00	10.62	10.47	10.47	5,342	6,855	6,855
Solomon Islands	0.45	1.46	19.7	62.2	0.09	0.91	0.03	5.83	0.30	67	4,000	204
Somalia	8.78	40.94	27.5	65.7	2.41	26.89	0.23	163.74	2.33	26	4,000	57
South Africa	43.31	47.30	56.9	90.3	24.64	42.74	181.52	254.40	254.40	4,191	5,378	5,378
Spain	39.91	31.28	77.6	89.8	30.97	28.11	201.16	202.32	202.32	5,040	6,468	6,468
Sri Lanka	18.92	23.07	22.8	58.1	4.31	13.40	6.16	92.27	61.56	325	4,000	2,669
Sudan	31.10	63.53	36.1	83.2	11.23	52.85	1.83	254.12	18.32	59	4,000	288
Suriname	0.42	0.42	74.1	94.5	0.31	0.40	1.31	1.68	1.68	3,137	4,025	4,025
Swaziland	0.92	1.39	26.4	57.6	0.24	0.80	0.90	5.57	5.57	974	4,000	4,000
Sweden	8.84	7.78	83.3	88.2	7.37	6.86	139.18	157.07	157.07	15,740	20,198	20,198
Switzerland	7.17	5.61	67.4	79.1	4.83	4.43	52.62	52.80	52.80	7,338	9,417	9,417
Syria	16.19	36.35	51.4	77.7	8.32	28.24	17.67	145.38	145.38	1,092	4,000	4,000
Taiwan	22.19	22.55	75.6	89.7	16.78	20.23	139.00	181.00	181.00	6,277	8,054	8,054
Tajikistan	6.09	9.76	27.6	47.2	1.68	4.61	12.54	39.05	39.05	2,060	4,000	4,000
Tanzania	35.12	82.74	32.3	85.3	11.34	70.60	2.62	330.96	26.16	75	4,000	316
Thailand	62.81	82.49	19.8	44.9	12.44	37.00	90.26	329.96	329.96	1,437	4,000	4,000
Togo	4.53	11.83	33.4	72.2	1.51	8.54	0.53	47.33	5.25	116	4,000	444
Tonga	0.10	0.13	32.7	100.0	0.03	0.13	0.03	0.50	0.28	282	4,000	2,230
Trinidad and Tobago	1.29	1.38	74.1	90.5	0.96	1.25	4.79	6.55	6.55	3,702	4,751	4,751
Tunisia	9.46	14.08	65.5	90.3	6.20	12.71	9.56	56.30	56.30	1,011	4,000	4,000
Turkey	66.67	98.82	65.8	86.4	43.87	85.38	114.19	395.27	395.27	1,713	4,000	4,000
Turkmenistan	4.74	8.40	44.8	69.8	2.12	5.86	7.71	33.60	33.60	1,627	4,000	4,000
Turks and Caicos Islands	0.02	0.04	45.2	76.5	0.01	0.03	0.00	0.15	0.05	278	4,000	1,205
Uganda	23.30	101.52	14.2	49.1	3.31	49.83	1.31	406.09	13.14	56	4,000	129
Ukraine	49.57	29.96	67.9	80.4	33.66	24.10	151.72	119.84	119.84	3,061	4,000	4,000
United Arab Emirates	2.61	3.71	86.7	99.3	2.26	3.68	35.99	65.74	65.74	13,811	17,723	17,723
United Kingdom	59.41	58.93	89.5	94.4	53.18	55.61	345.03	439.16	439.16	5,807	7,452	7,452
USA	283.23	397.06	77.2	90.1	218.65	357.75	3,621.00	6,514.05	6,514.05	12,785	16,406	16,406
Uruguay	3.34	4.25	91.9	98.4	3.07	4.18	7.35	16.99	16.99	2,203	4,000	4,000
Uzbekistan	24.88	40.51	36.7	52.8	9.13	21.37	41.89	162.05	162.05	1,684	4,000	4,000
Vanuatu	0.20	0.46	21.7	55.8	0.04	0.26	0.04	1.85	1.85	184	4,000	4,000
Venezuela	24.17	42.15	88.9	93.8	21.49	39.52	75.10	168.61	168.61	3,107	4,000	4,000
Vietnam	78.14	123.78	24.1	59.9	18.83	74.17	23.97	495.13	239.71	307	4,000	1,937
Western Sahara	0.25	0.60	95.4	100.0	0.24	0.60	0.08	2.39	0.84	332	4,000	1,398
Yemen	18.35	102.38	24.7	57.5	4.53	58.91	2.98	409.51	29.76	162	4,000	291
Yugoslavia	10.55	9.03	51.6	70.9	5.45	6.41	31.55	36.12	36.12	2,989	4,000	4,000
Zambia	10.42	29.26	39.6	67.2	4.13	19.67	5.84	117.05	58.38	560	4,000	1,995
Zimbabwe	12.63	23.55	35.3	77.2	4.46	18.18	10.48	94.18	94.18	830	4,000	4,000
Totals	**6,072**	**9,326**	**47.4**	**74.3**	**2,877**	**6,928**	**13,710**	**46,404**	**34,983**	**2,258**	**4,976**	**3,751**

***Table uses 0.5% per year increase in per capita electricity consumption**

TABLE 2-3(a): Electricity Consumption Projections (1% growth rate base)

Country	Total Population (Millions)		Total Urban Population (%)		Total Urban Population (Millions)		Total Electricity Consumption (Billion kWhrs)		After cutoff	Per Capita Consumption (kWhrs/person)		After Cutoff
	2000	2050	2000	2050	2000	2050	2000	2050	2050	2000	2050	2050
Afghanistan	21.76	72.27	21.9	61.2	4.77	44.20	0.45	289.07	4.54	21	4,000	63
Albania	3.13	3.90	66.3	50.4	2.08	1.97	5.38	15.62	15.62	1,716	4,000	4,000
Algeria	30.29	51.18	57.1	85.1	17.30	43.54	21.85	204.72	204.72	721	4,000	4,000
American Samoa	0.07	0.17	52.7	81.7	0.04	0.14	0.12	0.69	0.69	1,787	4,000	4,000
Angola	13.13	53.33	34.2	74.6	4.49	39.77	1.11	213.31	11.07	84	4,000	208
Antigua and Barbuda	0.06	0.07	36.8	67.1	0.02	0.05	0.09	0.29	0.29	1,434	4,000	4,000
Argentina	37.03	54.52	88.2	94.7	32.66	51.64	80.81	218.09	218.09	2,182	4,000	4,000
Armenia	3.79	3.15	67.2	80.0	2.54	2.52	4.89	12.60	12.60	1,291	4,000	4,000
Aruba	0.10	0.24	50.8	74.5	0.05	0.18	0.42	1.65	1.65	4,161	6,844	6,844
Australia	19.14	26.50	90.7	100.0	17.36	26.50	188.49	429.29	429.29	9,849	16,198	16,198
Austria	8.08	6.45	67.3	82.9	5.44	5.35	54.76	71.92	71.92	6,778	11,147	11,147
Azerbaijan	8.04	8.90	51.9	66.6	4.17	5.93	16.68	35.59	35.59	2,075	4,000	4,000
Bahamas	0.30	0.45	88.5	96.7	0.27	0.43	1.43	3.47	3.47	4,708	7,742	7,742
Bahrain	0.64	1.01	92.2	98.9	0.59	1.00	5.36	13.89	13.89	8,380	13,783	13,783
Bangladesh	137.44	265.43	25.0	67.2	34.36	178.48	12.55	1,061.73	125.48	91	4,000	473
Barbados	0.27	0.26	50.0	81.2	0.13	0.21	0.69	1.05	1.05	2,573	4,000	4,000
Belarus	10.19	8.30	69.4	83.0	7.07	6.89	26.78	33.22	33.22	2,629	4,000	4,000
Belgium	10.25	9.58	97.3	99.3	9.97	9.52	78.13	120.14	120.14	7,623	12,537	12,537
Belize	0.23	0.39	48.0	67.7	0.11	0.27	0.18	1.57	1.57	789	4,000	4,000
Benin	6.27	18.07	42.3	81.5	2.65	14.72	0.52	72.28	5.23	83	4,000	290
Bermuda	0.06	0.08	100.0	100.0	0.06	0.08	0.55	1.15	1.15	8,789	14,455	14,455
Bhutan	2.09	5.57	7.1	34.3	0.15	1.91	0.38	22.28	3.81	183	4,000	684
Bolivia	8.33	16.97	62.4	87.3	5.20	14.81	3.61	67.86	36.05	433	4,000	2,125
Bosnia and Herzegovina	3.98	3.46	43.0	74.8	1.71	2.59	2.58	13.83	13.83	648	4,000	4,000
Botswana	1.54	2.11	49.0	76.7	0.76	1.62	1.45	8.44	8.44	941	4,000	4,000
Brazil	170.41	247.24	81.2	99.3	138.37	245.54	360.64	988.98	988.98	2,116	4,000	4,000
Brunei Darussalam	0.33	0.56	72.2	91.8	0.24	0.52	2.06	5.84	5.84	6,289	10,343	10,343
Bulgaria	7.95	4.53	67.5	78.5	5.37	3.56	34.42	32.26	32.26	4,330	7,121	7,121
Burkina Faso	11.54	46.30	16.5	51.3	1.90	23.76	0.26	185.21	2.62	23	4,000	57
Burundi	6.36	20.22	9.0	41.0	0.57	8.28	0.17	80.87	1.67	26	4,000	82
Cambodia	13.10	29.88	16.9	64.0	2.21	19.14	0.12	119.53	1.23	9	4,000	41
Cameroon	14.88	32.28	48.9	84.0	7.27	27.13	3.37	129.14	33.69	227	4,000	1,044
Canada	30.76	40.41	78.7	89.9	24.21	36.31	499.77	1,079.82	1,079.82	16,249	26,724	26,724
Cape Verde	0.43	0.81	62.2	95.1	0.27	0.77	0.04	3.23	0.38	89	4,000	472
Cayman Islands	0.04	0.09	100.0	100.0	0.04	0.09	0.33	1.27	1.27	8,636	14,202	14,202
Central African Republic	3.72	8.19	41.2	75.6	1.53	6.19	0.10	32.78	0.97	26	4,000	118
Chad	7.89	27.73	23.8	59.1	1.88	16.39	0.09	110.93	0.86	11	4,000	31
Chile	15.21	22.22	85.8	95.5	13.05	21.21	37.90	88.86	88.86	2,491	4,000	4,000
China	1,275.13	1,462.06	35.8	89.8	456.50	1,312.95	1,206.26	5,848.23	5,848.23	946	4,000	4,000
China, Hong Kong	7.12	7.76	100.0	100.0	7.12	7.76	35.40	63.46	63.46	4,975	8,182	8,182
Colombia	42.10	70.86	75.0	96.1	31.58	68.10	40.35	283.45	283.45	958	4,000	4,000
Comoros	0.71	1.90	33.2	72.6	0.23	1.38	0.02	7.60	0.18	25	4,000	93
Congo, DR	50.95	203.53	30.3	41.8	15.44	85.08	4.58	814.11	45.75	90	4,000	225
Congo, Rep. (Brazzaville)	3.02	10.74	65.4	73.4	1.97	7.88	0.43	42.97	4.29	142	4,000	400
Cook Islands	0.02	0.03	59.0	76.1	0.01	0.02	0.02	0.11	0.11	1,138	4,000	4,000
Costa Rica	4.02	7.20	59.0	85.2	2.37	6.13	5.89	28.78	28.78	1,465	4,000	4,000
IvoryCoast	16.01	32.19	43.6	73.5	6.98	23.65	3.55	128.74	35.50	222	4,000	1,103
Croatia	4.65	4.18	57.7	82.5	2.69	3.45	12.64	16.72	16.72	2,716	4,000	4,000
Cuba	11.20	10.76	75.3	87.3	8.43	9.40	13.83	43.06	43.06	1,235	4,000	4,000
Cyprus	0.78	0.91	69.9	86.6	0.55	0.79	2.91	5.56	5.56	3,714	6,108	6,108
Czech Republic	10.27	8.43	74.5	84.0	7.65	7.08	54.70	73.83	73.83	5,325	8,758	8,758
Denmark	5.32	5.08	85.1	88.7	4.53	4.51	33.93	53.28	53.28	6,377	10,488	10,488
Djibouti	0.63	1.07	84.0	93.2	0.53	1.00	0.17	4.27	1.67	265	4,000	1,567
Dominica	0.07	0.07	71.0	88.1	0.05	0.06	0.06	0.29	0.29	883	4,000	4,000
Dominican Republic	8.37	11.96	65.4	89.5	5.48	10.70	8.81	47.84	47.84	1,052	4,000	4,000
Ecuador	12.65	21.19	63.0	85.3	7.97	18.07	9.67	84.76	84.76	764	4,000	4,000
Egypt	67.88	113.84	42.7	61.9	28.99	70.44	64.72	455.36	455.36	953	4,000	4,000
El Salvador	6.28	10.86	60.3	98.8	3.79	10.73	4.07	43.42	40.70	648	4,000	3,749
Equatorial Guinea	0.46	1.38	48.2	91.2	0.22	1.26	0.02	5.51	0.20	45	4,000	148
Eritrea	3.66	10.03	18.7	56.5	0.68	5.66	0.20	40.11	1.95	53	4,000	195
Estonia	1.39	0.75	69.4	80.2	0.97	0.60	5.36	4.76	4.76	3,848	6,329	6,329
Ethiopia	62.91	186.45	15.5	50.2	9.75	93.64	1.52	745.81	15.16	24	4,000	81
Falkland Islands (Malvinas)	0.00	0.00	80.8	96.1	0.00	0.00	0.01	0.03	0.03	5,619	9,242	9,242
Fiji	0.81	0.92	49.4	86.1	0.40	0.79	0.48	3.66	3.66	589	4,000	4,000
Finland	5.17	4.69	59.0	66.2	3.05	3.11	81.96	122.31	122.31	15,848	26,064	26,064
France	59.24	61.83	75.4	87.0	44.67	53.80	408.51	701.28	701.28	6,896	11,342	11,342
French Guiana	0.16	0.50	75.1	85.4	0.12	0.43	0.42	2.01	2.01	2,539	4,000	4,000
French Polynesia	0.23	0.37	52.7	65.6	0.12	0.24	0.38	1.49	1.49	1,626	4,000	4,000

TABLE 2-3(b): Electricity Consumption Projections (1.0% cont.)

Gabon	1.23	3.16	81.4	100.0	1.00	3.16	0.79	12.66	7.91	643	4,000	2,498
Gambia	1.30	2.60	30.7	72.0	0.40	1.87	0.07	10.42	0.70	54	4,000	268
Georgia	5.26	3.22	56.3	78.1	2.96	2.51	7.89	12.88	12.88	1,499	4,000	4,000
Germany	82.02	70.80	87.5	94.8	71.76	67.16	501.72	712.34	712.34	6,117	10,061	10,061
Ghana	19.31	40.06	36.1	65.2	6.97	26.10	5.48	160.23	54.84	284	4,000	1,369
Gibraltar	0.03	0.02	100.0	100.0	0.03	0.02	0.09	0.12	0.12	3,392	5,578	5,578
Greece	10.61	8.98	60.1	80.6	6.38	7.24	46.10	64.19	64.19	4,345	7,146	7,146
Greenland	0.06	0.06	82.0	92.5	0.05	0.06	0.23	0.42	0.42	4,136	6,801	6,801
Grenada	0.09	0.10	37.9	75.2	0.04	0.08	0.10	0.42	0.42	1,094	4,000	4,000
Guadeloupe	0.43	0.48	99.6	100.2	0.43	0.48	1.29	1.92	1.92	3,021	4,000	4,000
Guam	0.16	0.31	39.2	71.4	0.06	0.22	0.77	2.50	2.50	4,944	8,132	8,132
Guatemala	11.39	26.55	39.7	69.2	4.52	18.36	4.80	106.20	47.97	421	4,000	1,807
Guinea	8.15	20.71	27.5	63.8	2.24	13.22	0.72	82.84	7.16	88	4,000	346
Guinea-Bissau	1.20	3.28	31.5	77.8	0.38	2.55	0.06	13.10	0.56	47	4,000	170
Guyana	0.76	0.50	36.3	70.0	0.28	0.35	0.47	2.02	2.02	618	4,000	4,000
Haiti	8.14	13.98	35.7	75.5	2.91	10.55	0.49	55.93	4.85	60	4,000	347
Honduras	6.42	12.84	52.7	90.1	3.38	11.57	3.59	51.38	35.93	560	4,000	2,797
Hungary	9.97	7.49	64.5	83.1	6.43	6.22	35.10	43.35	43.35	3,521	5,791	5,791
Iceland	0.28	0.33	92.5	97.6	0.26	0.32	7.02	13.75	13.75	25,136	41,339	41,339
India	1,008.94	1,572.05	27.7	50.8	279.48	798.09	509.89	6,288.22	5,098.86	505	4,000	3,243
Indonesia	212.09	311.33	41.0	91.1	86.96	283.48	86.09	1,245.34	860.95	406	4,000	2,765
Iran	70.33	121.42	64.0	93.4	45.01	113.37	111.91	485.70	485.70	1,591	4,000	4,000
Iraq	22.95	53.57	67.5	77.0	15.49	41.26	25.39	214.30	214.30	1,106	4,000	4,000
Ireland	3.80	5.37	59.0	79.3	2.24	4.26	20.82	48.32	48.32	5,475	9,005	9,005
Israel	6.04	10.06	91.6	97.1	5.53	9.77	34.90	95.63	95.63	5,777	9,501	9,501
Italy	57.53	42.96	66.9	82.7	38.49	35.55	283.74	348.48	348.48	4,932	8,111	8,111
Jamaica	2.58	3.82	56.1	82.9	1.45	3.16	6.27	15.26	15.26	2,433	4,000	4,000
Japan	127.10	109.22	78.8	88.9	100.15	97.10	943.71	1,333.76	1,333.76	7,425	12,212	12,212
Jordan	4.91	11.71	78.7	88.2	3.87	10.32	7.09	46.84	46.84	1,443	4,000	4,000
Kazakhstan	16.17	15.30	55.8	70.7	9.02	10.81	48.34	61.21	61.21	2,989	4,000	4,000
Kenya	30.67	55.37	33.4	87.0	10.24	48.16	4.43	221.47	44.33	145	4,000	801
Kiribati	0.08	0.14	38.2	69.7	0.03	0.10	0.01	0.55	0.07	79	4,000	471
Korea, North (DROK)	22.27	28.04	60.2	67.8	13.41	19.02	31.06	112.15	112.15	1,395	4,000	4,000
Korea, South (ROK)	46.74	51.56	81.9	87.5	38.28	45.13	254.08	460.96	460.96	5,436	8,940	6,980
Kuwait	1.91	4.00	96.0	98.6	1.84	3.95	29.02	99.74	99.74	15,157	24,927	24,927
Kyrgyzstan	4.92	7.54	34.4	50.3	1.69	3.79	9.82	30.15	30.15	1,995	4,000	4,000
Lao People's Dem. Republic	5.28	11.44	19.3	58.1	1.02	6.65	0.69	45.75	6.91	131	4,000	604
Latvia	2.42	1.74	60.4	66.3	1.46	1.16	5.16	6.98	6.98	2,132	4,000	4,000
Lebanon	3.50	5.02	89.7	97.5	3.14	4.89	8.64	20.07	20.07	2,472	4,000	4,000
Lesotho	2.03	2.48	28.0	73.9	0.57	1.83	0.10	9.91	1.00	49	4,000	404
Liberia	2.91	14.37	44.9	79.1	1.31	11.37	0.42	57.48	4.19	144	4,000	291
Libya	5.29	9.97	87.6	95.6	4.63	9.53	18.04	55.92	55.92	3,411	5,609	5,609
Lithuania	3.70	2.99	68.5	81.9	2.53	2.45	6.90	11.95	11.95	1,866	4,000	4,000
Luxembourg	0.44	0.71	91.5	100.0	0.40	0.72	6.16	16.57	16.57	14,097	23,185	23,185
Madagascar	15.97	47.03	29.5	71.7	4.71	33.73	0.76	188.12	7.63	48	4,000	162
Malawi	11.31	31.11	14.7	49.6	1.66	15.43	0.77	124.45	7.67	68	4,000	247
Malaysia	22.22	37.85	57.4	87.1	12.75	32.96	58.59	151.40	151.40	2,637	4,000	4,000
Maldives	0.29	0.87	27.6	62.7	0.08	0.54	0.10	3.47	1.02	352	4,000	1,179
Mali	11.35	41.72	30.2	74.4	3.43	31.04	0.43	166.90	4.30	38	4,000	103
Malta	0.39	0.40	90.9	98.5	0.35	0.39	1.63	2.74	2.74	4,174	6,864	6,864
Martinique	0.38	0.41	94.9	100.0	0.36	0.41	1.05	1.65	1.65	2,729	4,000	4,000
Mauritania	2.66	8.45	57.7	100.0	1.54	8.45	0.14	33.81	1.43	54	4,000	169
Mauritius	1.16	1.43	41.3	72.4	0.48	1.03	1.20	5.70	5.70	1,029	4,000	4,000
Mexico	98.87	146.65	74.4	87.3	73.56	128.05	182.83	586.61	586.61	1,849	4,000	4,000
Moldova	4.30	3.58	41.6	62.3	1.79	2.23	3.65	14.31	14.31	851	4,000	4,000
Mongolia	2.53	4.15	56.6	72.6	1.43	3.01	2.73	16.58	16.58	1,078	4,000	4,000
Montserrat	0.00	0.01	13.0	37.2	0.00	0.00	0.00	0.04	0.04	1,240	4,000	4,000
Morocco	29.88	50.36	55.5	85.5	16.58	43.08	14.35	201.44	143.46	480	4,000	2,849
Mozambique	18.29	38.84	32.1	94.6	5.87	36.73	0.93	155.35	9.26	51	4,000	238
Myanmar	47.75	68.55	27.7	39.2	13.23	26.85	4.50	274.18	45.00	94	4,000	656
Namibia	1.76	3.66	30.9	68.5	0.54	2.51	0.89	14.65	8.91	507	4,000	2,433
Nauru	0.01	0.03	100.0	100.0	0.01	0.03	0.03	0.10	0.10	2,283	4,000	4,000
Nepal	23.04	52.41	11.8	45.6	2.72	23.91	1.43	209.66	14.31	62	4,000	273
Netherlands	15.86	15.85	89.5	94.8	14.20	15.02	100.71	165.44	165.44	6,349	10,441	10,441
Netherlands Antilles	0.22	0.26	69.2	84.3	0.15	0.22	1.09	2.16	2.16	5,076	8,348	8,348
New Caledonia	0.22	0.40	78.9	100.0	0.17	0.40	1.46	4.41	4.41	6,760	11,118	11,118
New Zealand	3.78	4.44	85.8	91.9	3.24	4.08	33.32	64.38	64.38	8,818	14,503	14,503
Nicaragua	5.07	11.48	56.1	81.0	2.85	9.29	2.18	45.91	21.76	429	4,000	1,896
Niger	10.83	51.87	20.6	61.5	2.23	31.91	0.40	207.49	4.05	37	4,000	78
Nigeria	113.86	278.79	44.1	84.4	50.21	235.23	14.77	1,115.15	147.68	130	4,000	530
Niue	0.00	0.00	32.8	62.8	0.00	0.00	0.00	0.01	0.01	1,394	4,000	4,000
Norway	4.47	4.88	74.7	88.9	3.34	4.34	112.50	202.03	202.03	25,172	41,399	41,399
Oman	2.54	8.75	76.0	95.1	1.93	8.32	7.53	35.01	35.01	2,968	4,000	4,000

TABLE 2-3(c): Electricity Consumption Projections (1.0% cont.)

Pakistan	141.26	344.17	33.1	63.1	46.76	217.16	58.30	1,376.68	582.99	413	4,000	1,694
Panama	2.86	4.26	56.3	78.1	1.61	3.33	4.65	17.05	17.05	1,629	4,000	4,000
Papua New Guinea	4.81	10.98	17.4	43.1	0.84	4.74	1.53	43.92	15.35	319	4,000	1,397
Paraguay	5.50	12.56	56.0	86.3	3.08	10.84	1.95	50.26	19.50	355	4,000	1,552
Peru	25.66	42.12	72.8	89.5	18.68	37.68	18.30	168.49	168.49	713	4,000	4,000
Philippines	75.65	128.38	58.6	91.7	44.33	117.71	37.82	513.53	378.20	500	4,000	2,946
Poland	38.61	33.37	62.3	80.0	24.05	26.70	119.33	133.48	133.48	3,091	4,000	4,000
Portugal	10.02	9.01	64.4	100.0	6.45	9.04	41.15	60.85	60.85	4,108	6,756	6,756
Puerto Rico	3.91	4.83	75.2	90.5	2.94	4.38	19.06	38.72	38.72	4,869	8,008	8,008
Qatar	0.57	0.83	92.7	98.8	0.52	0.82	8.56	20.67	20.67	15,132	24,886	24,886
Reunion	0.72	1.00	71.4	94.4	0.51	0.95	1.01	4.01	4.01	1,406	4,000	4,000
Romania	22.44	18.15	55.1	74.3	12.36	13.49	45.68	72.60	72.60	2,036	4,000	4,000
Russia	145.49	104.26	72.9	80.1	106.06	83.48	767.08	904.03	904.03	5,272	8,671	8,671
Rwanda	7.61	18.52	8.2	18.2	0.62	3.36	0.17	74.09	1.74	23	4,000	94
Saint Helena	0.01	0.01	70.6	97.3	0.00	0.01	0.00	0.04	0.04	739	4,000	4,000
Saint Kitts and Nevis	0.04	0.03	34.1	61.8	0.01	0.02	0.09	0.14	0.14	2,296	4,000	4,000
Saint Lucia	0.15	0.19	37.8	66.4	0.06	0.13	0.11	0.75	0.75	724	4,000	4,000
Saint Pierre and Miquelon	0.01	0.01	92.1	96.6	0.01	0.01	0.04	0.08	0.08	5,564	9,151	9,151
Saint Vincent and Grenadin	0.11	0.14	54.8	94.9	0.06	0.13	0.08	0.55	0.55	714	4,000	4,000
Samoa	0.16	0.22	22.1	100.0	0.04	0.71	0.10	0.89	0.89	604	4,000	4,000
Sao Tome and Principe	0.14	0.29	47.0	81.5	0.06	0.24	0.02	1.18	0.16	115	4,000	538
Saudi Arabia	20.35	59.68	86.2	98.4	17.54	58.73	114.86	554.10	554.10	5,645	9,284	9,284
Senegal	9.42	22.71	47.4	83.2	4.47	18.90	1.23	90.85	12.28	130	4,000	541
Seychelles	0.08	0.15	63.8	90.3	0.05	0.13	0.15	0.58	0.58	1,850	4,000	4,000
Sierra Leone	4.40	14.35	36.6	76.7	1.61	11.01	0.23	57.41	2.28	52	4,000	159
Singapore	4.02	4.62	100.0	100.0	4.02	4.62	25.95	49.06	49.06	6,458	10,620	10,620
Slovakia	5.40	4.67	57.4	78.0	3.10	3.64	25.20	35.89	35.89	4,668	7,678	7,678
Slovenia	1.99	1.53	49.2	65.6	0.98	1.00	10.62	13.42	13.42	5,342	8,786	8,786
Solomon Islands	0.45	1.46	19.7	62.2	0.09	0.91	0.03	5.83	0.30	67	4,000	204
Somalia	8.78	40.94	27.5	65.7	2.41	26.89	0.23	163.74	2.33	26	4,000	57
South Africa	43.31	47.30	56.9	90.3	24.64	42.74	181.52	326.05	326.05	4,191	6,893	6,893
Spain	39.91	31.28	77.6	89.8	30.97	28.11	201.16	259.31	259.31	5,040	8,289	8,289
Sri Lanka	18.92	23.07	22.8	58.1	4.31	13.40	6.16	92.27	61.56	325	4,000	2,669
Sudan	31.10	63.53	36.1	83.2	11.23	52.85	1.83	254.12	18.32	59	4,000	288
Suriname	0.42	0.42	74.1	94.5	0.31	0.40	1.31	2.16	2.16	3,137	5,159	5,159
Swaziland	0.92	1.39	26.4	57.6	0.24	0.80	0.90	5.57	5.57	974	4,000	4,000
Sweden	8.84	7.78	83.3	88.2	7.37	6.86	139.18	201.31	201.31	15,740	25,887	25,887
Switzerland	7.17	5.61	67.4	79.1	4.83	4.43	52.62	67.67	67.67	7,338	12,069	12,069
Syria	16.19	36.35	51.4	77.7	8.32	28.24	17.67	145.38	145.38	1,092	4,000	4,000
Taiwan	22.19	22.55	75.6	89.7	16.78	20.23	139.00	232.77	232.77	6,277	10,323	8,054
Tajikistan	6.09	9.76	27.6	47.2	1.68	4.61	12.54	39.05	39.05	2,060	4,000	4,000
Tanzania	35.12	82.74	32.3	85.3	11.34	70.60	2.62	330.96	26.16	75	4,000	316
Thailand	62.81	82.49	19.8	44.9	12.44	37.00	90.26	329.96	329.96	1,437	4,000	4,000
Togo	4.53	11.83	33.4	72.2	1.51	8.54	0.53	47.33	5.25	116	4,000	444
Tonga	0.10	0.13	32.7	100.0	0.03	0.13	0.03	0.50	0.28	282	4,000	2,230
Trinidad and Tobago	1.29	1.38	74.1	90.5	0.96	1.25	4.79	8.39	8.39	3,702	6,089	6,089
Tunisia	9.46	14.08	65.5	90.3	6.20	12.71	9.56	56.30	56.30	1,011	4,000	4,000
Turkey	66.67	98.82	65.8	86.4	43.87	85.38	114.19	395.27	395.27	1,713	4,000	4,000
Turkmenistan	4.74	8.40	44.8	69.8	2.12	5.86	7.71	33.60	33.60	1,627	4,000	4,000
Turks and Caicos Islands	0.02	0.04	45.2	76.5	0.01	0.03	0.00	0.15	0.05	278	4,000	1,205
Uganda	23.30	101.52	14.2	49.1	3.31	49.83	1.31	406.09	13.14	56	4,000	129
Ukraine	49.57	29.96	67.9	80.4	33.66	24.10	151.72	119.84	119.84	3,061	4,000	4,000
United Arab Emirates	2.61	3.71	86.7	99.3	2.26	3.68	35.99	84.25	84.25	13,811	22,714	22,714
United Kingdom	59.41	58.93	89.5	94.4	53.18	55.61	345.03	562.85	562.85	5,807	9,551	9,551
USA	283.23	397.06	77.2	90.1	218.65	357.75	3,621.00	8,348.66	8,348.66	12,785	21,026	21,026
Uruguay	3.34	4.25	91.9	98.4	3.07	4.18	7.35	16.99	16.99	2,203	4,000	4,000
Uzbekistan	24.88	40.51	36.7	52.8	9.13	21.37	41.89	162.05	162.05	1,684	4,000	4,000
Vanuatu	0.20	0.46	21.7	55.8	0.04	0.26	0.04	1.85	1.85	184	4,000	4,000
Venezuela	24.17	42.15	88.9	93.8	21.49	39.52	75.10	168.61	168.61	3,107	4,000	4,000
Vietnam	78.14	123.78	24.1	59.9	18.83	74.17	23.97	495.13	239.71	307	4,000	1,937
Western Sahara	0.25	0.60	95.4	100.0	0.24	0.60	0.08	2.39	0.84	332	4,000	1,398
Yemen	18.35	102.38	24.7	57.5	4.53	58.91	2.98	409.51	29.76	162	4,000	291
Yugoslavia	10.55	9.03	51.6	70.9	5.45	6.41	31.55	36.12	36.12	2,989	4,000	4,000
Zambia	10.42	29.26	39.6	67.2	4.13	19.67	5.84	117.05	58.38	560	4,000	1,995
Zimbabwe	12.63	23.55	35.3	77.2	4.46	18.18	10.48	94.18	94.18	830	4,000	4,000
Totals	**6,072**	**9,326**	**47.4**	**74.3**	**2,877**	**6,928**	**13,710**	**50,424**	**39,003**	**2,258**	**5,407**	**4,182**
Table represents 1% per year increase in electricity consumption from 2000 to 2050												

Note that in the table, countries like Vietnam, Turkey and Columbia (that are projected to be among the top 25 most populous nations) will, by the size of their population, become significant international players. Interestingly, there is a decline in population of Russia, Japan and Germany, while other countries that might drive future electricity expansion (e.g., United States, China and India), experience a significant population increase.

Although this algorithm used a very different method, it is nonetheless consistent with published electricity projections. The graph below shows that in 2020 the total world electricity consumption, based on this projection algorithm, is slightly below EIA reference case numbers. The projection algorithm with a per capita increase of 1%/year (0.5%/year) in industrialized nations yields a 2.1% (1.9%) per year increase in global electricity while the EIA projects a 1.6%, 2.5%, and 3.1% per year increase in global electricity consumption for their low, reference and high growth scenarios.

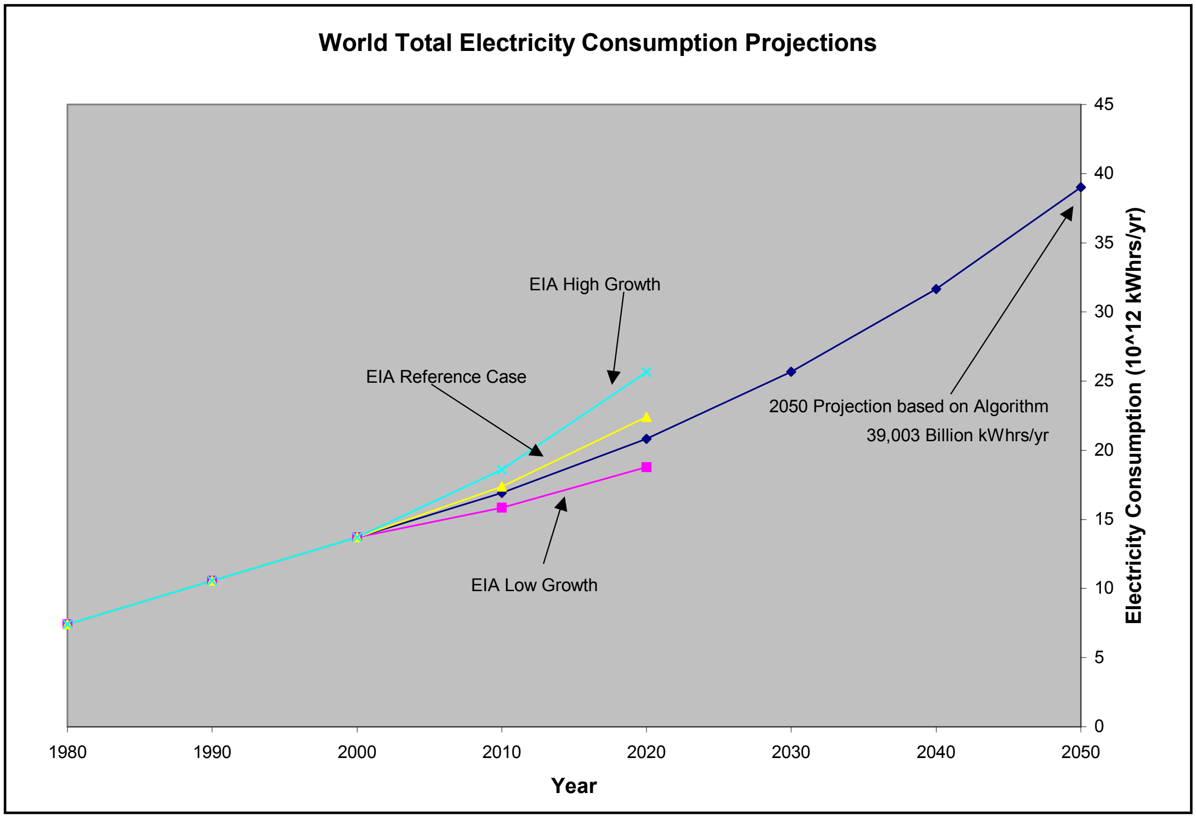

FIGURE 2-3: Comparison of TEC Projections (1% per year per capita increase)[4]

2.1.2 Nuclear Projections

We now move on to a projection of nuclear capacity in a robust global growth scenario. Nuclear production (as a percent of total electricity production) for 2000 is taken from the CIA World Factbook (2002). For 2050, we make a country-specific judgment for the rate of nuclear power's share of total electricity production; based upon 2000 nuclear percentages, total electricity consumption, urban population and per capita electricity consumption. The approximate algorithm, used for making these judgments, is shown in the box below (Figure 2-4). This algorithm assisted in systematically developing 2050 nuclear demand. This again is not

[4] Graph represents World Total Electricity projections each year from 2000 to 2050 and also reflects the factor of 10-growth cap.

based in forecasting or economic modeling but it is simply motivated in the goal of raising the "quality-of-life" of each country, within "reasonable" growth rates. Because this is an approximate algorithm, certain exceptions apply, for example, a country like Estonia (which is quite similar to Lithuania) would, based on the algorithm, reach 10% nuclear in 2050 because it is between 0 and 4% in 2000, but instead it remains at zero percent. These anomalies are due to country specific factors. <u>We stress that the nuclear "market shares" represent an aggressive development consistent with the assumption of a robust growth scenario, i.e., that nuclear power, perhaps because of rising concern about global warming, is viewed as a key technology for meeting increased demand.</u>

Approximate Nuclear Demand Algorithm

Developed World

2000	2050 Low	2050 High
0% to 4%	10%	20%
5% to 9%	20%	40%
10% to 19%	30%	50%
20% to 50%	Increase by 10%	Increase by 30%
Greater than 50	Country dependent	Country dependent

Developing World

4 Countries that have 0% (2000) are increased to 10% (2050 Low) and 20% (2050 High), with the exception of Iran, Indonesia and North Korea-which were increased to 20% (2050 Low) and 40% (2050 High).

5 5 of the 7 countries with nuclear in 2000 have less than 5% nuclear and are increased to 15% (2050 Low) and 30% (2050 High).

6 Remaining 2, Hungary and Romania, are increased by 10% (2050 Low) and 20% (2050 High) each.

Former Soviet Union

4 Increase 2000 percentage by 10 (Low case) and 20 (High case)

5 Russia and Lithuania taken separately

FIGURE 2-4: Nuclear Projections Algorithm

The final results of this projection algorithm are given in table 2-3. "Nuclear Equivalent Capacity" here means the total number of kWh produced by nuclear power divided by the number of hours in a year (8760 hours)[5]; i.e., no correction has been made for capacity factor, meaning that 10-15% more installed capacity would be needed. The tables show the annual increase in total electricity consumption and nuclear production required to reach the 2050 projections. The tables also show the percent per year increase in total electricity consumption (TEC) and nuclear production (for both low and high projections) required to reach these levels. Note also that in these tables, urban population data has been left out.

[5] Actual capacity can be found by dividing the "nuclear equivalent capacity" by the capacity factor.

TABLE 2-4(a): Electricity Consumption Projections (1% case with nuclear included)

Country	Total Population (Millions)		Total Electricity Consumption (Billion kWhrs)		Per Capita Consumption (kWhrs/per)		Nuclear Production (Billion kWhrs)						Nuclear Eq. "Capacity" (GWe)			%/yr TEC	%/yr Low Nuc.	%/yr High Nuc.
	2000	2050	2000	2050*	2000	2050*	2000	%	2050 L	%L	2050 H	%H	2000	2050 L	2050 H			
Afghanistan	21.76	72.27	0.45	4.54	21	63	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Albania	3.13	3.90	5.38	15.62	1,716	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.2%	--	--
Algeria	30.29	51.18	21.85	204.72	721	4,000	0	0%	20	10%	41	20%	0.00	2.34	4.67	4.6%	--	--
American Samoa	0.07	0.17	0.12	0.69	1,787	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.5%	--	--
Angola	13.13	53.33	1.11	11.07	84	208	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Antigua and Barbuda	0.06	0.07	0.09	0.29	1,434	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.3%	--	--
Argentina	37.03	54.52	80.81	218.09	2,182	4,000	6	7%	44	20%	87	40%	0.65	4.98	9.96	2.0%	4.2%	5.6%
Armenia	3.79	3.15	4.89	12.60	1,291	4,000	2	32%	5	40%	6	50%	0.18	0.58	0.72	1.9%	2.4%	2.8%
Aruba	0.10	0.24	0.42	1.65	4,161	6,844	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.8%	--	--
Australia	19.14	26.50	188.49	429.29	9,849	16,198	0	0%	43	10%	86	20%	0.00	4.90	9.80	1.7%	--	--
Austria	8.08	6.45	54.76	71.92	6,778	11,147	0	0%	7	10%	14	20%	0.00	0.82	1.64	0.5%	--	--
Azerbaijan	8.04	8.90	16.68	35.59	2,075	4,000	0	0%	4	10%	7	20%	0.00	0.41	0.81	1.5%	--	--
Bahamas	0.30	0.45	1.43	3.47	4,708	7,742	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.8%	--	--
Bahrain	0.64	1.01	5.36	13.89	8,380	13,783	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.9%	--	--
Bangladesh	137.44	265.43	12.55	125.48	91	473	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Barbados	0.27	0.26	0.69	1.05	2,573	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.9%	--	--
Belarus	10.19	8.30	26.78	33.22	2,629	4,000	0	0%	3	10%	7	20%	0.00	0.38	0.76	0.4%	--	--
Belgium	10.25	9.58	78.13	120.14	7,623	12,537	45	58%	72	60%	96	80%	5.17	8.23	10.97	0.9%	0.9%	1.5%
Belize	0.23	0.39	0.18	1.57	789	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.4%	--	--
Benin	6.27	18.07	0.52	5.23	83	290	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Bermuda	0.06	0.08	0.55	1.15	8,789	14,455	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.5%	--	--
Bhutan	2.09	5.57	0.38	3.81	183	684	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Bolivia	8.33	16.97	3.61	36.05	433	2,125	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Bosnia and Herzegovina	3.98	3.46	2.58	13.83	648	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.4%	--	--
Botswana	1.54	2.11	1.45	8.44	941	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.6%	--	--
Brazil	170.41	247.24	360.64	988.98	2,116	4,000	4	1%	148	15%	297	30%	0.41	16.93	33.87	2.0%	7.7%	9.2%
Brunei Darussalam	0.33	0.56	2.06	5.84	6,289	10,343	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.1%	--	--
Bulgaria	7.95	4.53	34.42	32.26	4,330	7,121	15	44%	16	50%	23	70%	1.73	1.84	2.58	-0.1%	0.1%	0.8%
Burkina Faso	11.54	46.30	0.26	2.62	23	57	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Burundi	6.36	20.22	0.17	1.67	26	82	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Cambodia	13.10	29.88	0.12	1.23	9	41	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Cameroon	14.88	32.28	3.37	33.69	227	1,044	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Canada	30.76	40.41	499.77	1,079.82	16,249	26,724	60	12%	324	30%	540	50%	6.85	36.98	61.63	1.6%	3.4%	4.5%
Cape Verde	0.43	0.81	0.04	0.38	89	472	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Cayman Islands	0.04	0.09	0.33	1.27	8,636	14,202	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.7%	--	--
Central African Republic	3.72	8.19	0.10	0.97	26	118	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Chad	7.89	27.73	0.09	0.86	11	31	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Chile	15.21	22.22	37.90	88.86	2,491	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.7%	--	--
China	1,275.13	1,462.06	1,206.26	5,848.23	946	4,000	12	1%	877	15%	1,754	30%	1.38	100.14	200.28	3.2%	9.0%	10.5%
China, Hong Kong	7.12	7.76	35.40	63.46	4,975	8,182	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.2%	--	--
Colombia	42.10	70.86	40.35	283.45	958	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.0%	--	--
Comoros	0.71	1.90	0.02	0.18	25	93	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Congo, DR	50.95	203.53	4.58	45.75	90	225	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Congo, Rep. (Brazzaville)	3.02	10.74	0.43	4.29	142	400	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Cook Islands	0.02	0.03	0.02	0.11	1,138	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.2%	--	--
Costa Rica	4.02	7.20	5.89	28.78	1,465	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.2%	--	--
Croatia	4.65	4.18	12.64	16.72	2,716	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.6%	--	--
Cuba	11.20	10.76	13.83	43.06	1,235	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.3%	--	--
Cyprus	0.78	0.91	2.91	5.56	3,714	6,108	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.3%	--	--
Czech Republic	10.27	8.43	54.70	73.83	5,325	8,758	10	19%	22	30%	30	40%	1.19	2.53	3.37	0.6%	1.5%	2.1%
Denmark	5.32	5.08	33.93	53.28	6,377	10,488	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.9%	--	--
Djibouti	0.63	1.07	0.17	1.67	265	1,567	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Dominica	0.07	0.07	0.06	0.29	883	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.1%	--	--
Dominican Republic	8.37	11.96	8.81	47.84	1,052	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.4%	--	--
Ecuador	12.65	21.19	9.67	84.76	764	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.4%	--	--
Egypt	67.88	113.84	64.72	455.36	953	4,000	0	0%	46	10%	91	20%	0.00	5.20	10.40	4.0%	--	--
El Salvador	6.28	10.86	4.07	40.70	648	3,749	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Equatorial Guinea	0.46	1.38	0.02	0.20	45	148	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Eritrea	3.66	10.03	0.20	1.95	53	195	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Estonia	1.39	0.75	5.36	4.76	3,848	6,329	0	0%	0	0%	0	0%	0.00	0.00	0.00	-0.2%	--	--
Ethiopia	62.91	186.45	1.52	15.16	24	81	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--

TABLE 2-4(b): Electricity Consumption Projections (cont.)

Falkland Islands (Malvinas)	0.00	0.00	0.01	0.03	5,619	9,242	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.8%	--	--
Fiji	0.81	0.92	0.48	3.66	589	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.2%	--	--
Finland	5.17	4.69	81.96	122.31	15,848	26,064	23	28%	49	40%	73	60%	2.62	5.59	8.38	0.8%	1.5%	2.4%
France	59.24	61.83	408.51	701.28	6,896	11,342	315	77%	561	80%	596	85%	35.91	64.04	68.05	1.1%	1.2%	1.3%
French Guiana	0.16	0.50	0.42	2.01	2,539	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.2%	--	--
French Polynesia	0.23	0.37	0.38	1.49	1,626	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.8%	--	--
Gabon	1.23	3.16	0.79	7.91	643	2,498	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Gambia	1.30	2.60	0.07	0.70	54	268	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Georgia	5.26	3.22	7.89	12.88	1,499	4,000	0	0%	1	10%	3	20%	0.00	0.15	0.29	1.0%	--	--
Germany	82.02	70.80	501.72	712.34	6,117	10,061	151	30%	285	40%	427	60%	17.18	32.53	48.79	0.7%	1.3%	2.1%
Ghana	19.31	40.06	5.48	54.84	284	1,369	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Gibraltar	0.03	0.02	0.09	0.12	3,392	5,578	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.5%	--	--
Greece	10.61	8.98	46.10	64.19	4,345	7,146	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.7%	--	--
Greenland	0.06	0.06	0.23	0.42	4,136	6,801	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.2%	--	--
Grenada	0.09	0.10	0.10	0.42	1,094	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.9%	--	--
Guadeloupe	0.43	0.48	1.29	1.92	3,021	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.8%	--	--
Guam	0.16	0.31	0.77	2.50	4,944	8,132	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.4%	--	--
Guatemala	11.39	26.55	4.80	47.97	421	1,807	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Guinea	8.15	20.71	0.72	7.16	88	346	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Guinea-Bissau	1.20	3.28	0.06	0.56	47	170	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Guyana	0.76	0.50	0.47	2.02	618	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.0%	--	--
Haiti	8.14	13.98	0.49	4.85	60	347	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Honduras	6.42	12.84	3.59	35.93	560	2,797	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Hungary	9.97	7.49	35.10	43.35	3,521	5,791	14	40%	22	50%	26	60%	1.60	2.47	2.97	0.4%	0.9%	1.2%
Iceland	0.28	0.33	7.02	13.75	25,136	41,339	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.4%	--	--
India	1,008.94	1,572.05	509.89	5,098.86	505	3,243	15	3%	765	15%	1,530	30%	1.75	87.31	174.62	4.7%	8.1%	9.6%
Indonesia	212.09	311.33	86.09	860.95	406	2,765	0	0%	172	20%	344	40%	0.00	19.66	39.31	4.7%	--	--
Iran	70.33	121.42	111.91	485.70	1,591	4,000	0	0%	97	20%	194	40%	0.00	11.09	22.18	3.0%	--	--
Iraq	22.95	53.57	25.39	214.30	1,106	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.4%	--	--
Ireland	3.80	5.37	20.82	48.32	5,475	9,005	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.7%	--	--
Israel	6.04	10.06	34.90	95.63	5,777	9,501	0	0%	10	10%	19	20%	0.00	1.09	2.18	2.0%	--	--
Italy	57.53	42.96	283.74	348.48	4,932	8,111	0	0%	35	10%	70	20%	0.00	3.98	7.96	0.4%	--	--
IvoryCoast	16.01	32.19	3.55	35.50	222	1,103	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Jamaica	2.58	3.82	6.27	15.26	2,433	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.8%	--	--
Japan	127.10	109.22	943.71	1,333.76	7,425	12,212	274	29%	534	40%	800	60%	31.24	60.90	91.35	0.7%	1.3%	2.2%
Jordan	4.91	11.71	7.09	46.84	1,443	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.8%	--	--
Kazakhstan	16.17	15.30	48.34	61.21	2,989	4,000	0	0%	6	10%	12	20%	0.00	0.70	1.40	0.5%	--	--
Kenya	30.67	55.37	4.43	44.33	145	801	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Kiribati	0.08	0.14	0.01	0.07	79	471	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Korea, North (DROK)	22.27	28.04	31.06	112.15	1,395	4,000	0	0%	22	20%	45	40%	0.00	2.56	5.12	2.6%	--	--
Korea, South (ROK)	46.74	51.56	254.08	460.96	5,436	6,980	97	38%	230	50%	323	70%	11.02	26.31	36.83	1.2%	1.8%	2.4%
Kuwait	1.91	4.00	29.02	99.74	15,157	24,927	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.5%	--	--
Kyrgyzstan	4.92	7.54	9.82	30.15	1,995	4,000	0	0%	3	10%	6	20%	0.00	0.34	0.69	2.3%	--	--
Lao People's Dem. Republic	5.28	11.44	0.69	6.91	131	604	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Latvia	2.42	1.74	5.16	6.98	2,132	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.6%	--	--
Lebanon	3.50	5.02	8.64	20.07	2,472	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.7%	--	--
Lesotho	2.03	2.48	0.10	1.00	49	404	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Liberia	2.91	14.37	0.42	4.19	144	291	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Libya	5.29	9.97	18.04	55.92	3,411	5,609	0	0%	6	10%	11	20%	0.00	0.64	1.28	2.3%	--	--
Lithuania	3.70	2.99	6.90	11.95	1,866	4,000	5	77%	10	80%	10	85%	0.61	1.09	1.16	1.1%	1.2%	1.3%
Luxembourg	0.44	0.71	6.16	16.57	14,097	23,185	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.0%	--	--
Madagascar	15.97	47.03	0.76	7.63	48	162	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Malawi	11.31	31.11	0.77	7.67	68	247	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Malaysia	22.22	37.85	58.59	151.40	2,637	4,000	0	0%	15	10%	30	20%	0.00	1.73	3.46	1.9%	--	--
Maldives	0.29	0.87	0.10	1.02	352	1,179	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Mali	11.35	41.72	0.43	4.30	38	103	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Malta	0.39	0.40	1.63	2.74	4,174	6,864	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.0%	--	--
Martinique	0.38	0.41	1.05	1.65	2,729	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.9%	--	--
Mauritania	2.66	8.45	0.14	1.43	54	169	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Mauritius	1.16	1.43	1.20	5.70	1,029	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.2%	--	--
Mexico	98.87	146.65	182.83	586.61	1,849	4,000	7	4%	88	15%	176	30%	0.83	10.04	20.09	2.4%	5.1%	6.6%
Moldova	4.30	3.58	3.65	14.31	851	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.8%	--	--
Mongolia	2.53	4.15	2.73	16.58	1,078	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.7%	--	--
Montserrat	0.00	0.01	0.00	0.04	1,240	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.5%	--	--
Morocco	29.88	50.36	14.35	143.46	480	2,849	0	0%	14	10%	29	20%	0.00	1.64	3.28	4.7%	--	--
Mozambique	18.29	38.84	0.93	9.26	51	238	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Myanmar	47.75	68.55	4.50	45.00	94	656	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--

TABLE 2-4(c): Electricity Consumption Projections (cont.)

Namibia	1.76	3.66	0.89	8.91	507	2,433	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Nauru	0.01	0.03	0.03	0.10	2,283	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.7%	--	--
Nepal	23.04	52.41	1.43	14.31	62	273	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Netherlands	15.86	15.85	100.71	165.44	6,349	10,441	4	4%	17	10%	33	20%	0.46	1.89	3.78	1.0%	2.9%	4.3%
Netherlands Antilles	0.22	0.26	1.09	2.16	5,076	8,348	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.4%	--	--
New Caledonia	0.22	0.40	1.46	4.41	6,760	11,118	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.2%	--	--
New Zealand	3.78	4.44	33.32	64.38	8,818	14,503	0	0%	6	10%	13	20%	0.00	0.73	1.47	1.3%	--	--
Nicaragua	5.07	11.48	2.18	21.76	429	1,896	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Niger	10.83	51.87	0.40	4.05	37	78	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Nigeria	113.86	278.79	14.77	147.68	130	530	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Niue	0.00	0.00	0.00	0.01	1,394	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.8%	--	--
Norway	4.47	4.88	112.50	202.03	25,172	41,399	0	0%	20	10%	40	20%	0.00	2.31	4.61	1.2%	--	--
Oman	2.54	8.75	7.53	35.01	2,968	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.1%	--	--
Pakistan	141.26	344.17	58.30	582.99	413	1,694	1	1%	87	15%	175	30%	0.07	9.98	19.97	4.7%	10.5%	12.1%
Panama	2.86	4.26	4.65	17.05	1,629	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.6%	--	--
Papua New Guinea	4.81	10.98	1.53	15.35	319	1,397	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Paraguay	5.50	12.56	1.95	19.50	355	1,552	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Peru	25.66	42.12	18.30	168.49	713	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.5%	--	--
Philippines	75.65	128.38	37.82	378.20	500	2,946	0	0%	38	10%	76	20%	0.00	4.32	8.63	4.7%	--	--
Poland	38.61	33.37	119.33	133.48	3,091	4,000	0	0%	13	10%	27	20%	0.00	1.52	3.05	0.2%	--	--
Portugal	10.02	9.01	41.15	60.85	4,108	6,756	0	0%	6	10%	6	10%	0.00	0.69	0.69	0.8%	--	--
Puerto Rico	3.91	4.83	19.06	38.72	4,869	8,008	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.4%	--	--
Qatar	0.57	0.83	8.56	20.67	15,132	24,886	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.8%	--	--
Reunion	0.72	1.00	1.01	4.01	1,406	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.8%	--	--
Romania	22.44	18.15	45.68	72.60	2,036	4,000	5	10%	15	20%	22	30%	0.52	1.66	2.49	0.9%	--	--
Russia	145.49	104.26	767.08	904.03	5,272	8,671	115	15%	271	30%	452	50%	13.13	30.96	51.60	0.3%	1.7%	2.8%
Rwanda	7.61	18.52	0.17	1.74	23	94	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Saint Helena	0.01	0.01	0.00	0.04	739	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.3%	--	--
Saint Kitts and Nevis	0.04	0.03	0.09	0.14	2,296	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.9%	--	--
Saint Lucia	0.15	0.19	0.11	0.75	724	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.0%	--	--
Saint Pierre and Miquelon	0.01	0.01	0.04	0.08	5,564	9,151	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.5%	--	--
Saint Vincent and Grenadines	0.11	0.14	0.08	0.55	714	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.9%	--	--
Samoa	0.16	0.22	0.10	0.89	604	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.6%	--	--
Sao Tome and Principe	0.14	0.29	0.02	0.16	115	538	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Saudi Arabia	20.35	59.68	114.86	554.10	5,645	9,284	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.2%	--	--
Senegal	9.42	22.71	1.23	12.28	130	541	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Seychelles	0.08	0.15	0.15	0.58	1,850	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.8%	--	--
Sierra Leone	4.40	14.35	0.23	2.28	52	159	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Singapore	4.02	4.62	25.95	49.06	6,458	10,620	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.3%	--	--
Slovakia	5.40	4.67	25.20	35.89	4,668	7,678	12	48%	22	60%	25	70%	1.38	2.46	2.87	0.7%	1.2%	1.5%
Slovenia	1.99	1.53	10.62	13.42	5,342	8,786	4	35%	7	50%	8	60%	0.42	0.77	0.92	0.5%	1.2%	1.6%
Solomon Islands	0.45	1.46	0.03	0.30	67	204	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Somalia	8.78	40.94	0.23	2.33	26	57	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
South Africa	43.31	47.30	181.52	326.05	4,191	6,893	13	7%	65	20%	130	40%	1.45	7.44	14.89	1.2%	3.3%	4.8%
Spain	39.91	31.28	201.16	259.31	5,040	8,289	56	28%	104	40%	156	60%	6.43	11.84	17.76	0.5%	1.2%	2.1%
Sri Lanka	18.92	23.07	6.16	61.56	325	2,669	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Sudan	31.10	63.53	1.83	18.32	59	288	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Suriname	0.42	0.42	1.31	2.16	3,137	5,159	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.0%	--	--
Swaziland	0.92	1.39	0.90	5.57	974	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.7%	--	--
Sweden	8.84	7.78	139.18	201.31	15,740	25,887	51	37%	101	50%	141	70%	5.88	11.49	16.09	0.7%	1.3%	2.0%
Switzerland	7.17	5.61	52.62	67.67	7,338	12,069	19	37%	34	50%	47	70%	2.22	3.86	5.41	0.5%	1.1%	1.8%
Syria	16.19	36.35	17.67	145.38	1,092	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.3%	--	--

TABLE 2-4(d): Electricity Consumption Projections (cont.)

Taiwan	22.19	22.55	139.00	232.77	6,277	8,054	35	25%	93	40%	140	60%	3.97	10.63	15.94	1.0%	2.0%	2.8%
Tajikistan	6.09	9.76	12.54	39.05	2,060	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	2.3%	--	--
Tanzania	35.12	82.74	2.62	26.16	75	316	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Thailand	62.81	82.49	90.26	329.96	1,437	4,000	0	0%	33	10%	66	20%	0.00	3.77	7.53	2.6%	--	--
Togo	4.53	11.83	0.53	5.25	116	444	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Tonga	0.10	0.13	0.03	0.28	282	2,230	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Trinidad and Tobago	1.29	1.38	4.79	8.39	3,702	6,089	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.1%	--	--
Tunisia	9.46	14.08	9.56	56.30	1,011	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	3.6%	--	--
Turkey	66.67	98.82	114.19	395.27	1,713	4,000	0	0%	40	10%	79	20%	0.00	4.51	9.02	2.5%	--	--
Turkmenistan	4.74	8.40	7.71	33.60	1,627	4,000	0	0%	3	10%	7	20%	0.00	0.38	0.77	3.0%	--	--
Turks and Caicos Islands	0.02	0.04	0.00	0.05	278	1,205	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Uganda	23.30	101.52	1.31	13.14	56	129	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Ukraine	49.57	29.96	151.72	119.84	3,061	4,000	65	43%	60	50%	72	60%	7.45	6.84	8.21	-0.5%	-0.2%	0.2%
United Arab Emirates	2.61	3.71	35.99	84.25	13,811	22,714	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.7%	--	--
United Kingdom	59.41	58.93	345.03	562.85	5,807	9,551	79	23%	169	30%	281	50%	9.06	19.28	32.13	1.0%	1.5%	2.6%
Uruguay	3.34	4.25	7.35	16.99	2,203	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	1.7%	--	--
USA	283.23	397.06	3,621.00	8,348.66	12,785	21,026	717	20%	2,505	30%	4,174	50%	81.84	285.91	476.52	1.7%	2.5%	3.6%
Uzbekistan	24.88	40.51	41.89	162.05	1,684	4,000	0	0%	16	10%	32	20%	0.00	1.85	3.70	2.7%	--	--
Vanuatu	0.20	0.46	0.04	1.85	184	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	8.2%	--	--
Venezuela	24.17	42.15	75.10	168.61	3,107	4,000	0	0%	17	10%	34	20%	0.00	1.92	3.85	1.6%	--	--
Vietnam	78.14	123.78	23.97	239.71	307	1,937	0	0%	24	10%	48	20%	0.00	2.74	5.47	4.7%	--	--
Western Sahara	0.25	0.60	0.08	0.84	332	1,398	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Yemen	18.35	102.38	2.98	29.76	162	291	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Yugoslavia	10.55	9.03	31.55	36.12	2,989	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	0.3%	--	--
Zambia	10.42	29.26	5.84	58.38	560	1,995	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.7%	--	--
Zimbabwe	12.63	23.55	10.48	94.18	830	4,000	0	0%	0	0%	0	0%	0.00	0.00	0.00	4.5%	--	--
Totals	**6,072**	**9,326**	**13,710**	**39,003**	**2,258**	**4,182**	**2,230**	**16%**	**8,321**	**21%**	**14,088**	**36%**	**255**	**950**	**1,608**	**2.1%**	**2.7%**	**3.8%**

***Table represents 1% per year increase in electricity consumption from 2000 to 2050**
****2050 After cutoff numbers**
*****TEC=Total Electricity Consumption**

There are several key features of the tables that are worth mentioning at this point. More specifically, the United States will have take a major lead role in the projected nuclear expansion, with European Nations not far behind. Certain countries (Pakistan and Indonesia) not only experience significant population increases, but they are also projected to become states with civilian nuclear power (both of which currently have little to no nuclear infrastructure). For these and other reasons, it became useful to categorize the various countries.

2.1.3 Country Categorization

Finally, in looking ahead to our nonproliferation discussion, it is useful to bin the countries into various categories. First, in order to narrow the scope of the projections, all countries with a 2050 TEC of less than or equal to 10 Billion kWhrs and a 2050 total population of less than or equal to 3 million were neglected. Next, the countries were grouped into three different categories: developed nations-countries whose 2000 PCEC was greater than or equal to 4,000 kWhrs (with the exception of Saudi Arabia, South Africa, and a number of smaller nations with non-industrialized economies which are placed in the developing nations category), developing nations-countries with 2000 PCEC less than 4,000 kWhrs per capita, and Former Soviet Union nations.

It is useful to further sub-divide the developing world into three categories- More Advanced Developing, Less Advanced Developing and Least Developed. The More Advanced Developing Nations have 2050 per capita electricity consumption greater than or equal to 4,000 kWhrs. With modest growth rates and improvements in various economic and political sectors, most of these countries are good candidates for expanded use of nuclear power. The Less Advanced Developing Nations were those developing nations with 2050 per capita electricity consumption between 1,500 and 4,000 kWhrs. The growth rates required for this would be quite substantial (4.7%/year in TEC) and would require considerable investment (presumably including substantial foreign investment) and good management. Many of these countries are candidates for nuclear power, but will need effective strategies to meet the capital requirements. Finally, the remaining countries are considered Least Developing Nations and will by no means come close to reaching the 4,000 kWhrs per capita threshold. They are unlikely to develop nuclear power. The results of this categorization are listed in Table 2-4.

TABLE 2-5(a): Electricity Consumption Projections (Developed World)

Country	Total Population (Millions)		Total Electricity Consumption (Billion kWhrs)		Per Capita Consumption (kWhrs/per)		Nuclear Production (Billion kWhrs)						Nuclear Eq. "Capacity" (GWe)			%/yr TEC	%/yr Low Nuc.	%/yr High Nuc.
	2000	2050	2000	2050*	2000	2050*	2000	%	2050 L	%L	2050 H	%H	2000	2050 L	2050 H			
Developed World																		
USA	283	397	3,621.0	8,349	12,785	21,026	717	20%	2,505	30%	4,174	50%	82	286	477	1.7%	2.5%	3.6%
France	59	62	408.5	701	6,896	11,342	315	77%	561	80%	596	85%	36	64	68	1.1%	1.2%	1.3%
Japan	127	109	943.7	1,334	7,425	12,212	274	29%	534	40%	800	60%	31	61	91	0.7%	1.3%	2.2%
Germany	82	71	501.7	712	6,117	10,061	151	30%	285	40%	427	60%	17	33	49	0.7%	1.3%	2.1%
Korea, South (ROK)	47	52	254.1	461	5,436	6,980	97	38%	230	50%	323	70%	11	26	37	1.2%	1.8%	2.4%
United Kingdom	59	59	345.0	563	5,807	9,551	79	23%	169	30%	281	50%	9	19	32	1.0%	1.5%	2.6%
Canada	31	40	499.8	1,080	16,249	26,724	60	12%	324	30%	540	50%	7	37	62	1.6%	3.4%	4.5%
Spain	40	31	201.2	259	5,040	8,289	56	28%	104	40%	156	60%	6	12	18	0.5%	1.2%	2.1%
Sweden	9	8	139.2	201	15,740	25,887	51	37%	101	50%	141	70%	6	11	16	0.7%	1.3%	2.0%
Belgium	10	10	78.1	120	7,623	12,537	45	58%	72	60%	96	80%	5	8	11	0.9%	0.9%	1.5%
Taiwan	22	23	139.0	233	6,277	8,054	35	25%	93	40%	140	60%	4	11	16	1.0%	2.0%	2.8%
Finland	5	5	82.0	122	15,848	26,064	23	28%	49	40%	73	60%	3	6	8	0.8%	1.5%	2.4%
Switzerland	7	6	52.6	68	7,338	12,069	19	37%	34	50%	47	70%	2	4	5	0.5%	1.1%	1.8%
Netherlands	16	16	100.7	165	6,349	10,441	4	4%	17	10%	33	20%	0	2	4	1.0%	2.9%	4.3%
Norway	4	5	112.5	202	25,172	41,399	0	0%	20	10%	40	20%	0	2	5	1.2%	--	--
Australia	19	27	188.5	429	9,849	16,198	0	0%	43	10%	86	20%	0	5	10	1.7%	--	--
New Zealand	4	4	33.3	64	8,818	14,503	0	0%	6	10%	13	20%	0	1	1	1.3%	--	--
Austria	8	6	54.8	72	6,778	11,147	0	0%	7	10%	14	20%	0	1	2	0.5%	--	--
Denmark	5	5	33.9	53	6,377	10,488	0	0%	0	0%	0	0%	0	0	0	0.9%	--	--
Israel	6	10	34.9	96	5,777	9,501	0	0%	10	10%	19	20%	0	1	2	2.0%	--	--
Ireland	4	5	20.8	48	5,475	9,005	0	0%	0	0%	0	0%	0	0	0	1.7%	--	--
China, Hong Kong	7	8	35.4	63	4,975	8,182	0	0%	0	0%	0	0%	0	0	0	1.2%	--	--
Italy	58	43	283.7	348	4,932	8,111	0	0%	35	10%	70	20%	0	4	8	0.4%	--	--
Greece	11	9	46.1	64	4,345	7,146	0	0%	0	0%	0	0%	0	0	0	0.7%	--	--
Subtotal	**924**	**1,010**	**8,211**	**15,810**	**8,888**	**15,659**	**1,926**	**23%**	**5,197**	**33%**	**8,071**	**51%**	**220**	**593**	**921**	**1.3%**	**2.0%**	**2.9%**

TABLE 2-5(b): Electricity Consumption Projections (More Advanced Developing)

Country	Total Population (Millions)		Total Electricity Consumption (Billion kWhrs)		Per Capita Consumption (kWhrs/per)		Nuclear Production (Billion kWhrs)						Nuclear Eq. "Capacity" (GWe)			%/yr TEC	%/yr Low Nuc.	%/yr High Nuc.
	2000	2050	2000	2050*	2000	2050*	2000	%	2050 L	%L	2050 H	%H	2000	2050 L	2050 H			
Developing World																		
More Advanced																		
Kuwait	2	4	29.0	100	15,157	24,927	0	0%	0	0%	0	0%	0	0	0	2.5%	--	--
United Arab Emirates	3	4	36.0	84	13,811	22,714	0	0%	0	0%	0	0%	0	0	0	1.7%	--	--
Singapore	4	5	25.9	49	6,458	10,620	0	0%	0	0%	0	0%	0	0	0	1.3%	--	--
Saudi Arabia	20	60	114.9	554	5,645	9,284	0	0%	0	0%	0	0%	0	0	0	3.2%	--	--
Puerto Rico	4	5	19.1	39	4,869	8,008	0	0%	0	0%	0	0%	0	0	0	1.4%	--	--
Bulgaria	8	5	34.4	32	4,330	7,121	15	44%	16	50%	23	70%	2	2	3	-0.1%	0.1%	0.8%
South Africa	43	47	181.5	326	4,191	6,893	13	7%	65	20%	130	40%	1	7	15	1.2%	3.3%	4.8%
Portugal	10	9	41.1	61	4,108	6,756	0	0%	6	10%	12	20%	0	1	1	0.8%	--	--
Hungary	10	7	35.1	43	3,521	5,791	14	40%	22	50%	26	60%	2	2	3	0.4%	0.9%	1.2%
Libya	5	10	18.0	56	3,411	5,609	0	0%	6	10%	11	20%	0	1	1	2.3%	--	--
Brazil	170	247	360.6	989	2,116	4,000	4	1%	148	15%	297	30%	0	17	34	2.0%	7.7%	9.2%
Mexico	99	147	182.8	587	1,849	4,000	7	4%	88	15%	176	30%	1	10	20	2.4%	5.1%	6.6%
Iraq	23	54	25.4	214	1,106	4,000	0	0%	0	0%	0	0%	0	0	0	4.4%	--	--
Costa Rica	4	7	5.9	29	1,465	4,000	0	0%	0	0%	0	0%	0	0	0	3.2%	--	--
Ecuador	13	21	9.7	85	764	4,000	0	0%	0	0%	0	0%	0	0	0	4.4%	--	--
Cuba	11	11	13.8	43	1,235	4,000	0	0%	0	0%	0	0%	0	0	0	2.3%	--	--
Algeria	30	51	21.8	205	721	4,000	0	0%	20	10%	41	20%	0	2	5	4.6%	--	--
Thailand	63	82	90.3	330	1,437	4,000	0	0%	33	10%	66	20%	0	4	8	2.6%	--	--
Syria	16	36	17.7	145	1,092	4,000	0	0%	0	0%	0	0%	0	0	0	4.3%	--	--
Egypt	68	114	64.7	455	953	4,000	0	0%	46	10%	91	20%	0	5	10	4.0%	--	--
Malaysia	22	38	58.6	151	2,637	4,000	0	0%	15	10%	30	20%	0	2	3	1.9%	--	--
Chile	15	22	37.9	89	2,491	4,000	0	0%	0	0%	0	0%	0	0	0	1.7%	--	--
Mongolia	3	4	2.7	17	1,078	4,000	0	0%	0	0%	0	0%	0	0	0	3.7%	--	--
Turkey	67	99	114.2	395	1,713	4,000	0	0%	40	10%	79	20%	0	5	9	2.5%	--	--
Oman	3	9	7.5	35	2,968	4,000	0	0%	0	0%	0	0%	0	0	0	3.1%	--	--
Croatia	5	4	12.6	17	2,716	4,000	0	0%	0	0%	0	0%	0	0	0	0.6%	--	--
Peru	26	42	18.3	168	713	4,000	0	0%	0	0%	0	0%	0	0	0	4.5%	--	--
China	1,275	1,462	1,206.3	5,848	946	4,000	12	1%	877	15%	1,754	30%	1	100	200	3.2%	9.0%	10.5%
Argentina	37	55	80.8	218	2,182	4,000	6	7%	44	20%	87	40%	1	5	10	2.0%	4.2%	5.6%
Lebanon	3	5	8.6	20	2,472	4,000	0	0%	0	0%	0	0%	0	0	0	1.7%	--	--
Uruguay	3	4	7.4	17	2,203	4,000	0	0%	0	0%	0	0%	0	0	0	1.7%	--	--
Albania	3	4	5.4	16	1,716	4,000	0	0%	0	0%	0	0%	0	0	0	2.2%	--	--
Jordan	5	12	7.1	47	1,443	4,000	0	0%	0	0%	0	0%	0	0	0	3.8%	--	--
Korea, North (DROK)	22	28	31.1	112	1,395	4,000	0	0%	22	20%	45	40%	0	3	5	2.6%	--	--
Venezuela	24	42	75.1	169	3,107	4,000	0	0%	17	10%	34	20%	0	2	4	1.6%	--	--
Dominican Republic	8	12	8.8	48	1,052	4,000	0	0%	0	0%	0	0%	0	0	0	3.4%	--	--
Poland	39	33	119.3	133	3,091	4,000	0	0%	13	10%	27	20%	0	2	3	0.2%	--	--
Jamaica	3	4	6.3	15	2,433	4,000	0	0%	0	0%	0	0%	0	0	0	1.8%	--	--
Zimbabwe	13	24	10.5	94	830	4,000	0	0%	0	0%	0	0%	0	0	0	4.5%	--	--
Colombia	42	71	40.3	283	958	4,000	0	0%	0	0%	0	0%	0	0	0	4.0%	--	--
Tunisia	9	14	9.6	56	1,011	4,000	0	0%	0	0%	0	0%	0	0	0	3.6%	--	--
Bosnia and Herzegovina	4	3	2.6	14	648	4,000	0	0%	0	0%	0	0%	0	0	0	3.4%	--	--
Iran	70	121	111.9	486	1,591	4,000	0	0%	97	20%	194	40%	0	11	22	3.0%	--	--
Romania	22	18	45.7	73	2,036	4,000	5	10%	15	20%	22	30%	1	2	2	0.9%	2.3%	3.2%
Yugoslavia	11	9	31.5	36	2,989	4,000	0	0%	0	0%	0	0%	0	0	0	0.3%	--	--
Panama	3	4	4.7	17	1,629	4,000	0	0%	0	0%	0	0%	0	0	0	2.6%	--	--
El Salvador	6	11	4.1	41	648	3,749	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--

TABLE 2-5(c): Electricity Consumption Projections (Less Advanced Developing)

Country	Total Population (Millions)		Total Electricity Consumption (Billion kWhrs)		Per Capita Consumption (kWhrs/per)		Nuclear Production (Billion kWhrs)						Nuclear Eq. "Capacity" (GWe)			%/yr TEC	%/yr Low Nuc.	%/yr High Nuc.
	2000	2050	2000	2050*	2000	2050*	2000	%	2050 L	%L	2050 H	%H	2000	2050 L	2050 H			
Developing World																		
Less Advanced																		
India	1,009	1,572	509.9	5,099	505	3,243	15	3%	765	15%	1,530	30%	2	87	175	4.7%	8.1%	9.6%
Philippines	76	128	37.8	378	500	2,946	0	0%	38	10%	76	20%	0	4	9	4.7%	--	--
Morocco	30	50	14.3	143	480	2,849	0	0%	14	10%	29	20%	0	2	3	4.7%	--	--
Honduras	6	13	3.6	36	560	2,797	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Indonesia	212	311	86.1	861	406	2,765	0	0%	172	20%	344	40%	0	20	39	4.7%	--	--
Sri Lanka	19	23	6.2	62	325	2,669	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Bolivia	8	17	3.6	36	433	2,125	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Zambia	10	29	5.8	58	560	1,995	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Vietnam	78	124	24.0	240	307	1,937	0	0%	24	10%	48	20%	0	3	5	4.7%	--	--
Nicaragua	5	11	2.2	22	429	1,896	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Guatemala	11	27	4.8	48	421	1,807	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Pakistan	141	344	58.3	583	413	1,694	1	1%	87	15%	175	30%	0	10	20	4.7%	10.5%	12.1%
Paraguay	5	13	2.0	20	355	1,552	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--

TABLE 2-5(d): Electricity Consumption Projections (Least Developed)

Country	Total Population (Millions)		Total Electricity Consumption (Billion kWhrs)		Per Capita Consumption (kWhrs/per)		Nuclear Production (Billion kWhrs)						Nuclear Eq. "Capacity" (GWe)			%/yr TEC	%/yr Low Nuc.	%/yr High Nuc.
	2000	2050	2000	2050*	2000	2050*	2000	%	2050 L	%L	2050 H	%H	2000	2050 L	2050 H			
Developing World																		
Least Advanced																		
Papua New Guinea	5	11	1.5	15	319	1,397	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Ghana	19	40	5.5	55	284	1,369	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
IvoryCoast	16	32	3.6	36	222	1,103	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Cameroon	15	32	3.4	34	227	1,044	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Kenya	31	55	4.4	44	145	801	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Myanmar	48	69	4.5	45	94	656	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Senegal	9	23	1.2	12	130	541	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Nigeria	114	279	14.8	148	130	530	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Bangladesh	137	265	12.5	125	91	473	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Tanzania	35	83	2.6	26	75	316	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Yemen	18	102	3.0	30	162	291	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Sudan	31	64	1.8	18	59	288	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Nepal	23	52	1.4	14	62	273	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Congo, DR	51	204	4.6	46	90	225	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Angola	13	53	1.1	11	84	208	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Uganda	23	102	1.3	13	56	129	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Ethiopia	63	186	1.5	15	24	81	0	0%	0	0%	0	0%	0	0	0	4.7%	--	--
Subtotal	**4,614**	**7,395**	**4,224**	**21,315**	**916**	**2,882**	**91**	**2%**	**2,690**	**13%**	**5,347**	**25%**	**10**	**307**	**610**	**3.3%**	**7.0%**	**8.5%**

TABLE 2-5(e): Electricity Consumption Projections (Former Soviet Union)

Country	Total Population (Millions)		Total Electricity Consumption (Billion kWhrs)		Per Capita Consumption (kWhrs/per)		Nuclear Production (Billion kWhrs)						Nuclear Eq. "Capacity" (GWe)			%/yr TEC	%/yr Low Nuc.	%/yr High Nuc.
	2000	2050	2000	2050*	2000	2050*	2000	%	2050 L	%L	2050 H	%H	2000	2050 L	2050 H			
Former Soviet Union																		
Russia	145	104	767.1	904	5,272	8,671	115	15%	271	30%	452	50%	13	31	52	0.3%	1.7%	2.8%
Ukraine	50	30	151.7	120	3,061	4,000	65	43%	60	50%	72	60%	7	7	8	-0.5%	-0.2%	0.2%
Slovakia	5	5	25.2	36	4,668	7,678	12	48%	22	60%	25	70%	1	2	3	0.7%	1.2%	1.5%
Czech Republic	10	8	54.7	74	5,325	8,758	10	19%	22	30%	30	40%	1	3	3	0.6%	1.5%	2.1%
Lithuania	4	3	6.9	12	1,866	4,000	5	77%	10	80%	10	85%	1	1	1	1.1%	1.2%	1.3%
Slovenia	2	2	10.6	13	5,342	8,786	4	35%	7	50%	8	60%	0	1	1	0.5%	1.2%	1.6%
Armenia	4	3	4.9	13	1,291	4,000	2	32%	5	40%	6	50%	0	1	1	1.9%	2.4%	2.8%
Estonia	1	1	5.4	5	3,848	6,329	0	0%	0	0%	0	0%	0	0	0	-0.2%	--	--
Tajikistan	6	10	12.5	39	2,060	4,000	0	0%	0	0%	0	0%	0	0	0	2.3%	--	--
Kazakhstan	16	15	48.3	61	2,989	4,000	0	0%	6	10%	12	20%	0	1	1	0.5%	--	--
Uzbekistan	25	41	41.9	162	1,684	4,000	0	0%	16	10%	32	20%	0	2	4	2.7%	--	--
Moldova	4	4	3.7	14	851	4,000	0	0%	0	0%	0	0%	0	0	0	2.8%	--	--
Kyrgyzstan	5	8	9.8	30	1,995	4,000	0	0%	3	10%	6	20%	0	0	1	2.3%	--	--
Belarus	10	8	26.8	33	2,629	4,000	0	0%	3	10%	7	20%	0	0	1	0.4%	--	--
Georgia	5	3	7.9	13	1,499	4,000	0	0%	1	10%	3	20%	0	0	0	1.0%	--	--
Turkmenistan	5	8	7.7	34	1,627	4,000	0	0%	3	10%	7	20%	0	0	1	3.0%	--	--
Azerbaijan	8	9	16.7	36	2,075	4,000	0	0%	4	10%	7	20%	0	0	1	1.5%	--	--
Subtotal	**306**	**261**	**1,202**	**1,598**	**3,925**	**6,118**	**213**	**18%**	**433**	**27%**	**677**	**42%**	**24**	**49**	**77**	**0.6%**	**1.4%**	**2.3%**
Totals	**5,844**	**8,666**	**13,636**	**38,723**	**2,333**	**4,468**	**2,230**	**16%**	**8,321**	**21%**	**14,094**	**36%**	**255**	**950**	**1,609**	**2.1%**	**2.7%**	**3.8%**

***Table represents 1% per year increase in electricity consumption from 2000 to 2050**
****2050 After cutoff numbers**
*****Countries ranked by 2000 Nuclear Production**

2.2 Discussion

It is useful to look at the categorization as it applies to the 25 countries with the largest populations as projected by the UN, shown in Table 2-5. The 2050 total population for these 25 countries is approximately three fourths of the 9.3 billion world total projected population. This snapshot shows key growth countries, some of which appear surprising.

TABLE 2-6: 25 Countries with Largest 2050 Population

TWENTY-FIVE COUNTRIES WITH LARGEST PROJECTED POPULATION IN 2050
(UNITED NATIONS PROJECTIONS)

	2050 Total Pop.	2050 Urban Percent	2050 Electricity Consumption		2050 Per Capita	Equivalent Nuclear Capacity (GWe)		
	(millions)	(%)	(billion kWhr/yr)	(%/yr)	(kWhr/person/yr)	2000	2050 Low	2050 High
1. India	1572	(51)	5099	(4.7%)	3243	2	87	175
2. China	1462	(90)	5848	(3.2%)	4000	1	100	200
3. United States	397	(90)	8349	(1.7%)	21026	82	286	477
4. Pakistan	344	(63)	583	(4.7%)	1694	0	10	20
5. Indonesia	311	(91)	861	(4.7%)	2765	0	20	39
6. Nigeria	278	(84)	148	(4.7%)	530	0	0	0
7. Bangladesh	265	(67)	126	(4.7%)	473	0	0	0
8. Brazil	247	(99)	989	(2.0%)	4000	0.4	17	34
9. Dem. Rep. Congo	204	(42)	46	(4.7%)	225	0	0	0
10. Ethiopia	186	(50)	15	(4.7%)	81	0	0	0
11. Mexico	146	(87)	587	(2.4%)	4000	1	10	20
12. Philippines	128	(92)	378	(4.7%)	2946	0	4	9
13. Vietnam	123	(60)	240	(4.7%)	1937	0	3	5
14. Iran	121	(93)	486	(3.0%)	4000	0	11	22
15. Egypt	114	(62)	455	(4.0%)	4000	0	5	10
16. Japan	109	(89)	1334	(0.7%)	12212	31	61	91
17. Russia	104	(80)	904	(0.3%)	8671	13	31	52
18. Yemen	102	(58)	30	(4.7%)	291	0	0	0
19. Uganda	101	(49)	13	(4.7%)	129	0	0	0
20. Turkey	99	(86)	395	(2.5%)	4000	0	5	9
21. Tanzania	83	(85)	26	(4.7%)	316	0	0	0
22. Thailand	82	(45)	330	(2.6%)	4000	0	4	8
23. Afghanistan	72	(61)	5	(4.7%)	63	0	0	0
24. Colombia	71	(96)	283	(4.0%)	4000	0	0	0
25. Germany	71	(95)	712	(0.7%)	10061	17	33	49

Notes:
1. 1%/yr/person increase in developed countries
2. 4000 kWhrs/person/yr quality-of-life target for developing countries
3. Maximum 4.7%/yr increase in national electricity consumption
4. Top 25 population = 6792 million, out of 9326 total (73%)
5. Rest of G-7 (France, U.K., Italy, Canada): population 204 million

The only FSU country on the list is Russia, which does not need a separate discussion and will be included in the developed country discussion. Although the top 25 populated countries do not include all potential nuclear countries (for example, France has and will have one of the world's largest fleets of nuclear reactors), the list does provide valuable insight into the major potential proliferation concerns and also into the critical assumptions that must be true for the robust growth scenario to occur.

Taking a closer look, however, at only the nuclear power countries yields some very interesting and significant results. For example, 6 of the top 15 nuclear powers for 2050 are new entrants, of particular interest are Indonesia, Pakistan, Brazil, Mexico, and China all of which were not even among the top 20 nuclear nations in 2000 (Indonesia had no nuclear in 2000). Also, of the top 5 nuclear powers for 2050, only the US, Japan, and France are current leaders, with new entrants of China and India. Only 5 (France, Canada, United Kingdom, South Korea, and Spain) of the top 15 nuclear power countries are not also in the top 25 most populous countries for 2050. The table (table 2-6) below clearly illustrates these findings. It shows an interesting shift from what we have today.

TABLE 2-7: Top 15 Nuclear Powers in 2050

Ranking of Nuclear "Powers"				
2050 Rank	Country	2050* Nuclear Eq. "Capacity" (GWe)	2000 Rank	2000 Nuclear Eq. "Capacity" (GWe)
1	USA	477	1	82
2	China	200	21	1
3	India	175	16	2
4	Japan	91	3	31
5	France	68	2	36
6	Canada	62	9	7
7	Russia	52	5	13
8	Germany	49	4	17
9	Indonesia	39	NR	0
10	United Kingdom	32	7	9
11	Korea, South (ROK)	37	6	11
12	Brazil	34	29	0.41
13	Mexico	20	23	0.83
14	Pakistan	20	31	0.07
15	Spain	18	10	6

*High Projection Case
NR = Not Ranked (no nuclear capacity in 2000)

Focusing the categorization (mentioned above-table 2-6) only on the top 25 most populous nations in 2050 also provides interesting observations. What follows is a discussion of these observations.

Developed Countries: Among the 25 countries with the largest 2050 total population projections, the United States, Japan, Russia, and Germany are the only countries above the 4000 kWh/capita/year threshold. At an average of 1.7% increase per year, the United States sustains a significant increase in electricity consumption. Due to their population decline, Japan, Russia, and Germany experience relatively little change in total electricity consumption. These countries will almost certainly be major players in the nuclear market of 2050, and in fact must be if the robust growth scenario is to be realized on the necessary scale. However, the most striking result is the role that the United States must play in the growth scenario. US share of nuclear power likely needs to increase from its current 20% to about 50%, reflecting the combination of its economic strength and projected population increase. These countries are considered of little proliferation concern (the US and Russia are already nuclear weapons states), although the geopolitical situation in East Asia has led to renewed discussion about Japan in the nonproliferation context.

More Advanced Developing Countries: Eight countries would reach the 4000 kWh/capita/year benchmark with modest growth rates in total electricity production in the 2-3%/year range. The countries are China, Brazil, Mexico, Iran, Egypt, Turkey, Thailand, and Colombia. Most of these countries are good candidates for expanded use of nuclear power, but several may raise concerns about proliferation. Of course, China, as a weapons state, is not one of those of concern. The scenario anticipates substantial nuclear infrastructure in virtually all of these, with several introducing nuclear power during this period (Iran, Egypt, Turkey, Thailand).

Less Advanced Developing Countries: In the table, there are five countries (India, Pakistan, Indonesia, Philippines, and Vietnam) that will not reach the 4000 kWh per capita benchmark even with annual TEC growth of 4.7%, but will come within reasonable proximity. The substantial growth rate would call for considerable advancements. These countries, though definite candidates for nuclear expansion, will need very creative deployment strategies for the expansion to occur in their economies. In this group, India and Pakistan have already demonstrated nuclear weapons capability and so are not of principal concern. However, Indonesia, Philippines and Vietnam, as with several of the countries above, would introduce nuclear power in the growth scenario, inevitably raising the proliferation concern.

Least Advanced Developing Countries: There are also eight countries (Nigeria, Bangladesh, Democratic Republic of Congo, Ethiopia, Yemen, Uganda, Tanzania, and Afghanistan) among the 25 largest in 2050 that are very unlikely to come close to reaching the 4000 kWh per capita benchmark. Indeed they typically reach only 100-500 kWh APCEC even by expanding their electricity production by a factor of ten. These are not good candidates for nuclear power, in which case proliferation associated with the nuclear fuel cycle would not be a concern.

The nuclear growth scenario is summarized in Table 2-7. The nuclear global market share of electricity production goes from 17% to a range of 21-36%.

TABLE 2-8: Nuclear Growth Scenario Deployment

	Nuclear Capacity (GWe)		Nuclear Share[a] (%)		
	2050 Low	2050 High	2000	2050 L	2050 H
Developed World	**593**	**921**	**23%**	**33%**	**51%**
USA	286	477	20%	30%	50%
Europe	167	227	31%	41%	55%
Developed East Asia	98	144	30%	42%	62%
Others (Canada, South Africa,…)	42	73			
Developing World	**307**	**610**	**2%**	**13%**	**25%**
China, India, Pakistan	197	395	1.6%	15%	28.5%
Indonesia, Brazil, Mexico	47	93	2%	17%	34%
Iran, Egypt, Turkey, Philippines, Thailand, Argentina, Vietnam, Algeria	39	78	1%	13%	25%
Others (Libya, North Korea,…)	24	44			
Former Soviet Union	**50**	**78**	**18%**	**27%**	**42%**
TOTAL	**950**	**1609**	**16%**	**21%**	**36%**

a) Nuclear share of total electricity market

The developing world and Former Soviet Union states account for about 40% of the mid-century scenario nuclear capacity, versus only 4% today. Though a significant portion of this would be in China and India, a number of nations with relatively little nuclear infrastructure today are likely candidates for nuclear power; as noted above, Indonesia, Philippines, Vietnam, Iran, Egypt, Turkey and Thailand are in this category. This will no doubt raise proliferation concerns as nuclear power deployment spreads into regions subject to significant geopolitical uncertainty. Iran, for instance, is actively pursuing nuclear power, with Russian help, even though it has tremendous natural gas reserves and could easily meet its electricity needs more economically and quickly without nuclear power.

2.3 World Demand Map

A set of regional maps helps bring all these issues into focus. The following maps were modified and electricity demand data was added. They highlight the magnitude of the infrastructure changes needed in various regions throughout the world. The maps also help to add perspective on regional factors that might motivate a country to pursue civilian nuclear power or even nuclear weapons capabilities (e.g., Countries like Iran and Israel might find it in the best interest of national security to pursue nuclear weapons capability if there is an increase in nuclear infrastructure among their neighbors, like Turkey, Libya and Egypt. North African countries like Egypt, Libya, Algeria and Morocco could conceivably find benefit in simultaneously developing their nuclear infrastructure.). The maps can ultimately be used as a visual aid to better understand the world (and regional) trends in electricity demand and how expansion might occur. *Note: the tables give nuclear capacities for each country in the following order (2000/2050Low/2050High).*

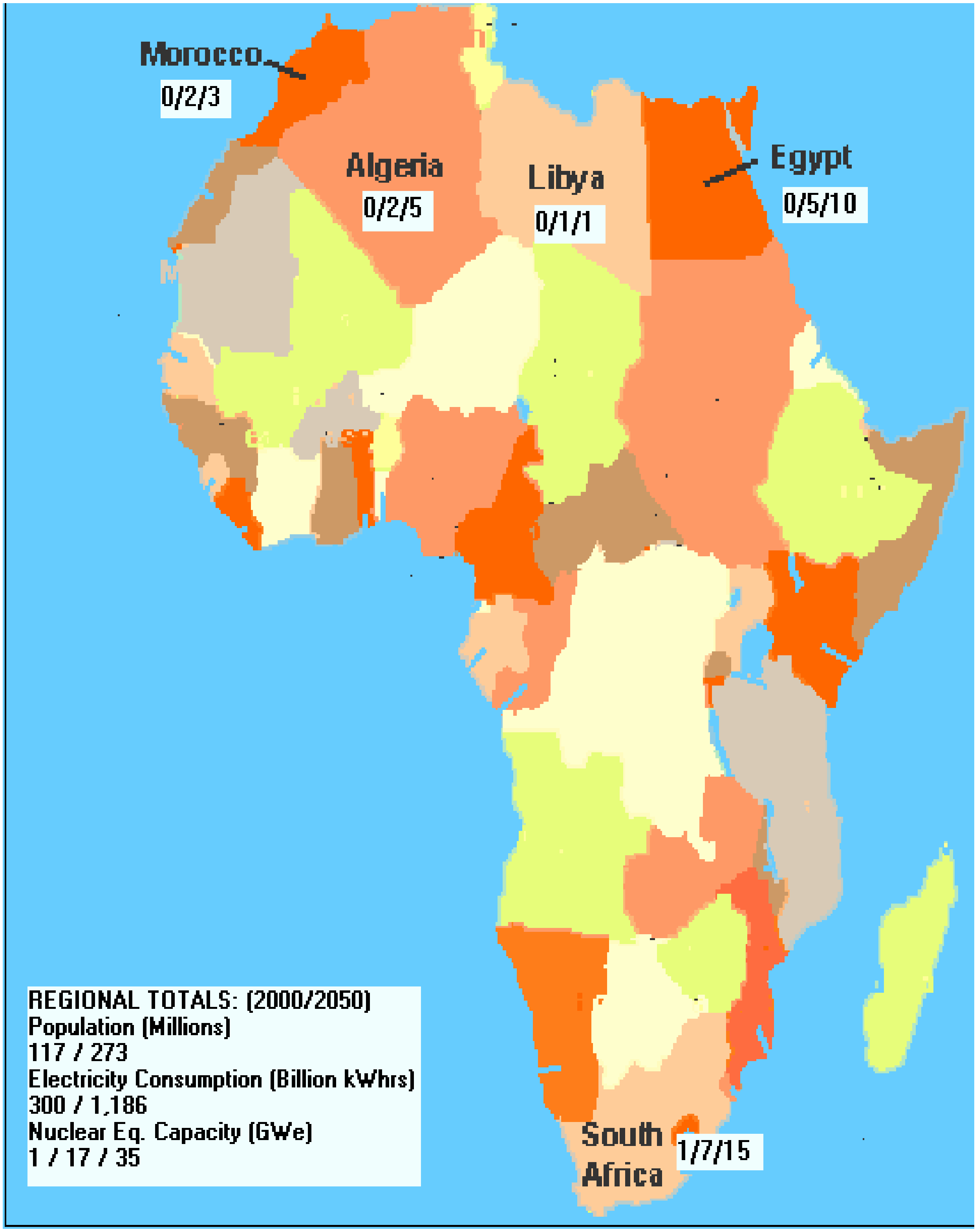

FIGURE 2-5: Nuclear Capacity Trends in Africa

Nuclear Capacities (GWe) are shown for 2000, 2050 low projections and 2050 high projections. The Map also includes regional information.

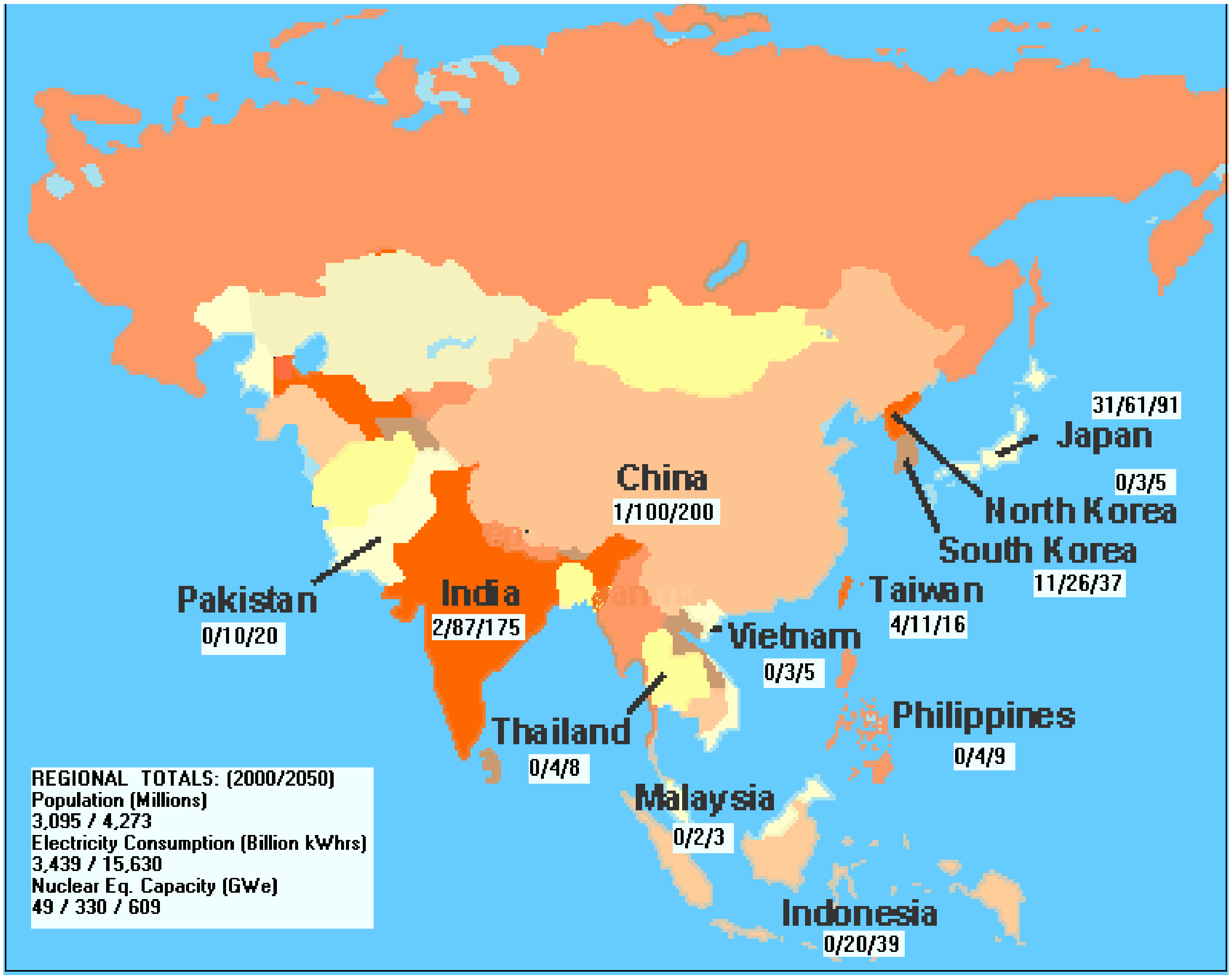

FIGURE 2-6: Nuclear Capacity Trends in Asia

Nuclear Capacities (GWe) are shown for 2000, 2050 low projections and 2050 high projections. The Map also includes regional information. Asia is tied with Europe for having the most new nuclear countries (7). It is number one, just ahead of North America (US, Canada and Mexico), in projected nuclear capacity and in population. Only nuclear countries were counted in this ranking.

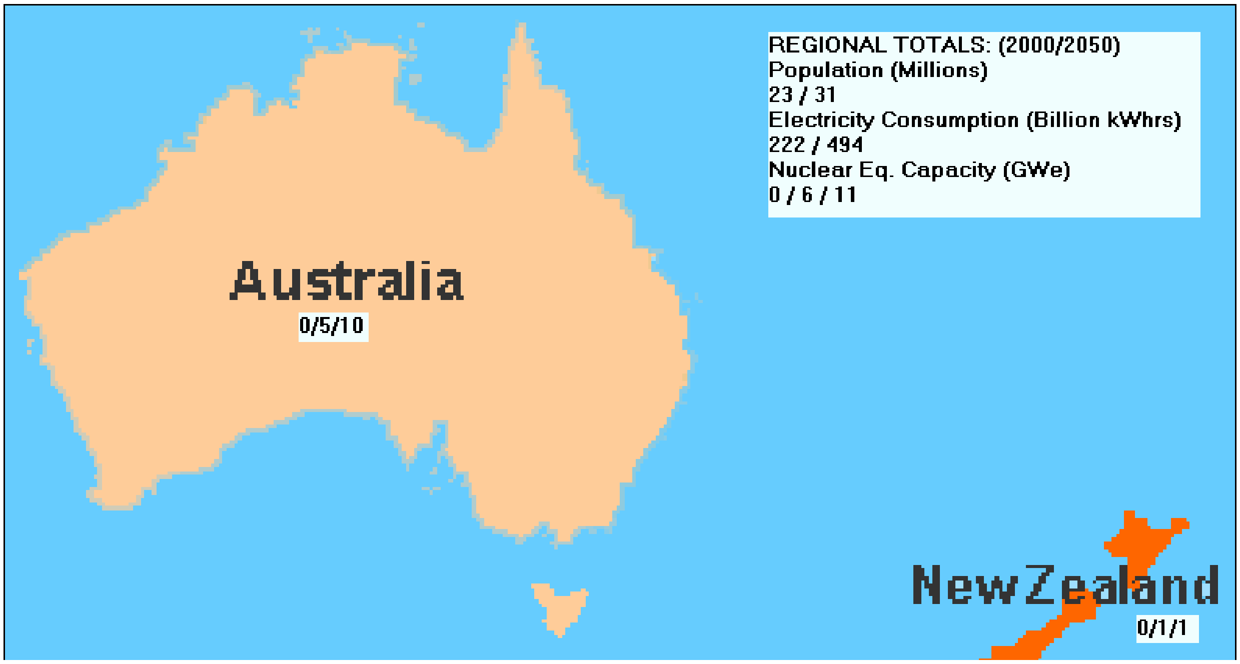

FIGURE 2-7: Nuclear Capacity Trends in Australasia

Nuclear Capacities (GWe) are shown for 2000, 2050 low projections and 2050 high projections. The Map also includes regional information.

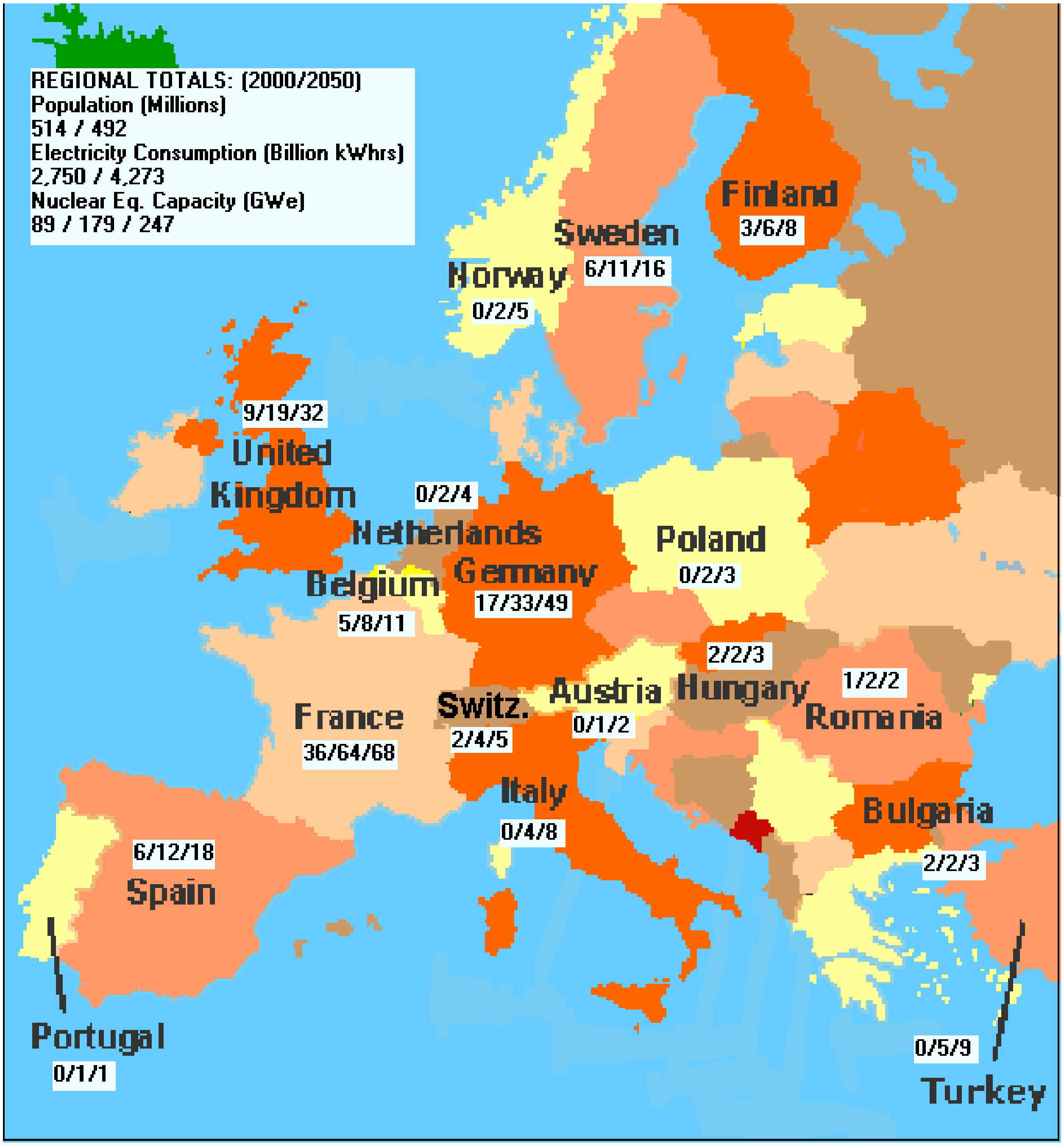

FIGURE 2-8: Nuclear Capacity Trends in Europe
Nuclear Capacities (GWe) are shown for 2000, 2050 low projections and 2050 high projections. The Map also includes regional information. Europe is tied with Asia for having the most new nuclear countries (7) ranking.

FIGURE 2-9: Nuclear Capacity Trends in The Former Soviet Union

Nuclear Capacities (GWe) are shown for 2000, 2050 low projections and 2050 high projections. The Map also includes regional information. Several countries are not shown, but were calculated in totals.

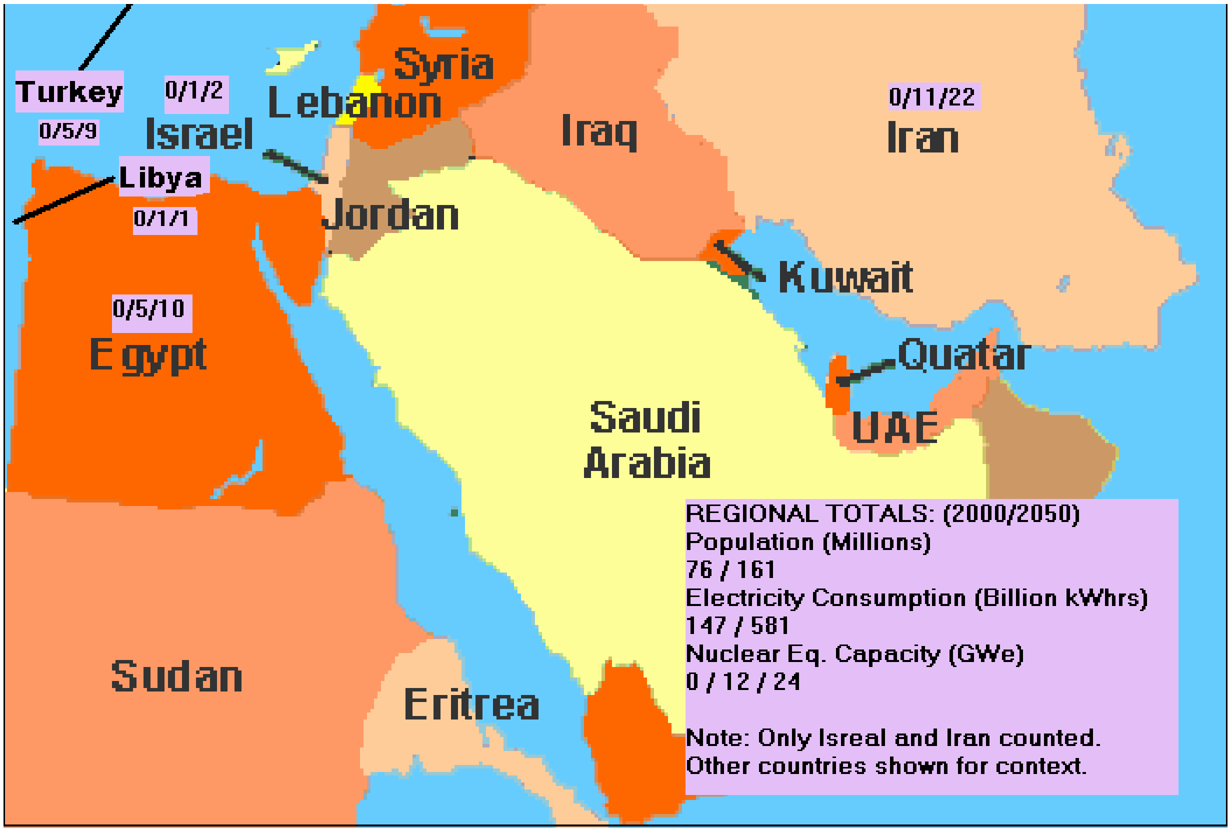

FIGURE 2-10: Nuclear Capacity Trends in The Middle East

Nuclear Capacities (GWe) are shown for 2000, 2050 low projections and 2050 high projections. The Map also includes regional information. The Middle East is considered the region of greatest proliferation concern. Several countries are only shown for context and are not calculated into the totals.

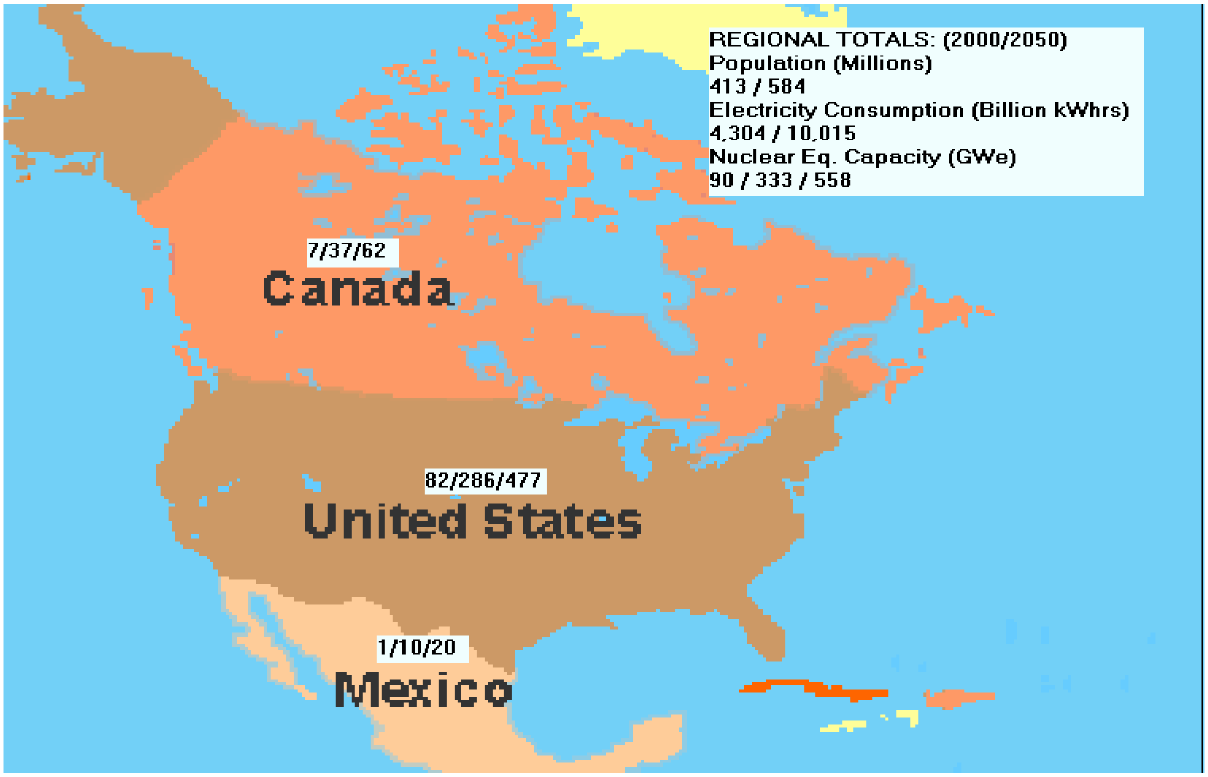

FIGURE 2-11: Nuclear Capacity Trends in North America
Nuclear Capacities (GWe) are shown for 2000, 2050 low projections and 2050 high projections. The Map also includes regional information.

FIGURE 2-12: Nuclear Capacity Trends in South America

Nuclear Capacities (GWe) are shown for 2000, 2050 low projections and 2050 high projections. The Map also includes regional information.

This scenario for robust growth of nuclear power deployment around the globe provides the context for addressing proliferation concerns associated with the fuel cycle during the next several decades. The concern does not depend entirely upon or await realization of the scenario, which after all has a considerable probability of not being achieved. Nevertheless, movement in this direction perhaps spurred by environmental and energy security arguments can result in the nuclear infrastructure developments that can present proliferation risks long before a major nuclear power deployment is in place.

3 PROLIFERATION MATRIX AND PROLIFERATION PATHWAYS

3.1 Assessing Nonproliferation

There have been numerous discussions in many countries on assessing the risks of nuclear-weapons proliferation. In particular, in the 1970's, the Nonproliferation Alternative Systems Assessment Program (NASAP, 1978) review was carried out by the United States. The main NASAP conclusions were: that there is no "purely technical" fix for the proliferation risks associated with nuclear fuel cycles; that there would be substantial differences in proliferation resistance between various fuel cycles if they were to be deployed in Non-Nuclear Weapons States; and that technical and institutional improvements could help increase proliferation resistance. Thereafter, the International Atomic Energy Agency (IAEA) organized the major International Nuclear Fuel Cycle Evaluation (INFCE, 1980) that involved more than 60 nations and international organizations. The main conclusions of the INFCE assessment were generally very similar to NASAP conclusions, with an emphasis on sensitivity to the specific threat under consideration.

Fuel cycle proliferation assessments, including those mentioned above, are primarily qualitative in nature given the difficulty of developing quantitative metrics and the complication of a broad threat spectrum. Frameworks are being developed that aspire to quantitative analysis (e.g., the EIA assessment methodology (Finucane and Ledergerber, 2000); a probabilistic approach (Sentell, et. al., 2001); an electrical circuit model (Ko, 1998); a multi-attribute utility approach (Heising, 1980);…). We will necessarily remain in a basically qualitative framework, using the "attributes methodology" developed originally in National Academy of Sciences reports (NAS, 1994, 1995, 1999) and focusing on proliferation pathways highlighted by the growth scenario.

The attributes methodology was used and further developed by a Department Of Energy task force, the Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS, 2000). The goal of the TOPS task force was to identify near-term and long-term technical opportunities to further increase the proliferation resistance of global civilian nuclear power systems. Subsequent efforts were made to apply the methodology to several specific nuclear power systems. The results were considered an initial "field test" of the application of the attributes methodology. More recently, J. A. Hassberger, of Lawrence Livermore National Labs, used the proliferation matrix and looked at several fuel cycles with a common basis (Hassberger, 2001). Our approach is most similar to that of Hassberger, but with fuel cycles chosen specifically in the context of growth scenario proliferation concerns and as vehicles for formulating a set of recommendations.

3.2 The Attributes Methodology

3.2.1 Framework

The assessment of overall proliferation risk posed by a given nuclear fuel system involves evaluations of vulnerabilities associated with each step in the nuclear fuel cycle of that system.

Evaluations must consider both the inherent properties[1] of the materials used or produced in a fuel cycle and the availability of appropriate technologies and facilities for converting these materials into nuclear weapons or other nuclear explosive devices. Several factors are involved in this evaluation and assessment, these include:

- Number, type and location of nuclear installations
- Form, quality and quantity of fissile material used during fuel cycle operations
- Accessibility of fissile materials during fuel cycle operations and transportation
- Inherent design features of fuel cycle
- Possibility of direct misuse of a nuclear facility
- Time required for facility misuse modifications
- Detectability of facility misuse modifications
- Detectability of diversion or theft of fissile materials
- Technical capabilities and expertise required to design, build and operate the nuclear facilities

General proliferation threats arising from civilian nuclear power systems include: (1) the misuse of material through its diversion or theft; (2) misuse of facilities, equipment, and technology; and (3) transfer of nuclear skills, knowledge, and expertise useful in the weapons area. Threats may be either *overt* or *covert* in nature. The assessment includes three primary steps: first, identifying proliferation pathways that result from a particular threat and the linkage between fuel cycle activities and proliferation; then, identifying various barriers to those proliferation pathways; and finally, outlining the important attributes that characterize the effectiveness of the barriers, for each system or subsystem.

3.2.2 Proliferation Pathways

A Proliferation Pathway is defined as the nuclear fuel cycle assisted path taken to acquire nuclear weapons capabilities. The key components in any proliferation pathway are materials (in particular, high enriched uranium (HEU) and plutonium), technology (e.g., enrichment and reprocessing), and facilities and skills (e.g., hot fuel cell handling and separations operations)

Potential proliferators are Non-Nuclear Weapons States or Sub-National Groups. Non-Nuclear Weapons States can be divided further between those that have very high technical levels of nuclear sophistication and those that do not, with all degrees in between. Sub-National Groups can be divided between those that will use material or information for themselves and those that will transfer it to someone else. Nuclear Weapons States already possess the facilities, technologies, and capabilities required to produce weapons and have little need to rely on civilian nuclear technologies for military purposes. These Weapons States could transfer technology to Non-Nuclear Weapons States (e.g., Russia and China transferring nuclear technology to Iran), but the critical focus will remain on the Non-Nuclear Weapons State.

The identification of proliferation threats, the understanding of pathways that enable those threats, and the evaluation of barriers to these threats must recognize the evolving nature of the problems and issues. Many and diverse threat scenarios involve numerous actors, pathways, and actions. Scenarios must be examined to determine which are most serious, involve the most likely threats and are therefore the most important—and then systems and subsystems must be

[1] Those properties that make the material suitable for nuclear weapons

proposed to deal with the most important threats. The technical capabilities and sophistication of potential proliferators will likely also increase with time. Research and development advances change the nature and degree of a threat and of the fuel cycle itself and are likely to enhance the need for safeguards.

The proliferation pathways can be captured by the event tree below, which will be used in the following chapter to highlight specific pathways.

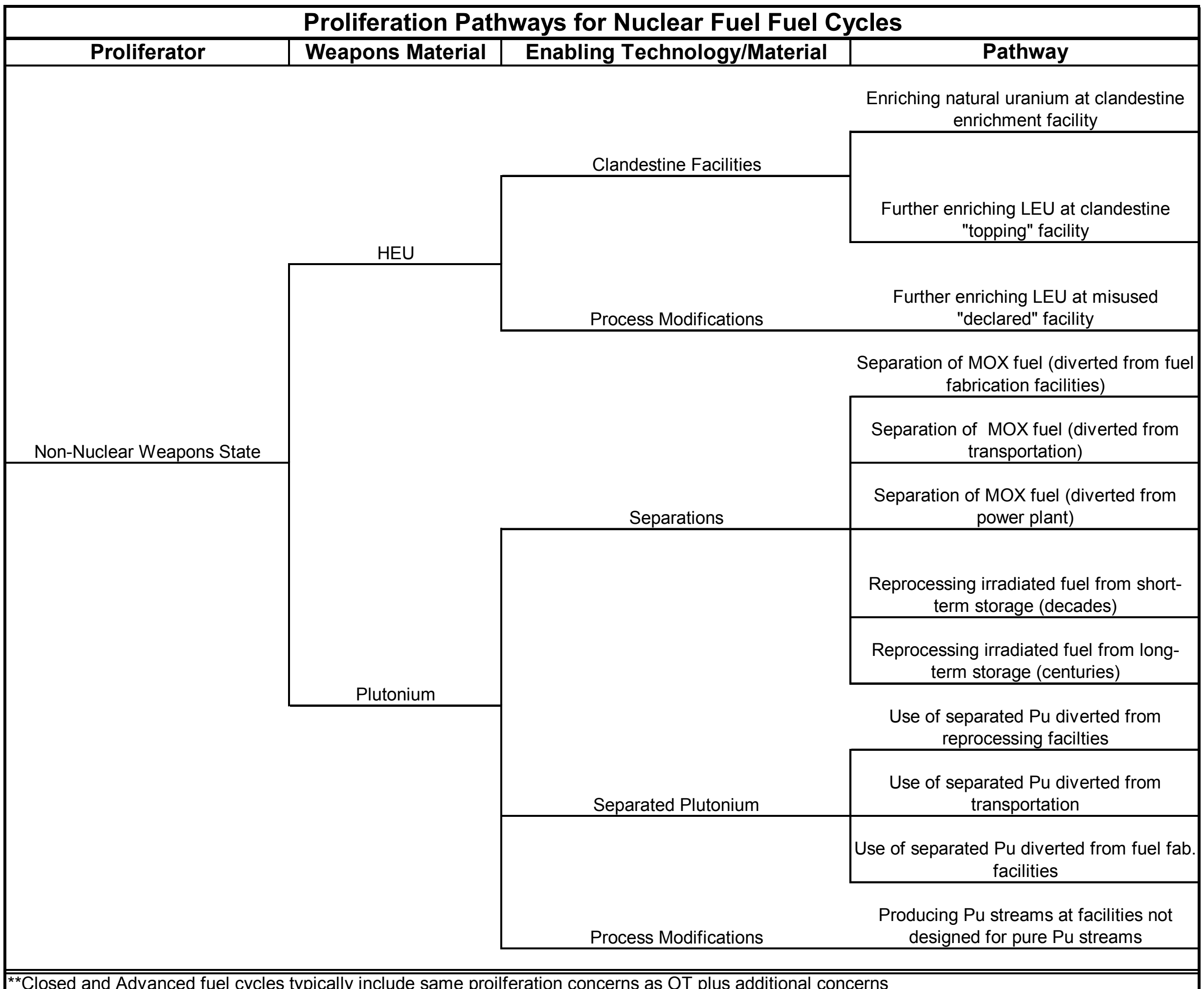

FIGURE 3-1[2]: Proliferation Pathways Diagram

The Weapons Materials, Enabling Technology/Materials and Pathways will be discussed and developed in detail in chapter 4. They are included here for completeness.

3.2.3 Proliferation Barriers

Material qualities, technical impediments, and institutional arrangements (including a range of measures known as material protection, control, and accounting or MPC&A) present barriers

[2] Front-end: fuel cycle activities beginning at mining and ending at shipment of fresh fuel to reactor. Back-end: fuel cycle activities beginning with shipment from reactor to long-term disposal of spent fuel. Note: all fabrication facilities are considered front-end activities. HEU = High Enriched Uranium. LEU = Low Enriched Uranium. MOX = Mixed Oxide.

that make it more difficult for proliferators to exploit civilian nuclear power systems. These barriers are essentially roadblocks to proliferation pathways. The first two types of barriers above are intrinsic (material and technical) and the last is extrinsic (institutional). Extrinsic barriers depend on implementation protocols and processes and compensate for weaknesses in the intrinsic barriers. Intrinsic barriers are those inherent to technical and related elements of a fuel cycle, and its facilities and equipment. Most analyses (with the exception of the TOPS committee analysis) available to-date focus on the extrinsic barriers.

Barriers also do not act independently, and the effect of multiple barriers can be greater than the sum of their individual effects. To better understand this, a classification system was designed.

3.3 Barriers Classification

Various NAS panels (1994, 95, and 99) devised a classification of barriers and their associated attributes. For example, material isotopic, radiological and chemical characteristics would be material barrier attributes. The TOPS task force later built upon these classifications with slight modifications. It was noted by the task force that proposals to analyze proliferation resistance using risk-based methodologies, similar to those used for reactor safety studies, require knowledge or estimates of the probabilities of those risks but such knowledge is lacking or poor, and the probability estimates required are subject to significant debate. The barriers approach avoids this difficulty by requiring only an assessment of the relative effectiveness of individual barriers, lending it to qualitative and transparent comparisons among various system concepts and options.

The goal of their assessment was to define a set of attributes that describe the relationship between the elements of a fuel cycle, the threats arising from those elements, the pathways to actualizing these threats, and the effectiveness of barriers to inhibit these pathways. This process helps identify where technologies can advance the goal of enhancing the proliferation resistance of civilian nuclear power systems.

The original assessment methodology and that used by the TOPS task force are fully outlined in (TOPS, 2000). A brief summary of this detailed and in-depth discussion of the barrier classification can be found in the appendix. In general, the process identifies all stages of the nuclear fuel cycle system and presents the information in a useful proliferation assessment matrix. The following tables outline each barrier attribute and the matrices used to assess their effectiveness.

Table 3-1 summarizes the material barriers and their effectiveness. In the table, I represents an ineffective barrier, L a low barrier, M a medium barrier, H a high barrier and VH a very high barrier. This scale is not linear and some qualitative differences may exist between different rankings. The scale is also not comparable among the various barriers. That is to say, the effectiveness of an H radiological barrier is not necessarily equivalent to an H chemical barrier in the overall risk evaluation.

TABLE 3-1: Classification of Material Barriers[3]

Material Barriers					
Barrier	**Classification**				
	I	**L**	**M**	**H**	**VH**
Isotopic	Weapons-grade HEU (80% or greater U-235)	HEU(50-80%), Weapons-grade Pu(>90%Pu-239), Typical Reactor-Grade Pu(60%Pu-239), HEU (35-50%U-235), very high burnup reactor-grade Pu (40%or<Pu239)	HEU (20-35%U235)	LEU	Natural, depleted U
Radiological	No significant radiation hazard, capable of unlimited hands-on access, includes natural, depleted, and enriched uranium		Moderate radiation hazards, normally requiring glove-box handling, includes separated plutonium	Dangerous radiation hazards, levels fall below "self-protection standard"(100R/hr @ 1meter)	Lethal levels of radiation meeting the self-protecting standard, includes most spent fuel and high-level wastes
Chemical	Pure metals	Single compounds (requiring relatively few and simple chemical steps to extract a pure metal)	Mixed compounds (MOX fuel, dilutents and burnable poisons, but not fission products or other radiation barriers)		Spent fuel and vitrified wastes
Mass/Bulk	Small amounts of weapons usable materials, easily concealed and transported, with sufficient concentrations that require few trips for accumulation	Similar to I, but significantly more difficult to conceal	Large quantities must be transported (multiple trips and/or several individuals)	Large quantities must be transported, requiring commonly used equipment and vehicles	Large quantities, specialized equipment and/or low concentrations requiring many trips
Detectability	No reliable signature for remote detection	Materials requiring active means of detection	Materials that can be reliably detected		Materials easily dected by passive means

Table 3-2 summarizes the technical barriers and their effectiveness.

[3] Adapted from TOPS report. Note also that while "weapons-grade HEU" is rated I, "weapons-grade plutonium" is rated L. This is principally due to the isotopic characteristics of plutonium that make is more difficult to handle.

TABLE 3-2: Classification of Technical Barriers[4]

Technical Barriers					
Barrier	**Classification**				
	I	**L**	**M**	**H**	**VH**
Facility Unattractiveness	Facilities that routinely use, handle or produce significant quantities of directly weapons-usable materials	Facilities that can be modified quickly, safely and easily. With observables difficult to detect prior to accumulation of significant quantities of materials	Facilities that require expertise, expense and time (~month) to modify	Facilities capable of modification given substantial time (months to years), money and expertise. Safety and throughput issues involved	Facilities with little appeal for modification
Facility Access	Access to sensitive materials is quick and easy. Frequent hands-on access		Access is normally accomplished via automated, remote processes. Manual operations are limited		Access is extremely difficult, requiring highly specialized skills and equipment
Available Mass	Very large quantites (multiple critical masses) of potentially weapons-usable materials present	A significant quantity (on the order of a critical mass) of potentially weapons-usable material is present		Small quantities (<10% critical mass) of potentially weapons-usable materials present	Very small quantities (<1% critical mass) of potentially weapons-usabe materials present
Facility Diversion Detectability	Facilities with no or minimal detection equipment. Procedures that allow materials to easily move with detection				Facilities with detection equipment. Procedures that make it very difficult for material to move without detection]
Skills, Knowledge, Expertise	Process, technology, or facility provides significant and unique technical expertise having direct weapons-development application. "Dual-use skills"		Existence of skills, knowledge and expertise provide support valuable to weapons-development programs, but is not directly applicable		Only general industrial skills are needed to support the technology or facility. These skills are well known and readily available
Time	Long storage time (decades) with oportunity for access to materials and/or equipment	Long storage time but with low access opportunity	Intermediate storage time (years) and low opportunity for access	Short to intermediate storage times with high opportunity for access	Short or no storage time (days to months) and low opportunity for access

Table 3-3 summarizes the institutional barriers and their effectiveness.

[4] Adapted from TOPS report

TABLE 3-3: Classification of Institutional Barriers[5]

Institutional Barriers					
Barrier	**Classification**				
	I	**L**	**M**	**H**	**VH**
Safeguards Effectiveness	Safeguards monitoring parameters are limited and complex. Uncertainty in materials status increases rapidly if monitoring is delayed or restiricted. Margins for error in meeting timeliness of detection goals are small				Multiple monitored parameters provide easily interpreted data. Uncertainty in material status increases slowly with delays or restrictions. Margins for error are large and robust
Access Control, Security	Materials could be easily moved without detection.	With some prior planning, materials could be removed with a small probability of detection. Could be stolen by a small group of lightly armed outsiders	At most times, theft attempts by a single insider would be detected. System vulnerabilities to circumstances (emergencies/power outages) are high. Theft by outsiders would require well-trained, well-armed individuals properly equiped	Theft by a single insider or small group of armed outsiders (or both) can be blocked with good confidence. Design basis threat includes possible use of equipment brought in by vehicles	Theft attempts by multiple insiders or large groups of armed outsiders (or both) can be blocked with high confidence. Design basis threat also includes the possible use of helicopters
Location	Proliferation threat is highly dependent upon facility location				Facility location poses no additional threat to proliferation

The barriers and systems are evaluated and then presented in a table similar to the matrix in table 3-4 below.

[5] Adapted from TOPS report

TABLE 3-4: Proliferation Assessment Matrix[6]

Proliferation Assessment Matrix

Stages of fuel cycle	Material Barriers					Technical Barriers						Institutional		
	Isotopic	Radiological	Chemical	Mass and Bulk	Detectability	Facility Unattractiveness	Facility Access	Available Mass	Facility Diversion Detectability	Skills, Knowledge, Expertise	Time	Safeguards Effectiveness	Access Control, Security	Location
Beginning of the cycle														
Mining														
Transport														
Miling														
Transport														
Conversion														
Storage														
Transport														
Uranium Enrichment														
Storage														
Transport														
Manufacture of fuel material (fissle material)/thorium														
Production of fuel (pellets,pebbles, etc.)														
Production of Fuel Assemblies, Cast														
Storage														
Fresh fuel transport to NPP														
Operation at NPP														
Storage of fresh fuel														
Loading of fresh fuel into the core														
Reactor irradiation														
Unloading of irradiated fuel from the core														
On-site pool storage of spent fuel														
On-site dry storage of spent fuel														
Closed cycles														
Dissassembly of fuel assembly														
Separation of fissile materials														
Storage of highly-concentrated fissile material														
Manufacture of fresh fuel from recovered fissile materials														
Collection, processing and storage of actinide-containing waste														
Transport of actinide-containing waste for burial														
Transport of recovered fuel														
End of fuel cycle (includes once-through)														
Off-site transport of irradiated spent fuel														
Temporary storage of irradiated fuel														
Processing of irradiated fuel for storage and disposition														
Storage of processed materials														
Long-term geolgical burial of irradiated fuel and actinide-containing waste														

The matrix shows each stage of a closed fuel cycle and can be easily altered, by addition or removal of stages, to accommodate any nuclear fuel cycle. It was suggested that each system be

[6] Adapted from TOPS report

evaluated separately for each threat to that system (e.g., covert diversion by a Sophisticated Non-Nuclear Weapons State,…). In Chapter 4, we use this framework to present an assessment of five reactor/fuel cycle combinations that may be especially relevant for the growth scenario. We start with the major deployed reactor/fuel cycle combinations, that is, light water reactors operated in once-through mode (open fuel cycle) or in MOX recycle mode ("closed" fuel cycle); widespread deployment today suggests that these technologies are likely to dominate at least the early parts of the growth scenario. We then turn to two reactor concepts, high temperature gas reactors and long-life core reactors, that may be attractive for deployment in many countries, specifically including developing countries, because of their modular design; these would be operated in once-through mode. Finally, we examine an advanced closed fuel cycle (fast spectrum reactor with recycle of plutonium and minor actinides) that is thought to have advantages with regard to uranium resource extension and waste management. The gas reactor might be practical for significant deployment well into the growth scenario (say, twenty years). The others (especially the fast reactor/closed fuel cycle) face major development and cost challenges and are very unlikely to be deployed significantly for at least fifty years.

Within the framework[7] outlined above, we evaluate the effectiveness of the various barriers at different stages of the nuclear fuel cycle. Some stages of the fuel cycle may have relatively little influence on proliferation resistance and also do not significantly affect relative comparisons of most fuel cycles. There is also substantial commonality for most fuel cycles in the storage and disposition of spent fuel and processed high-level radiation waste. Our focus will be on proliferation pathways particular to the technology, in relation to the baseline LWR/open fuel cycle. A detailed analysis of the effectiveness of each barrier (at each stage of the particular nuclear fuel cycle) was performed for both the threat posed by sub-national groups and non-nuclear weapons states. However, we only present those pathways (posed by non-nuclear weapons states) that are of greatest concern or relevance.

3.4 Discussion

In summary, the assessment methodology used for each reactor/fuel cycle, follows the steps below:

a. Step One: Define the proliferation pathway that a nation or organization might take to acquire nuclear weapons capabilities.
b. Step Two: Using the proliferation matrix, assess the nuclear fuel cycle given each defined pathway.
c. Step Three: Highlight key vulnerabilities and barriers in the fuel cycle with respect to a particular pathway.
d. Step Four: Develop recommendations that address the key vulnerabilities.

The principal focus is on non-nuclear weapons states. We assume that sub-national groups would practically need to start from weapons-usable material to produce a nuclear

[7] J. Hassberger, in his assessment noted that the framework requires consideration of two important factors: the *effectiveness* of a fuel cycle in supporting each barrier in the framework; and the *importance* of that barrier to each of the particular threats. He pointed out that it could be very tedious and cumbersome to consider both the barrier *effectiveness* and the barrier *importance* for each barrier, each fuel cycle stage, and each threat. His conclusion, was that the extent to which a particular fuel cycle and/or technology supports the *effectiveness* of a particular barrier is dependent only on the fuel cycle and/or technology itself and not on the threat. Also, the *importance* of a particular barrier in overall evaluation of proliferation resistance depends mainly on the threat and the viability of the threat to be realized.

weapon, that is, that such groups do not have the capability to produce the material without the active support and protection of a state (in which case the problem is effectively one of state proliferation). Consequently, fuel cycles that make weapons-usable material available during normal fuel cycle operations are singled out for special concern with respect to sub-national groups.

4 NUCLEAR FUEL CYCLE ASSESSMENT

The reactor/fuel cycle combinations chosen for assessment fall into three time frames: 1) "baseline" technologies (LWR once-through; LWR MOX) chosen because they are the dominant commercial nuclear fuel cycles currently operational; 2) relatively near-term technologies (MPBR) chosen because this represents a technology that could become a commercial option in the near future; and 3) long-term technologies (Lifetime Cores-Encapsulated Nuclear Heat Source and IFR) chosen because they represent technologies that are still in the concept stages but could be available for deployment by mid-century. These are particularly appropriate for our nonproliferation considerations in the global growth scenario since the baseline technologies are those that would dominate its early stages, the once-through cycles built around next-generation modular reactors may be especially relevant for developing countries, and the advanced closed fuel cycles will generate considerable development activity over the next decades.

4.1 Once Through Fuel Cycles

The sketch below represents the typical stages of a generic once through nuclear fuel cycle.

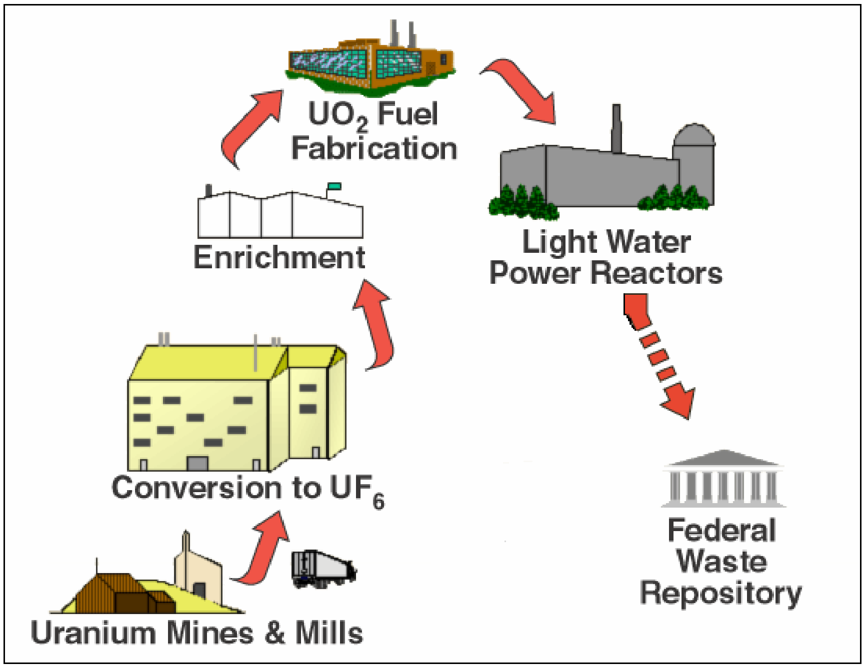

FIGURE 4-1: Typical Stages of Once Through Nuclear Fuel Cycle[1].

Arrows represent transportation of materials. There are currently no operational permanent waste repository sites, only spent fuel storage facilities. Note: UF_6 and UO_2, are notation for uranium hexaflouride and uranium oxide, respectively.

Steps before reactor operation are considered the *front end* of the fuel cycle. Those that follow reactor operation, which generally have high radiation levels, constitute the *back end* of the fuel cycle. In the figure, red arrows represent transportation of materials.

[1] Diagram courtesy of U.S. Nuclear Regulatory Commission (modified) http://www.nrc.gov/materials/fuel-cycle-fac/stages-fuel-cycle.html

The exploration process usually begins with geologic evaluation to determine potential uranium deposits and develop a uranium ore mapping. Major uranium resources are located in Africa, Australia, Brazil, Canada, the western US, and the USSR (see figure 4-2 below). The following map shows 2002 World Uranium Resources (Reasonably Assured Resources).

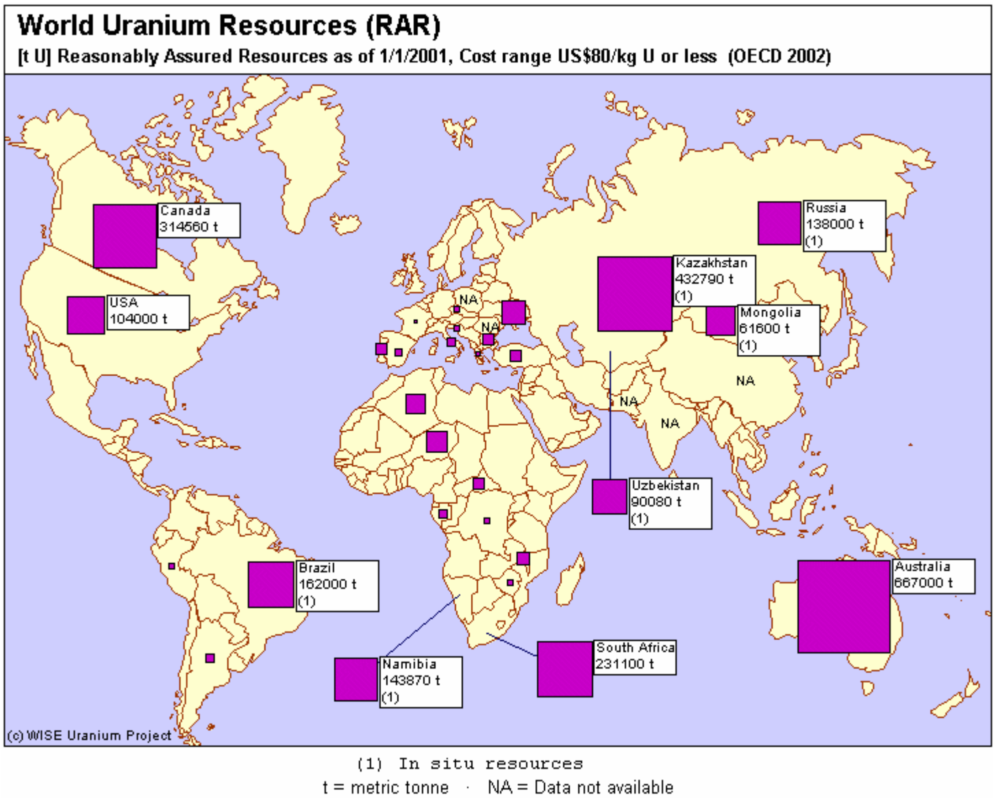

FIGURE 4-2: World Uranium Resources[2]

Uranium is mined by either open pit or underground operations. Next, a *milling* process removes uranium from the ore by chemical and physical operations.

Natural uranium is composed of two isotopes, ^{235}U (0.711wt%) and ^{238}U (99.3wt%), which cannot be chemically separated. The ore must be converted in preparation for being enriched. The *conversion* step begins by purifying the U_3O_8 (yellowcake); then chemical reactions with fluorine produce UF_6 (uranium hexafluoride). Most reactors in operation require that the ^{235}U fraction of the total uranium be higher than 0.711wt% and it thus must be *enriched* (see figures 4-3 and 4-4). The *fabrication* step of the cycle produces fuel in a form that is ready for power production in the reactor. In this step, the enriched uranium hexafluoride is converted to uranium dioxide and then formed into thimble-sized pellets (or pebbles for high temperature gas reactors). These pellets are loaded into cladding tubes and placed into final fuel assemblies (see figure 4-5). The completed fuel assemblies are loaded into the *reactor core* for use and irradiation. Since fuel assemblies are highly radioactive at discharge, they are allowed to cool

[2] Map courtesy of World Information Service on Energy (WISE) Uranium Project (April 2003) http://www.antenna.nl/wise/uranium/umaps.html

for a period in pools (or dry cooling storage). In the Once-Through fuel cycle, these cooled spent fuel assemblies are then taken to long term *waste disposal facilities*.

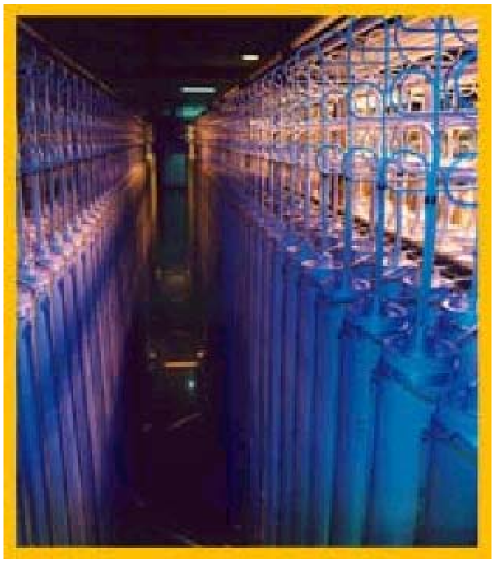

FIGURE 4-3: Centrifuge Enrichment Facility[3]. The photo shows a typical centrifuge enrichment cascade.

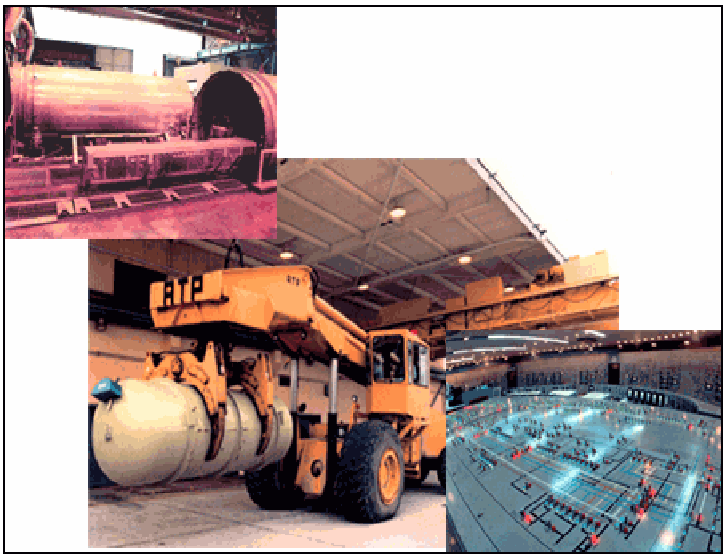

FIGURE 4-4: **Gas Diffusion Enrichment Facility[4]** The photo shows operations at a gaseous diffusion enrichment facility.

[3] Photo courtesy of Urenco (2002) http://www.urenco.com/uranium_enrichment_services.htm
[4] Photo courtesy of USEC (2002) http://www.usec.com/v2001_02/HTML/Facilities_PaducahTour02.asp

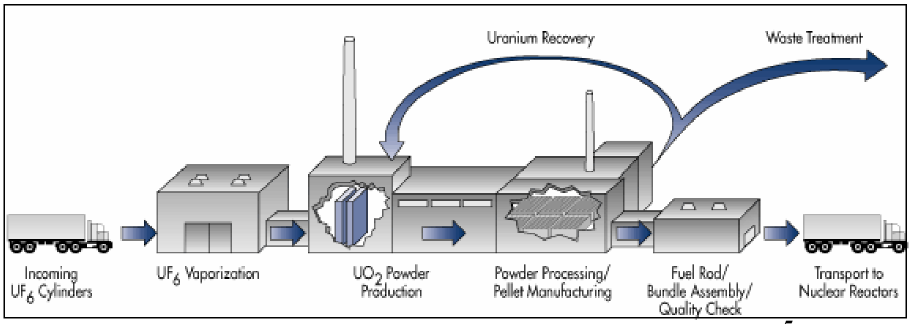

FIGURE 4-5: Uranium Fuel Fabrication Facility[5]

For the once-through fuel cycles, the major variation is with the reactor design and associated fuel form and enrichment.

4.1.1 Light-Water-Moderated Reactors (operated in Once Through Mode)

There are two types of light-water-moderated reactors (LWRs) commercially operational: the pressurized-water reactor (PWR) (see figure 4-6) and the boiling-water reactor (BWR). These reactors are typically designed to operate at a thermal power of about 3,900 megawatts (MWt) yielding electrical power of about 1,300 megawatts (MWe) (Mozley, 1998). In both reactors, the uranium fuel is encased in tubing that can withstand the high temperatures and the high neutron flux of the reactor. Water is circulated past the encased uranium rods to cool them, and the same or additional water acts as a moderator to slow down the neutrons produced by fissioning of uranium-235[6].

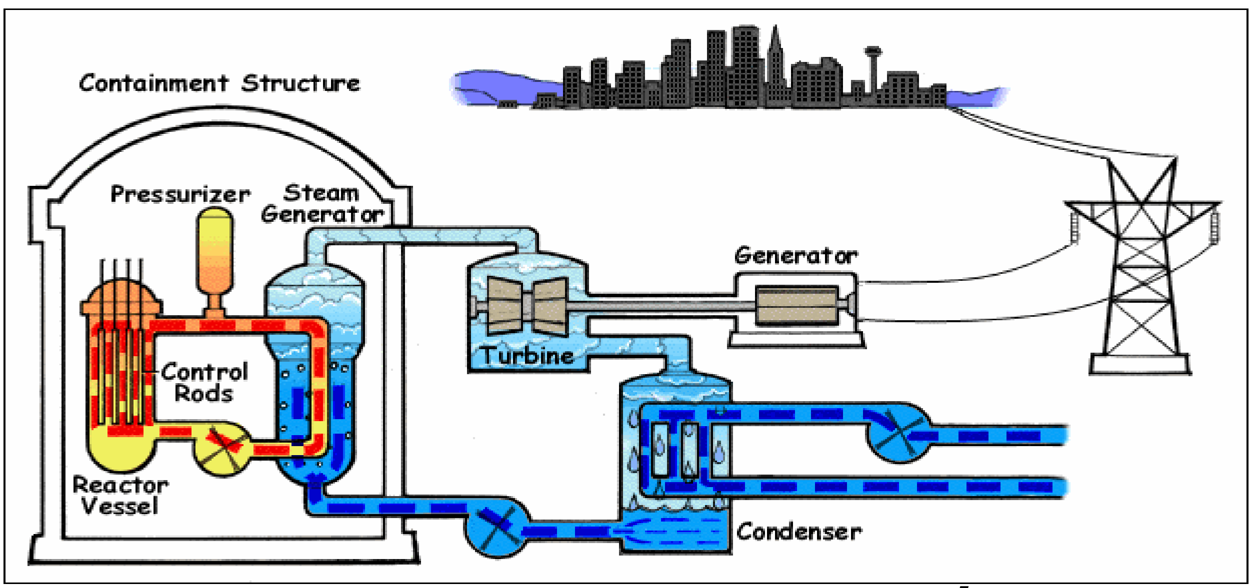

FIGURE 4-6: Pressure Water Reactor Fuel Cycle[7]

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[5] Photo courtesy of the US Nuclear Regulatory Commission http://www.nrc.gov/materials/fuel-cycle-fac/fuel-fab.html

[6] For more detailed discussion of reactor types see (Knief, 1992)

[7] Photo courtesy US Nuclear Regulatory Commission (2002) http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html

In a PWR the hot water may be under a pressure of about 2,200psi, so that its boiling point is higher than the temperature at which the reactor operates (over 570°F). This hot water circulates past a heat exchanger where it transfers its heat to water that is under a much lower pressure, possibly only 60 atmospheres. The high-pressure steam is used to power turbines to produce electricity. The PWR is fueled with low-enriched uranium irradiated to moderate burnups, reaching perhaps 50,000 MWD/ton.

The BWR, which is similar to the PWR, features a direct-cycle steam system. Feed water enters the reactor vessel, has its flow adjusted by the re-circulation system, and leaves as steam. The high-pressure turbine stage receives steam at about 550^{o}F and 1000psi. By use of successive low-pressure stages and a condenser loop in a standard regenerative cycle, a maximum thermal efficiency of approximately 33% is obtained (Kneif, 1992).

The LWR-OT, with institutional arrangements similar to those in force today, is generally considered an "acceptable" baseline from a non-proliferation point of view. The INFCE study[8] noted that "on the whole, it appears that an adequate degree of proliferation resistance can be attained, at least in the short and medium term, with present thermal reactors in the once-through mode, provided that appropriate safeguards are applied to enrichment, fuel fabrication and irradiated fuel storage facilities" (INFCE, 1980)

4.1.2 Proliferation Pathways

The ultimate goal of any proliferation pathway is the acquisition of highly enriched uranium, plutonium or other weapons usable materials for the purpose of either creating nuclear weapons capability or creating the threat of nuclear weapons capability. Examination of the LWR-OT[9] (from the context of a Non-Nuclear Weapons State with the relevant skills, technologies and facilities to supports its particular civilian nuclear fuel cycle) reveals several potential proliferation pathways. A proliferator could acquire high-enriched uranium through diversion of natural uranium to a clandestine enrichment facility, through diversion of LEU to a clandestine topping plant, or through reconfiguring a declared fuel cycle enrichment facility to produce HEU. If plutonium was the material of choice, it could be acquired through pre-disposal diversion of spent fuel to a clandestine reprocessing facility, or through retrieval of spent fuel from a long-term disposal site.

Pathway A: High-Enriched Uranium

A-1: Diversion of natural uranium

If a non-nuclear weapons state has clandestine enrichment capabilities, there are several points (mining, milling, conversion, storage and transport of natural uranium) prior to the uranium enrichment stage, which must be closely examined to determine their effectiveness in preventing successful proliferation. The diversion path is illustrated in the figure below, where the particular path is in bold.

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[8] Discussed more in chapter 3

[9] Assessments were done using PWR characteristics, but are applicable to BWRs

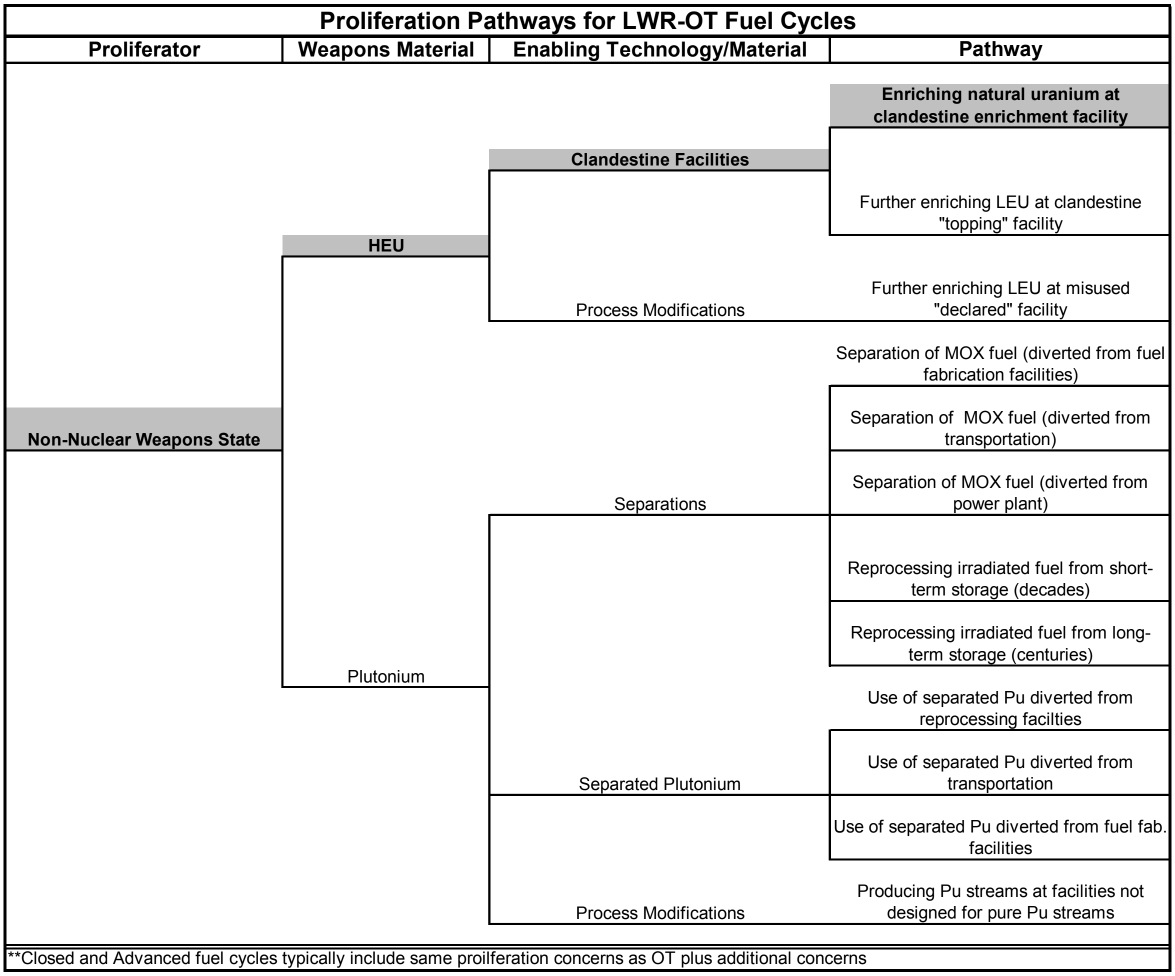

FIGURE 4-7: LWR-OT Pathway A-1 (HEU: Diversion of Natural Uranium)

In this pathway, a Non-Nuclear Weapons State (proliferator) desires to acquire HEU (weapons material) by using clandestine facilities to enrich natural uranium. This pathway is quite possible, but by no means the most efficient or preferred pathway to nuclear weapons.

At any point in the steps above, natural uranium might be diverted to a clandestine enrichment facility. Mining operations and milling plants are not included in the "facilities" that IAEA is authorized to safeguard (INFCIRC/153, 1971). The result, as can be seen in table 4-1, is that mining and milling stages not only have low material and technical barriers to proliferation, but they also have low institutional barriers to proliferation. While diversion of natural uranium would not be a suitable route for sub-national groups to acquire nuclear weapons capabilities, non-nuclear weapons states could conceivably divert considerable amounts of material. The danger of this pathway is further increased by the IAEA's limitation on investigation of undeclared facilities.

A-2: Diversion of LEU

Although diversion of natural uranium to a clandestine enrichment facility is a potential proliferation pathway, it is technically and economically less demanding to produce HEU if one starts with low enriched uranium (LEU). This could be diverted to a small, undeclared, clandestine topping plant[10] (this pathway is detailed in the High Temperature Gas Reactor section, because this technology is typically more vulnerable to topping plants because of the higher enrichment requirement—sometimes 8-11% uranium) or used in a reconfigured part of a declared enrichment facility. Figure 4-8 below is an illustration of this proliferation pathway.

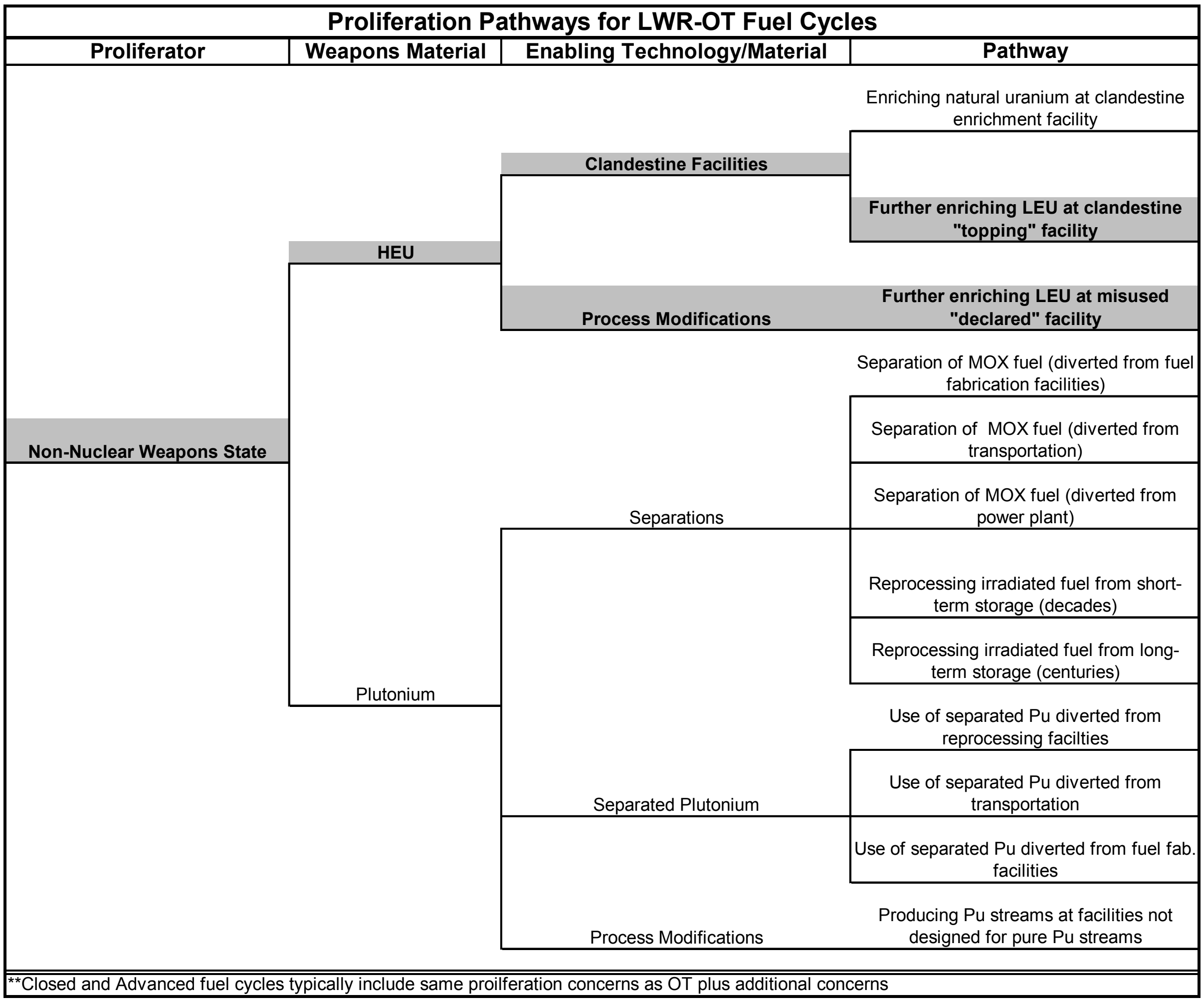

FIGURE 4-8: LWR-OT Pathway A-2 (HEU: Diversion of LEU)

In this pathway, a Non-Nuclear Weapons State (proliferator) desires to acquire HEU (weapons material) either by using clandestine facilities to enrich LEU, or by process modification at declared enrichment facilities. This is a major proliferation pathway, particularly within the context of expanding nuclear power.

Typically, commercial Light Water Reactors use natural uranium enriched to 3-4wt% ^{235}U. The methods of uranium enrichment range used commercially are gaseous diffusion or centrifuge[11] (Krass, 1983). Today's world nominal separative work unit[12] (SWU) capacity is close to 35 million SWU per year (Lenders, 2001). It is estimated that a centrifuge plant requires

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[10] Topping plants are small-scale enrichment facilities that are typically configured to use enriched feed, thereby reducing the SWU requirement for obtaining HEU (see figure 4-9). Topping plants are much less resource intensive than typical commercial enrichment facilities and thus are ideal for clandestine use.

[11] Additional detailed information on each method can be found in Krass, 1983

[12] Separative Work Unit (SWU) is defined as the amount of energy expended in enriching uranium per unit mass of product.

1/10 the energy per SWU than that required by gaseous diffusion plants (Cochran, 1999). A highly efficient centrifuge plant can produce 25 kilograms of weapons-grade uranium using roughly 500,000 kilowatt-hours of electricity (Mozley, 1998, p. 102).

Centrifuge plants require approximately 10 stages in an ideal cascade to enrich natural uranium (0.3wt% tails) to 3wt%, while on the order of 35 stages are required to enrich natural uranium to 90wt%. A minimum-sized plant might involve as few as 1,000 centrifuges to provide a capacity of 5,000 SWU per year. One could attain greater capacities simply by adding centrifuges in parallel or by using larger capacity facilities (Greenwood, 1977).

It is the existence of this enriched uranium that brings the facilities under IAEA safeguard agreements as pursuant to the Non-Proliferation Treat (NPT). The natural or low enriched uranium can be considered usable, though indirectly, for nuclear weapons production. The IAEA has stated, "that while the establishment of an enrichment facility…is a costly and lengthy process, the subsequent enrichment of LEU, once enrichment facilities have been established, could be achieved in less than one year (Nilsson, 1994)." IAEA inspection goals are specified such that when implementing its' safeguards system, the Agency "shall be able to detect a diversion of at least 75 kilograms of uranium-235 contained in LEU during a time period of one year.

To reach their inspection goals, the IAEA created a safeguards approach that enables an annual evaluation and independent verification of the facility's material balance over periods of time. Routine inspections are conducted to verify the operator's declarations of material accountancy, i.e. the accountancy records and supporting source documents. At enrichment facilities, monthly inspections are performed. The inspection planning is based both on operational information given semi-annually and advance notifications of receipts and shipments of nuclear material. Weighing and sampling for subsequent chemical analysis, as well as non-destructive assay for enrichment performance verification of nuclear material in flow. When comparing the inventory as registered (book inventory) with the measured inventory (physical inventory) for a facility handling nuclear material in bulk form, there is always a difference. This difference is called material unaccounted for (MUF). A statistical evaluation of the material balance leads to a conclusion of whether or not the MUF is within acceptable limits. Though this system accurately verifies the correctness and completeness of a nation's declared nuclear activities, it does not provide credible assurances of the absence of undeclared nuclear activities.

Countries that possess enrichment technology have the skills, knowledge and expertise to enrich natural uranium to >90wt% ^{235}U, which is considered weapons-grade and could do so clandestinely with the possibility of subverting current IAEA safeguards, which are not constructed to search for these clandestine activities. The presence of this enrichment technology thus creates vulnerability within the Light Water Reactor Once-Through Fuel Cycles.

Another point to consider is that, with the use of modified civilian facilities or "topping" plants, enriching to >90wt% ^{235}U could be done using previously enriched fuel as feed. This can be seen in figure 4-9, which shows the mass of feed required, given an initial feed enrichment, to enrich 1kg, of uranium product, to 93wt% with 0.25wt% tails, using separative work of 200 kgSWU[13].

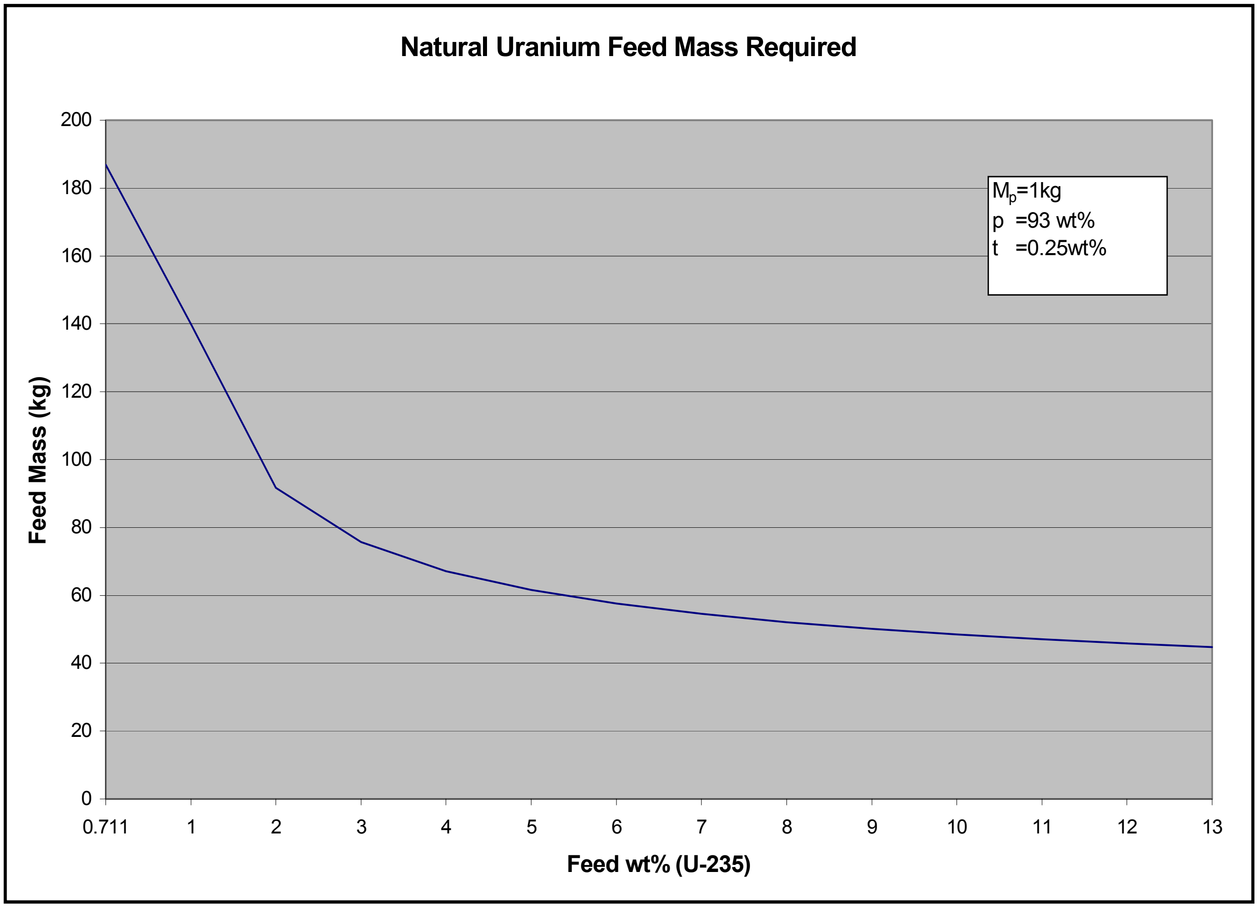

FIGURE 4-9: Required Feed Mass[14]

The graph shows the amount (kg) of uranium-235 needed, given an initial feed enrichment and using 200 kgSWU, to produce 1 kg of 93% enriched uranium that has 0.25% tails.

The above figure shows that separative work of 200 kgSWU will convert 187kg of natural uranium feed to 1kg of 93wt% uranium with 0.25wt% tails. It can be seen from the graph that the same work (200 SWU) requires only 75kg of 3wt% enriched feed to obtain the 1kg of 93wt% enriched uranium with the same tails.

A 1996 Committee on Separations Technology and Transmutation Systems found that an enrichment plant with a capacity of 1 million SWU/yr configured for low enrichment from natural uranium feed could produce 20 tonnes of 3wt% LEU fuel feed per month or 240Mg/yr (NRC, 1996). The same plant reconfigured for HEU production could produce about 350kg of HEU per month or enough for about a dozen nuclear weapons per month (NRC, 1996). The

[13] Separative work can be calculated as the net increase in value (i.e., of the product and tails less that of the initial feed) that results from a given enrichment operation and may be reported in units of mass. Separative Work Unit (SWU) is dimensionless. Often SWU and separative work are used interchangeably.

[14] Graph was generated using the standard formula for separative work units SWU=V(*p*)+V(*t*)(F-1)-V(*f*)F found in (Kneif, 1992).

committee also found that "*material diverted…could be further enriched in a small, covert 'topping' plant, using the same or another enrichment technique, to achieve HEU from the combination. The topping plant itself might be hard to locate without some intelligence information.*"

In a discussion paper, Matthew Bunn (2001) reports that the "HEU for Pakistan's nuclear weapons was produced at a plant using centrifuge technology stolen from a contractor for the civilian URENCO enterprise in Europe". Bunn, in his examination of the aspects of civilian nuclear energy that have contributed to nuclear weapons programs, also reports that Iraq successfully hid both large undeclared facilities and covert activities at declared facilities from the IAEA inspection regime. This can be seen in the photo below:

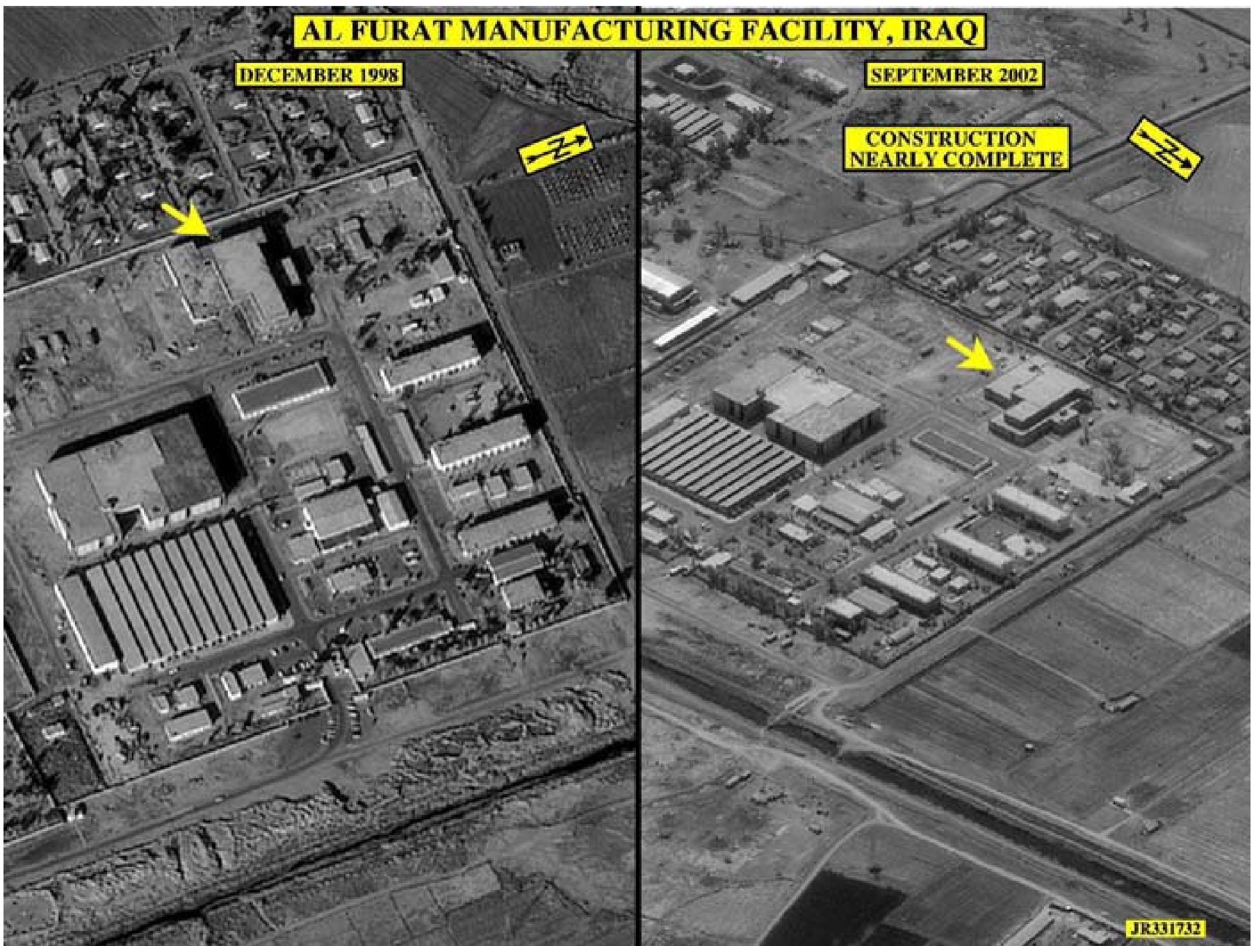

FIGURE 4-10: AL FURAT Manufacturing Facility[15]
The United Nations Special Commission (UNSCOM) reported that this facility was intended for the design, assembly and testing of gas centrifuges for uranium enrichment.

Construction of the building depicted on this graphic was suspended in 1991. Construction resumed in 2001, and the building appears to be nearly complete and operational by September 2002. The building was originally intended to house a centrifuge enrichment cascade

[15] Information and photo taken from www.globalsecurity.org

operation supporting Iraq's uranium enrichment efforts. Global Security, from which this information was obtained, noted that:

> Al Furat, located 27-30 km SW of Baghdad, was intended for the design, assembly, and testing of gas centrifuges for uranium enrichment. Iraq construction of an industrial-scale plant to manufacture centrifuges was conducted under the code-name Al Furat Project. The exact location of this facility remains obscure, but the location reported by UNSCOM appears to correlate with an area enclosed by a security perimeter noted on the Tactical Pilotage Chart for Baghdad, located on the west bank of the Euphrates River. The plant, designed to build all the components for centrifuges, was slated for completion by mid-1991. By various estimates, it could have been capable of manufacturing at least 2,000 and perhaps as many as 5,000 centrifuges annually. Plans called for a 100-machine prototype centrifuge cascade at Al Furat by the end of 1992, with operations beginning by mid-1993. By late 1991, IAEA inspectors had concluded that the German firm Interatom GmbH and Strabag AG, a German construction firm, had worked at the building at al-Furat planned as the 100-centrifuge cascade hall. Iraq was planning to build a 1,000-machine production cascade at Taji. Based on performance achieved by the Iraqis with their prototype centrifuge, IAEA estimated the potential output of a 1,000-centrifuge cascade at about ten kilograms of weapons-grade highly enriched uranium annually. All centrifuge related components were destroyed under IAEA supervision.

Pathway B: Plutonium

A large number of new radioactive species, fission products and actinides, are produced after a nuclear reactor has been operational for a few months. Fresh LWR fuel consists of ^{235}U and ^{238}U in uranium dioxide and after substantial operation will have produced over 50 nuclear species. Plutonium isotopes are among the numerous radionuclides generated. This plutonium is produced when a ^{238}U isotope absorbs a neutron to become ^{239}U. The ^{239}U then decays in a short time by β^- emission to become ^{239}Np, which in turn, decays to ^{239}Pu. There are two pathways to acquiring plutonium from an LWR-OT nuclear fuel cycle. A proliferator could either divert spent fuel that has not been placed in long-term disposal or, after decades, a proliferator could remove plutonium from “plutonium mines” created by “cooling” of spent fuel in terms of heat, radioactivity, and radiotoxicity. Both pathways can be seen in the diagram below:

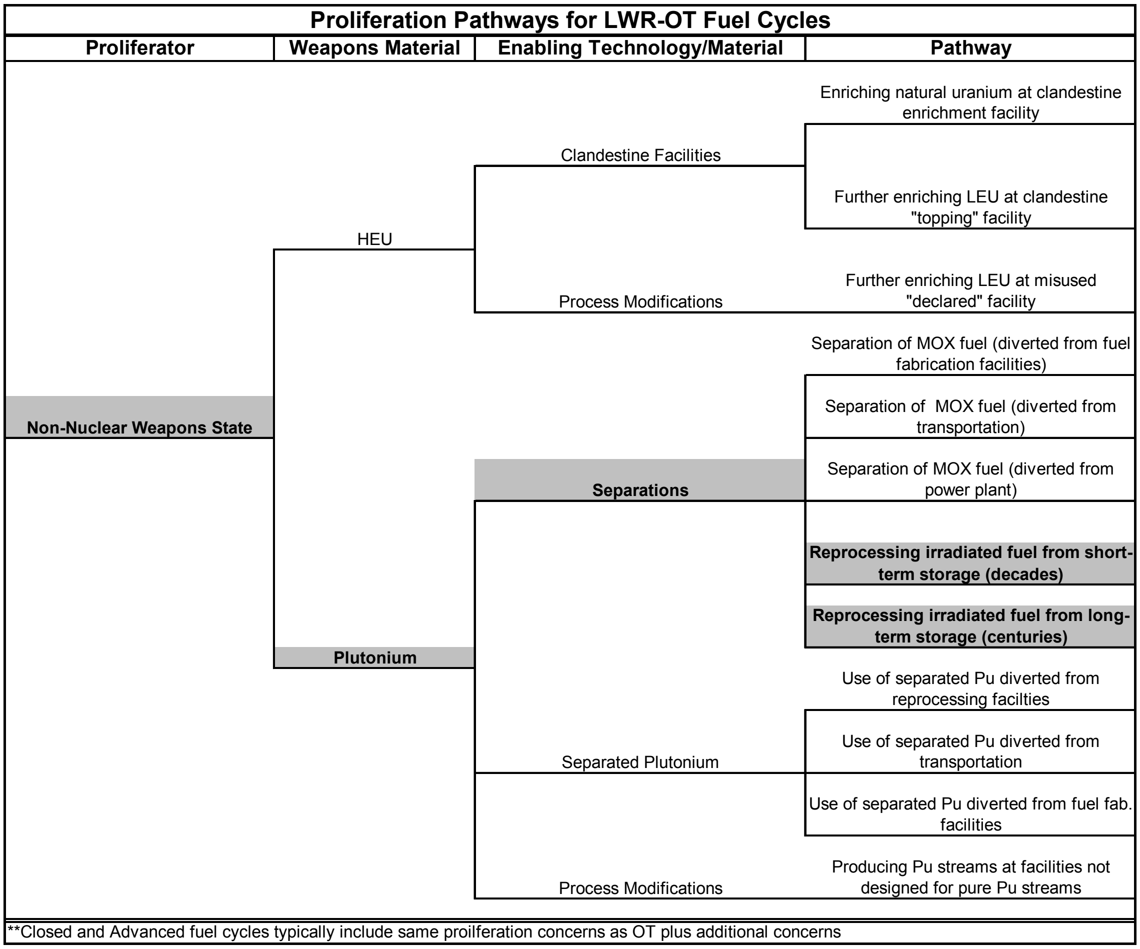

FIGURE 4-11: LWR-OT Pathway B (Diversion of spent fuel)

In this pathway, a Non-Nuclear Weapons State (proliferator) desires to acquire plutonium (weapons material) by reprocessing spent nuclear fuel that was diverted from intermediate storage facilities or retrieved from long-term disposal sites.

The plutonium isotopics of irradiated fuel at discharge, of various burn-up levels are listed in the table below (Pellaud, 2002). For comparison sake, the isotopic composition of weapons grade plutonium is also included. Though reactor-grade plutonium has a much lower fissile fraction than weapons-grade plutonium, thereby increasing the complexity of actually producing a weapon, multiple critical masses are still available in reactor-grade plutonium. Even at the burn-ups listed in the table below, the plutonium can still be used for weapons production.

TABLE 4-1: Plutonium Isotopic Compositions

Nominal Plutonium Isotopic Composition (w/o)			
Pu-Isotope	Weapons-Grade	LWR-OT Spent Fuel (35 GWD/T)	LWR-OT Spent Fuel (60 GWD/T)
Pu-238	0.01	1.2	3.5
Pu-239	93.6	58	44
Pu-240	5.9	23	27
Pu-241	1.4	14	15
Pu-242	0.1	4	11

In either case, once diverted, spent fuel assemblies would have to be sent to a reprocessing facility to separate the plutonium from the other fission products and actinides. The presence of these radionuclides generates a tremendous amount of radioactivity, radiotoxicity and decay heat[16].

Unloading these fuel elements from the reactor, storage, and reprocessing of spent nuclear fuel must be done remotely. This is because of the radiation generated. The gamma dose rate from a typical 15-year old spent fuel assembly is 2000 rad/hr at 1 meter from the assemblies' center (NAS, 1994). It is this gamma radiation that makes thick shielding and remote handling requirements both substantial and necessary. Host countries that possess the skills, knowledge and expertise[17] to handle these highly radioactive, radiotoxic and hot fuel assemblies are essentially one step (reprocessing) away from possessing directly weapons usable materials.

Another important aspect of irradiated nuclear fuel is its' long term characteristics. The graphs below show the decay behavior of spent PWR fuel with a burnup of 33,000 MWD/MT (Croff, 1982).

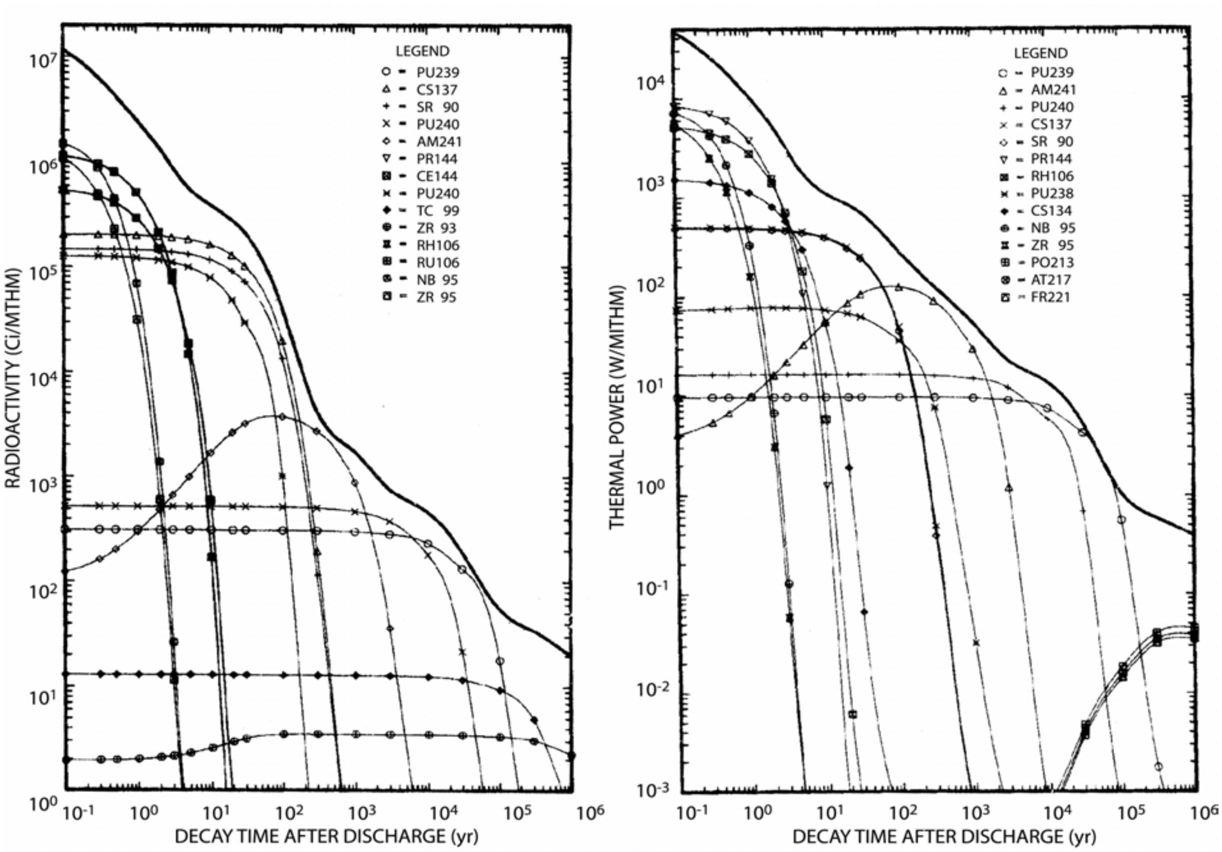

FIGURE 4-12: Decay Behavior of Spent PWR Fuel

16 See isotopic characteristics table in appendix

17 These are considered "dual-use" skills (skills that can be used for both civilian and military purposes).

Both the radioactivity and thermal power graphs above show that as spent fuel ages radiation levels drop. Gamma-emitting fission products, notably cesium-137 and strontium-90, that give spent fuel its initial proliferation resistance have far shorter half-lives than plutonium. The half-life of ^{137}Cs is approximately 30 years; therefore even applying the "rule of thumb" that after 10 half-lives the material will have decayed enough to be *safe,* puts cesium's protective effects at 300 years compared to the half-life of ^{239}Pu, which is 24,400 years.

After a few hundred years, the radioactivity and thermal power of spent fuel would have decayed enough to greatly ease handling requirements. For example, after 300 years the thermal power of PWR spent fuel will have decreased from 10^4 W/MTHM to roughly 100 W/MTHM. Looking at the radioactivity of spent PWR fuel at 300 years out shows that it has decreased by more than 3 orders of magnitude. In both cases the dominant nuclide is ^{241}Am.

More importantly, because of the cesium and strontium isotopes, most of the decrease in the radioactivity and decay heat of spent fuel assemblies (almost 2 orders of magnitude) will occur after only 30 years post-discharge[18]. Though this is still not within the range of being able to be handled directly, it does significantly reduce the remote handling requirements thereby increasing access potential.

Effectively *plutonium mines*-relatively low-cost sources of weapons-usable material for nuclear weapons- are created after a hundred years or so of post-irradiation storage. These mines could be used by a nation or sub-national group to extract plutonium from the spent fuel assemblies with minimal difficulty. In a paper on the proliferation risks of plutonium mines, Lyman and Feiveson (1998) make the following comments:

> The concern that repositories will become "plutonium mines" over time stems principally from two factors. First, the time and effort necessary to recover spent fuel from a repository, although significant, may compare favorably with other ways that a nation may acquire spent fuel, the "ore" from which plutonium can be extracted. Second, as a result of the relatively short (30-year) half-life of cesium-127, the spent fuel radiation barrier will decay to a low level within a few centuries after discharge from a reactor, so that older spent fuel can be handled and reprocessed with lower risk of injury.

Thus, the presence of extractable plutonium in retrievable mines creates another proliferation pathway within the LWR-OT fuel cycle. It should be noted that even if spent fuel assemblies are extractable, the relative plutonium isotope concentrations must also be taken into account. The higher the concentration of even number isotopes the more difficult it is to create an effective nuclear weapon[19]. This is because of the extremely high decay heat and neutron generation of these isotopes. The relatively short lifetime of Pu-238 means that the quality of the plutonium for weapons use improves with time. Lyman and Feiveson (1998) concluded, "the range of conditions under which repository mining will look attractive compared to other means of acquiring plutonium is extremely narrow." However, they also concluded that, "if spent fuel is

[18] From 30 to a hundred years post-irradiation, the radioactivity of spent LWR fuel drops by a factor of 7 or 8, while the decay heat only decreases by a factor of four.

[19] Refer to appendix for discussion of plutonium isotopics and weapons usability

not put into a repository, and is instead left in retrievable storage and eventually reprocessed, with the plutonium and other actinides in the spent fuel separated and transmuted, that course will itself generate significant risks of plutonium diversion or theft." It is therefore important to examine this pathway from the perspective of an aggressive nuclear growth scenario. A scenario, which would lead to, increased demands on waste facilities and could eventually lead to construction of short or long-term facilities in locations, which are less than ideal.

4.1.3 Assessments

Pathway A-1 Assessment

Table 4-2 below gives an assessment of the proliferation resistance of the LWR-OT nuclear fuel cycle to this particular pathway and highlights the vulnerabilities mentioned above. The assessment includes transport between and storage within each stage. A key is included in the tables and the coloring is simply to illustrate each barrier.

TABLE 4-2: LWR-OT Proliferation Assessment (Pathway A-1)

LWR Proliferation Pathway A-1: HEU (pre-enrichment natural U diversion)

Stages of fuel cycle	Material Barriers					Technical Barriers						Institutional		
	Isotopic	Radiological	Chemical	Mass and Bulk	Detectability	Facility Unattractiveness	Facility Access	Available Mass	Facility Diversion Detectability	Skills, Knowledge, Expertise	Time	Safeguards Effectiveness	Access Control, Security	Location
Beginning of the cycle														
Mining	H	I	I	H	L	I	I	I	L	I	H	I	L	L
Transport	H	I	I	H	L	I	I	I	L	I	VH	I	L	L
Milling	H	I	I	H	L	I	I	I	L	I	H	I	L	L
Transport	H	I	I	H	L	I	I	I	L	I	VH	I	L	L
Conversion	H	I	M	H	L	I	I	I	L	I	H	M	L	L
Storage	H	I	M	H	L	I	I	I	L	I	M	M	L	L
Transport	H	I	M	H	L	I	I	I	L	I	VH	M	L	L
Uranium Enrichment														
Storage														
Transport														
Uranium Oxide Fabrication Facilities														
Production of fuel (pellets,pebbles, etc.)														
Production of Fuel Assemblies, Cast														
Storage														
Fresh fuel transport to NPP														
Operation at NPP														
Storage of fresh fuel														
Loading of fresh fuel into the core														
Reactor irradiation														
Unloading of irradiated fuel from the core														
On-site pool storage of spent fuel														
On-site dry storage of spent fuel														
End of fuel cycle														
Off-site transport of irradiated spent fuel														
Temporary storage of irradiated fuel														
Processing of irradiated fuel for storage and disposition														
Storage of processed materials														
Long-term geolgical burial of irradiated fuel and actinide-containing waste														

KEY
I =Ineffective Barrier
L =Low Barrier
M =Medium Barrer
H =High Barrier
VH =Very High Barrier

The assessment methodology was used to determine the relevant proliferation pathways for the LWR-OT (the same is done for the remaining technologies) fuel cycle. The reader should be reminded that in assessing the nuclear fuel cycle's proliferation resistance, we choose to focus on the context of a Non-Nuclear Weapons State that has in its possession the skills, knowledge, expertise, technology and facilities to support its particular nuclear fuel cycle. The proliferation assessment tables highlight the results of the assessment for each particular pathway. The reader should also be reminded that the matrix assessment, though based on the attributes criteria discussed in chapter 3 and the appendix, required a certain level of subjectivity and is open for debate.

Pathway A-2 Assessment

The table below gives an assessment of the LWR-OT nuclear fuel cycle's resistance to using modified and/or undeclared enrichment facilities.

TABLE 4-3: LWR-OT Proliferation Assessment (Pathway A-2)

LWR Proliferation Pathway A-2: HEU (LEU diversion)														
Stages of fuel cycle	**Material Barriers**					**Technical Barriers**						**Institutional**		
	Isotopic	**Radiological**	**Chemical**	**Mass and Bulk**	**Detectability**	**Facility Unattractiveness**	**Facility Access**	**Available Mass**	**Facility Diversion Detectability**	**Skills, Knowledge, Expertise**	**Time**	**Safeguards Effectiveness**	**Access Control, Security**	**Location**
Beginning of the cycle														
Mining														
Transport														
Miling														
Transport														
Conversion														
Storage														
Transport														
Uranium Enrichment	M	I	M	M	L	I	i	I	H	I	H	H	L	L
Storage	M	I	M	M	L	I	I	I	H	I	M	H	L	L
Transport	M	I	M	M	L	I	I	I	H	I	VH	H	L	L
Uranium Oxide Fabrication Facilities	M	I	M	M	L	I	I	I	H	I	H	H	L	L
Production of fuel (pellets,pebbles, etc.)														
Production of Fuel Assemblies, Cast														
Storage														
Fresh fuel transport to NPP														
Operation at NPP														
Storage of fresh fuel														
Loading of fresh fuel into the core														
Reactor irradiation														
Unloading of irradiated fuel from the core														
On-site pool storage of spent fuel														
On-site dry storage of spent fuel														
End of fuel cycle														
Off-site transport of irradiated spent fuel														
Temporary storage of irradiated fuel														
Processing of irradiated fuel for storage and disposition														
Storage of processed materials														
Long-term geolgical burial of irradiated fuel and actinide-containing waste														

KEY
I =Ineffective Barrier
L =Low Barrier
M =Medium Barrer
H =High Barrier
VH =Very High Barrier

Pathway B Assessment

The table below gives the matrix assessment for LWR's proliferation resistance to acquisition of plutonium.

TABLE 4-4: LWR-OT Proliferation Assessment (Pathway B)

LWR Proliferation Pathway B: Plutonium (pre and post-disposal spent fuel diversion)														
Stages of fuel cycle	**Material Barriers**					**Technical Barriers**						**Institutional**		
	Isotopic	**Radiological**	**Chemical**	**Mass and Bulk**	**Detectability**	**Facility Unattractiveness**	**Facility Access**	**Available Mass**	**Facility Diversion Detectability**	**Skills, Knowledge, Expertise**	**Time**	**Safeguards Effectiveness**	**Access Control, Security**	**Location**
Beginning of the cycle														
Mining														
Transport														
Miling														
Transport														
Conversion														
Storage														
Transport														
Uranium Enrichment														
Storage														
Transport														
Uranium Oxide Fabrication Facilities														
Production of fuel (pellets,pebbles, etc.)														
Production of Fuel Assemblies, Cast														
Storage														
Fresh fuel transport to NPP														
Operation at NPP														
Storage of fresh fuel														
Loading of fresh fuel into the core														
Reactor irradiation	L	H	VH	H	VH	M	I	L	VH	I	H	H	M	L
Unloading of irradiated fuel from the core	L	H	VH	H	VH	M	I	L	VH	I	VH	H	M	L
On-site pool storage of spent fuel	L	H	VH	H	VH	I	I	L	VH	I	L	H	M	L
On-site dry storage of spent fuel	L	H	VH	H	VH	I	I	L	VH	I	L	H	M	L
End of fuel cycle														
Off-site transport of irradiated spent fuel	L	H	VH	H	VH	I	I	L	VH	I	VH	H	M	L
Temporary storage of irradiated fuel	L	H	VH	H	VH	I	I	L	VH	I	M	H	M	L
Processing of irradiated fuel for storage and disposition														
Storage of processed materials														
Long-term geolgical burial of irradiated fuel and actinide-containing waste	L	L	VH	H	VH	I	H	I	H	I	M	H	M	I

KEY
I =Ineffective Barrier
L =Low Barrier
M =Medium Barrer
H =High Barrier
VH =Very High Barrier

4.1.4 Recommendations

Based on the vulnerabilities mentioned above, the following sets of recommendations are proposed.

Recommendation 1: Enrichment facilities

Safeguarding against reconfiguration

The IAEA should increase its' safeguards system for enrichment facilities. This would include installation of additional containment and surveillance equipment. It would particularly include safeguards involvement in the design stage to ensure that the facilities are amenable to monitoring, containment, surveillance and protection.

Limiting technology spread

To assist in addressing the concern brought about by the spread of nuclear enrichment technologies in the mid-century scenario, proposals have been made for the internationalization of regional enrichment facilities. These facilities would ensure that enrichment processes are being operated to design and would limit the need for spreading these technologies to certain parts of the world. Additional facilities needed to support world uranium demand would also fall under international control and monitoring. Several international locations strategically placed throughout the world could service the fuel needs of many nuclear reactors within a given region. This would also provide increased accuracy of accounting for nuclear fuel material because the international community would monitor outgoing supply. International enrichment centers in the growth scenario would provide assurance of fresh fuel supply to countries honoring NPT commitments.

Recommendation 2: LEU safeguards

Containment and Surveillance

The IAEA should incorporate additional containment and surveillance techniques to points in the nuclear fuel cycle that have LEU inventories. Additional techniques include real-time video monitoring and additional un-scheduled inspections among others. These increased measures would reduce the potential for LEU to be diverted to "topping" facilities.

Recommendation 3: Additional IAEA protocols

Authority to seek undeclared facilities

Current IAEA protocol does not authorize inspectors to search for undeclared facilities. The IAEA should be allowed to search for undeclared nuclear facilities that could assist in nuclear weapons development.

Improved tracking of Materials

The IAEA should develop improved methods of tracking material flows in to and out of various countries. The emphasis should be on current special nuclear material and also on potential special nuclear material (e.g., natural uranium).

Recommendation 4: International spent fuel repository and resolution of long-term disposal issues

Re-examination of retrievability as a criteria

To address the issue of spent fuel being retrieved after several hundred years from "plutonium mines", geological repositories should be designed to emphasize irretrievability. This is counter to the trend in recent years of emphasizing retrievability as a virtue of geologic repository design or, indeed, even as a criterion for licensing. While this may act to enhance public acceptance, retrievability is of minimal benefit for long-term isolation (more than a couple hundred years) and detrimental to the nonproliferation regime. Geologic isolation in mined repositories is the preferred option for the disposal of spent fuel in the world (Lyman, 1998). The alternatives include deep bore-holes. This approach emphasized irretrievability and may give added confidence for long-term isolation.

International spent fuel storage

International spent fuel storage provides the opportunity for international monitoring prior to geologic disposal and for ensuring irretrievability subsequently. It should be pursued vigorously in the growth scenario.

The highest priority recommendations above for the LWR-OT based growth scenario are those concerning limitation of technology spread (especially enrichment), irretrievability, and international spent fuel storage.

4.2 Closed Fuel Cycles

This section will describe the baseline closed nuclear fuel cycle. The first part is an overview of closed nuclear fuel cycles with a closer look at LWRs using mixed oxide as fuel. This is followed by a discussion of the proliferation pathways of a MOX-PUREX fuel cycle and an assessment of these pathways. Finally, recommendations to address these pathways are explored.

The diagram below shows the steps involved in a closed nuclear fuel cycle.

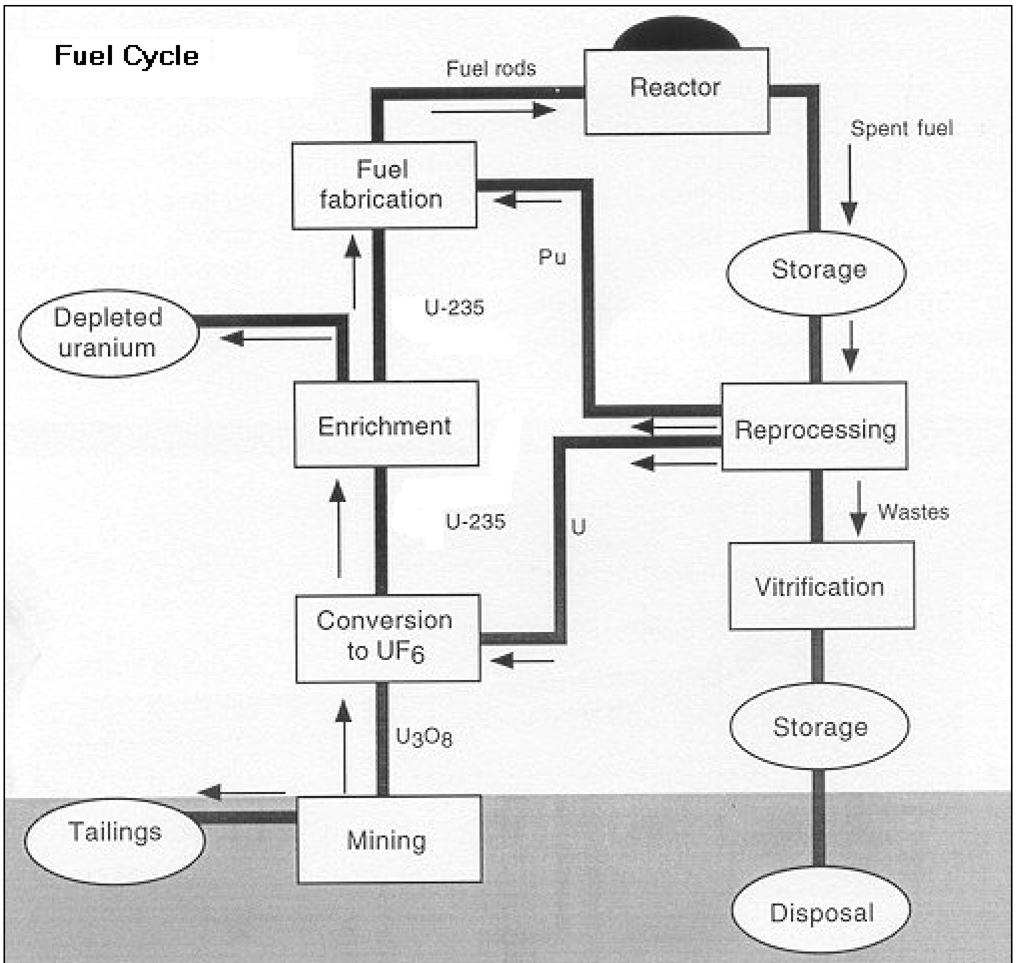

FIGURE 4-13: Typical Closed Fuel Cycle Diagram[20]

The previous section provided a detailed discussion of the once-through fuel cycle. For once-through cycles, the spent fuel is considered a waste product that would be disposed of without further alteration. Closing the nuclear fuel cycle is done by extracting useful isotopes from the spent fuel in a step known as reprocessing, then re-fabricating and re-circulating them in nuclear reactors.

[20] Diagram courtesy of The Australian Academy of Technological Sciences and Engineering, *Academy Symposium* November 1997

The main useful isotopes of irradiated fuel are those of uranium and plutonium. Spent fuel contains most of the original ^{238}U and about one third of the original ^{235}U. See figure below:

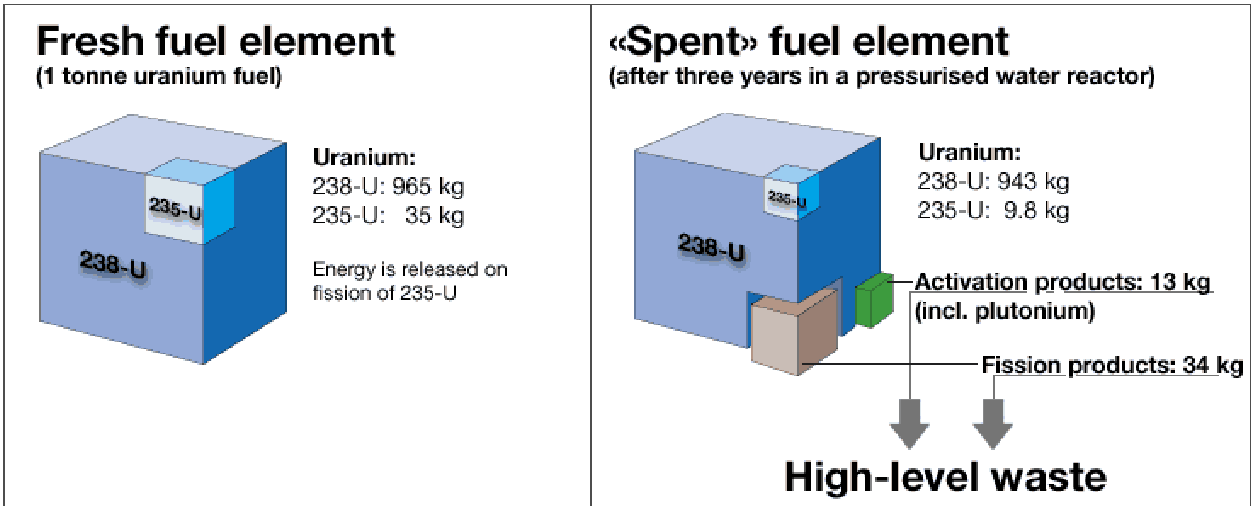

Figure 4-14: Isotopic Composition of Fresh and Spent Fuel[21]

Fission products and activation products (including plutonium) are generated as a result of uranium fissioning.

Following reactor irradiation the ^{238}U has activation products, fission products and plutonium. The plutonium content is typically about 6 to 10g/kg, which is roughly 1% of spent fuel and the fission product content is roughly 3%. Reprocessing recovers the uranium and plutonium isotopes, which may be used again as fuel for either thermal or fast reactors. If the recovered material is going to be used in thermal reactors, the reprocessed plutonium is sent directly to the fuel fabrication plant. The reprocessed uranium can be sent to the fuel fabrication plant, sent to the enrichment plant, or stored, depending on its intended use and needs.

4.2.1 MOX Reprocessing Experience

The key difference between open and closed fuel cycles is the reprocessing of spent nuclear fuel. Reprocessing is used to separate waste from the uranium and plutonium, which can then be recycled into new fuel. It effectively reduces the waste volume and reduces the need to mine new supplies of uranium. In 1952, the British were among the first to engage in reprocessing. They started with a plant at Windscale designated B-204. The plant initially reprocessed only metallic fuel, but later went on to handle oxide fuel as well. After satisfactory experience at Windscale, the United Kingdom decided to build a plant at Sellafield to reprocess irradiated fuel from thermal reactors. In general, reprocessing experience has been more abundant in Western Europe and Japan than in the United States. The US experience consists primarily of defense-related reprocessing operations. Of the commercial plants constructed in the United States, only the Nuclear Fuel Services (NFS) plant at West Valley, New York, ever operated. Operating from 1967 until 1972, the NFS plant reprocessed approximately 600 tons of irradiated fuel.

France and the United Kingdom are the most active Western European nations in the pursuit of reprocessing. The French have reprocessed fuel for defense programs, two breeder

[21] Diagram courtesy of Nagra http://www.nagra.ch/english/lager/bkreis.htm

reactors and for recycling of plutonium and uranium in LWR's. There are currently three reprocessing plants in France, UP-1 at Marcoule and UP-2 and UP-3 at La Hague. The La Hague facility had a design capacity of 400 ton/yr until 1981 when its' parent company, Cogema, increased the capacity to 800 ton/yr. The figure below is a simplified flow chart of the process used at La Hague's reprocessing facility.

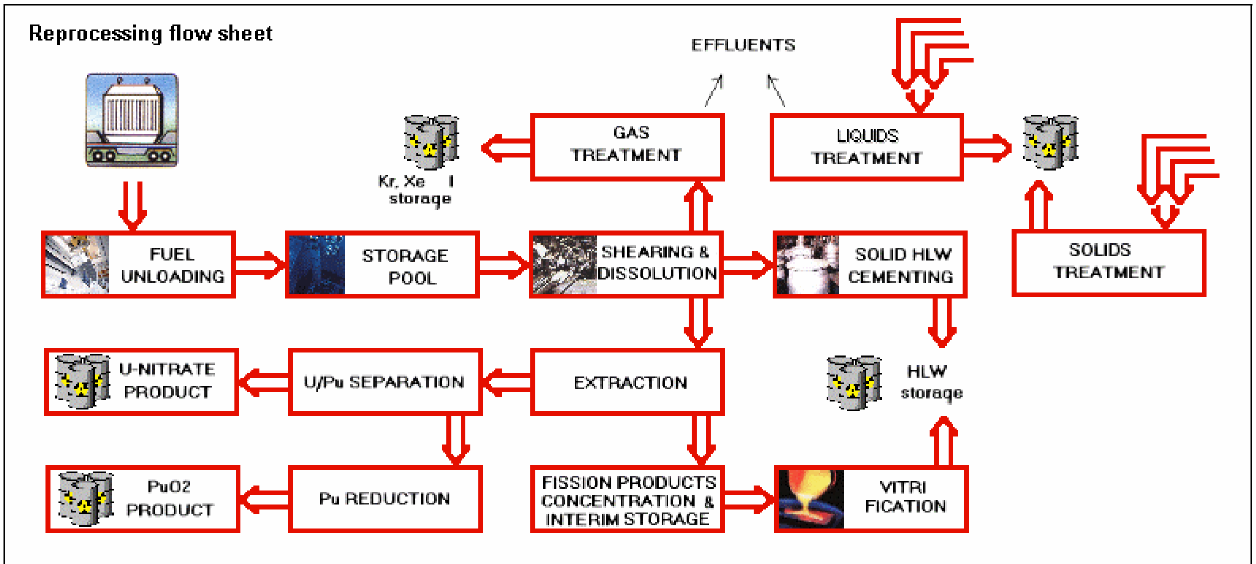

FIGURE 4-15: Simplified Flow Sheet of PUREX Reprocessing Facility[22]

As mentioned above, reprocessing is used to separate the waste from the uranium and plutonium in spent fuel. When the uranium has been separated it can be made into fresh fuel or mixed with the plutonium to produce a ceramic Mixed Oxide (MOX) fuel. The fuel can then be used in conventional reactors. The sections below will examine five similarities and differences (in front-end operations, reactor operations, reprocessing of MOX assemblies, transportation of special nuclear material, and current IAEA safeguards) that arise throughout the nuclear fuel cycle when MOX fuel is used in conventional reactors.

1) Front-end Operations

The mining, milling and conversion operations for closed fuel cycles are identical to those used in open fuel cycles. In a typical MOX fuel assembly, there is approximately 4% plutonium oxide and the remainder is uranium oxide. The uranium oxide may be either natural, depleted or enriched depending on the application. The plutonium oxide typically comes from reprocessed materials. The principal difference in the fuel fabrication process used for MOX fabrication and that used for fabrication of uranium oxide fuels is the radiation environment of these facilities.

2) Reactor Operations

Replacing uranium oxide, normally used to fuel the LWR core, by MOX fuel changes certain characteristics of the core because of the physical, chemical, and neutronic differences in

[22] Diagram courtesy of http://www.ricin.com/nuke/bg/lahague.html

MOX fuel relative to UO_2. It is the neutronic differences that present the greatest concern, because it determines a materials usability for weapons production.

The plutonium isotopes have relative concentrations that depend on the origin of the plutonium, the storage time that the plutonium experiences and the number of times the plutonium has been recycled. Examples of the effect of these conditions are in the table below (table 4-5), which shows the relative concentrations of plutonium at various nuclear reactors (Pellaud, 2002).

TABLE 4-5: Plutonium Concentrations

Isotopic contents in % of total Pu	**Pu-238**	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-242**
Burnup - irradiated LWR uranium oxide:					
20 MWd/kg heavy metals (Siemens)	0.7	70	18	10	1.6
33 MWd/ kg heavy metals (Siemens)	1.2	58	23	14	4
60 MWd/ kg heavy metals (Siemens)	3.5	44	27	15	11
Burnup - irradiated LWR mixed oxide:					
33 MWd/ kg heavy metals (Mark)	1.9	40	32	18	8

The fissile fraction—concentration of Pu-239 and Pu-241, which are the two useful fissile isotopes—of the irradiated LWR mixed oxide fuel above, is 58wt%. This characteristic is important, as it is one determinant of the degree of difficulty a proliferator would face in making plutonium weapons. Higher fissile fractions are more suitable for weapons production because of the reduction in even numbered isotopes (less neutron background and decay heat).

A daughter of ^{241}Pu, ^{241}Am is, through its own daughters, a source of many gamma rays and also a neutron absorber. Plutonium coming from LWR fuel irradiated to burnups of approximately 35,000 MWD/MT must be utilized no later than 3 years after discharge. Otherwise, because of the ^{241}Am buildup, purification is necessary before it can be used in MOX fuel for LWRs. LWRs irradiated with MOX fuel assemblies have operated with burnup levels that range from 30-50,000 MWD/MT depending upon irradiation cycles.

3) Reprocessing of MOX assemblies

Typical reprocessing operations consist of several major steps: mechanically chopping the spent fuel assembly into small pieces, dissolving the parts from step 1 into nitric acid, using solvent extraction to separate into streams containing the products of interest and the wastes, and handling the waste (mostly high level wastes) appropriately (see figure 4-15). The method is referred to as the "chop and leach" system. A particular plutonium-uranium recovery extraction process known as PUREX is used in almost all reprocessing plants in the world. PUREX uses a solvent TBP (tri-n-butyl phosphate) and liquid-liquid extraction principles, combined with oxidation-reduction chemical reactions to separate the spent fuel into uranium-nitrate and plutonium oxide products.

4) Transportation of Special Nuclear Material

After the spent fuel assemblies have been reprocessed, uranium and plutonium products are typically stored and then transported to fuel fabrication facilities. The transported plutonium is in the form of $Pu(NO_3)_4$ and this compound is first converted into PuO_2 powder then mechanically blended with ceramic-grade UO_2 to produce mixed oxide that is later fabricated into pellets. These pellets are loaded into assemblies, identical to UO_2 fuel assemblies, for use in LWRs.

5) Current IAEA safeguards of closed fuel cycle

The specific Non-Proliferation Treat (NPT) safeguards objective of the IAEA is set forth by Information Circular 153 (INFCIRC/153) as being "the *timely detection* of diversion of significant quantities of nuclear material from nuclear activities…and the deterrence of such diversion by risk of early detection." Information Circular 66 (INRCIRC/66) adds that safeguards are to be employed "in a manner designed to avoid hampering a state's economic and technological development…and safe conduct of nuclear activities."

The IAEA safeguards regime for closed fuel cycles are identical to those associated with open fuel cycles with the addition of safeguards for MOX fabrication facilities, reprocessing facilities, and transportation of plutonium[23]. Outlined below are the methods, specific to closed fuel cycles, used by the IAEA to adhere to guidelines set forth by INFCIRC/153 and INFCIRC/66.

MOX fabrication facilities

In fabrication facilities, special nuclear materials can be in the form of powders, solutions, fuel pellets, and finished fuel assemblies. For this reason, safeguards for fuel processing facilities are more complex than those for reactors where special nuclear material is only in the form of fuel assemblies. The inspection program includes a combination of non-destructive assay (NDA) capabilities and use of an IAEA Safeguards Analytical Laboratory[24]. Isotopic ratios of plutonium in MOX fuels can be measured using high-resolution gamma-ray spectrometry. This method, combined with passive neutron-coincidence counting and calorimetry provide very good NDA results.

Reprocessing facilities

Adequate IAEA safeguarding of reprocessing facilities depends on several things (Kneif, 1992, p. 624). Sampling of local inputs and outputs and of all streams that leave the plant must be reliable, and the inspectors must take frequent inventories with controlled clean-outs. Calibration of all accountancy vessels, located between the dissolution and extraction steps, must be extremely accurate. There must exist rapid verification of contents of the product-output and waste streams (See Figure 4-15). This is done using appropriate NDA methods. Finally, containment must be maintained. This is done by using easily checked seals or by continuous surveillance of the output.

Transportation

Currently, the IAEA agreements note that a State must have a system of accounting for and controlling of all nuclear materials subject to safeguards under the Agreement. The system has to be based on a structure of *material balance areas,* and be able to determine the quantities of nuclear material received or shipped. It must also have procedures for identifying, reviewing and evaluating differences in shipper/receiver measurements (INFCIRC/153, paragraph 32).

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[23] For more detail on IAEA procedures for nuclear fuel cycles see previous section on open fuel cycle

[24] Nondestructive assay (NDA) is based on direct physical measurements of unique signatures of fissionable materials, i.e., distinctive characteristics such as gamma-ray energy or spontaneous-fission half-life.

4.2.2 Proliferation Pathways

As of 1996, commercial power reactors had produced over 1000 MT of plutonium and these stocks continued to grow at a rate of about 70 MT per year (Albright, et. al., 1996). While over 80% is contained in stored spent fuel a growing amount is being separated at reprocessing plants in France, the UK, Russia and India. By the end of 1995 there were some 140 MT of separated civilian plutonium stored in Europe and Asia. That number is now, estimated by some, at over 200MT of separated civilian plutonium around the world. This equates to well over 20,000 significant quantities[25]. These inventories are "directly" weapons usable and only small quantities would need to be diverted if a state or sub-national group is interested in producing only a few nuclear weapons.

The pathways of interest in MOX/PUREX fuel cycles involve diversion of separated plutonium or MOX fuel assemblies[26]. Separated plutonium pathways are explored more in the sections below. It should be noted that the MOX/PUREX fuel cycle would additionally have those proliferation pathways associated with the LWR-OT fuel cycle.

[25] Based on UN definition (1 significant quantity is 8kg Pu-239)

[26] Use of diverted MOX fuel assemblies is not discussed because it is similar to use of diverted spent fuel assemblies, with the additional requirement of needing a separations facility.

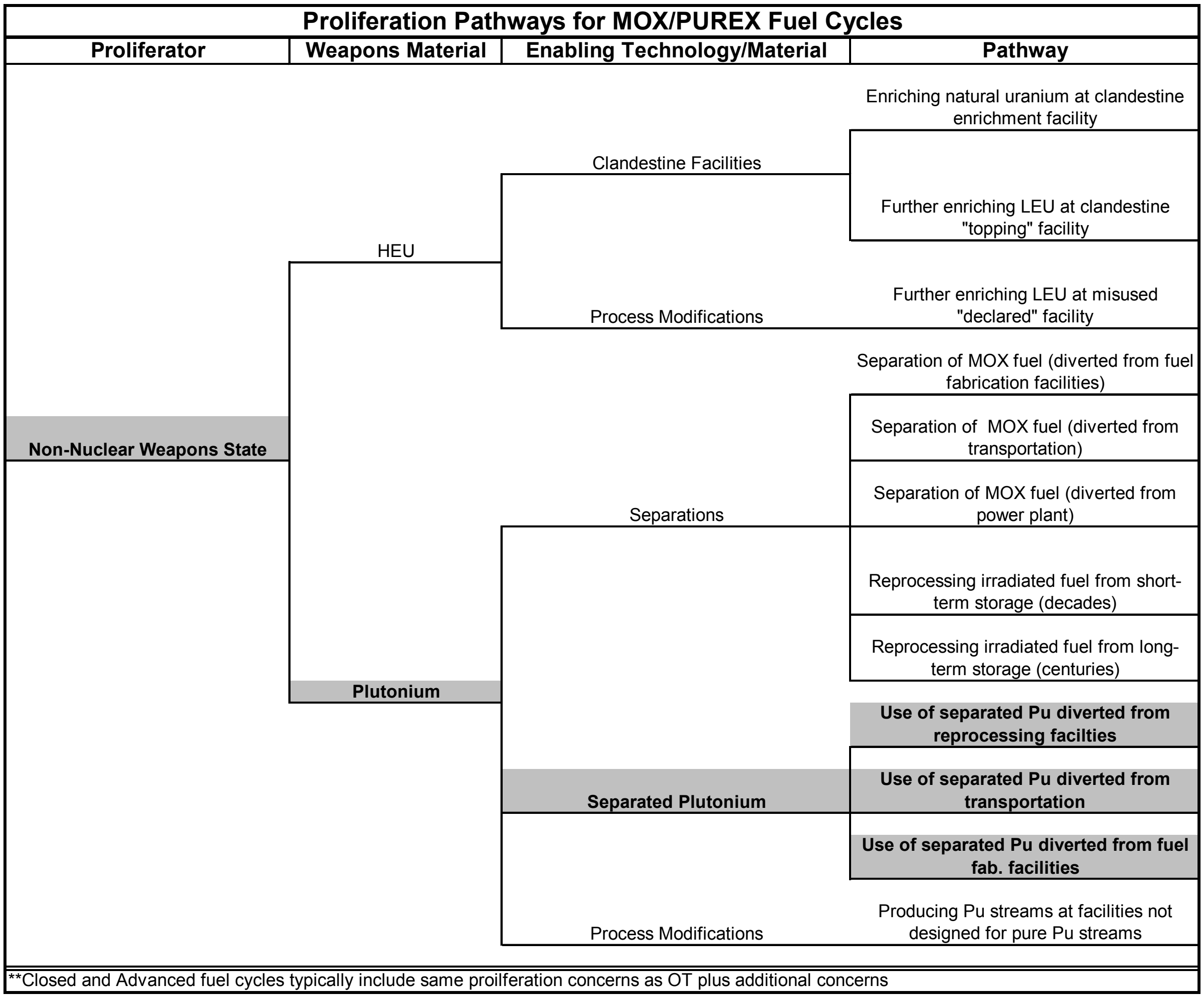

FIGURE 4-17: MOX Pathway A (Diversion of Separated Plutonium)

In this pathway, a Non-Nuclear Weapons State (proliferator) desires to acquire plutonium (weapons material) by diversion of separated plutonium from storage (at reprocessing or fuel fabrication facilities) or from off site transportation

Pathway A: Separated plutonium

A-1: Diversion from reprocessing facilities

The PUREX process became the most widespread of a multitude of fuel regeneration methods for extraction of weapons plutonium. Because it was developed for weapons, it leads to a very high purity product. Although commercial reprocessing facilities are expensive and require enormous buildings and specific equipment, the process has been around for some time, the details of it are available in the open literature, and a batch scale operation can be fairly modest in scale.

This issue, of separated plutonium in reprocessing facilities, is further complicated by the lack of IAEA experience with and high measurement uncertainty in reprocessing facilities. The IAEA goal is to detect the diversion of a defined quantity of nuclear material within a defined timeframe. These goals are specified based on the type of material. It is desired to be able to detect one significant quantity (8kg) of plutonium within a one-month timeframe. The one-month comes from what IAEA considers the shortest conversion time possible to build a nuclear bomb, starting with plutonium oxide, nitrate or even metallic plutonium. Large throughputs of plutonium and high measurement uncertainties make it difficult for reprocessing facilities to meet the IAEA safeguards goals. See table below for annual plutonium-throughput uncertainties in reprocessing plants:

TABLE 4-6: Plutonium Uncertainties in Various Reprocessing Plants[27]

Annual Plutonium-Throughput Uncertainties in Reprocessing Plants						
Nominal measurement uncertainty	**Small reprocessing plant (30 t HM/yr)**		**Medium reprocessing plant (100 t HM/yr)**		**Large reprocessing plant (800 t HM/yr)**	
%	Monthly (kg)	Yearly (kg)	Monthly (kg)	Yearly (kg)	Monthly (kg)	Yearly (kg)
0.2	0.04	0.48	0.13	1.6	1.1	12.8
1.0	0.2	2.4	0.67	8	5.3	**64**

Note:
*Uncertainties given in kilograms of plutonium, assuming 0.8 percent plutonium by weight in spent fuel (nominal average of commercial spent fuel from a mixture of 80% light-water reators and 20% heavy-water reactors). Plutonium concentrations can range from under 0.1% in very low burnup fuel to about 1% in high burnup spent fuel from commercial LWRs.

In the table, the 64kg lost yearly (in large reprocessing plants with 1.0% nominal uncertainty) equals 8 significant quantities per year. If the uncertainties in the table represent one standard deviation uncertainties in MUF determinations, then the amount of diverted plutonium that could be detected with a 95% detection probability and a 5% false alarm rate—the nominal safeguards goal—is 3.3 times the amount given in the table. Therefore, in a large reprocessing plant, more than 2 significant quantities per month and at least 25 significant quantities per year would be undetected. Diversions of the amounts shown could be detected, but only with about 26% probability if the 5% false alarm probability is to be maintained (Hakkila, et. al., 1980, p. 8).

A-2: Diversion in transport

The IAEA has current rules of engagement (either explicit or implicit) for transportation of separated plutonium that do not meet the challenge of a small number of civilians seeking to peacefully make a point. This is seen clearly in a recent Greenpeace protest[28]. In February of this year, twenty-five greenpeace activities blocked a truck carrying 150kg of weapons-usable plutonium. They chained themselves to the truck publicly to denounce the circulation of plutonium in France. The truck, carrying separated plutonium, was coming from the La Hague reprocessing plant in northern France, and was headed to the Marcoule nuclear facility in southern France. This suggests that the risk of having well-trained terrorists successfully hijack a shipment of weapons-usable fissile material is not negligible.

4.2.3 Assessments

Table 4-7 below gives an assessment of the proliferation resistance of the MOX/PUREX nuclear fuel cycle to this particular pathway and highlights the vulnerabilities mentioned above.

[27] Reproduced from the US Office of Technology Assessment Annual Publication (1995)
[28] Greenpeace, *Greenpeace blocks top secret transport of plutonium in France, revealing global proliferation threat is not in Iraq* http://www.greenpeace.org/press/release?item_id=144770&campaign_id=4023

TABLE 4-7: PUREX/MOX Proliferation Assessment

PUREX/MOX Proliferation Pathway A: Separated plutonium

Stages of fuel cycle	Material Barriers					Technical Barriers						Institutional		
	Isotopic	Radiological	Chemical	Mass and Bulk	Detectability	Facility Unattractiveness	Facility Access	Available Mass	Facility Diversion Detectability	Skills, Knowledge, Expertise	Time	Safeguards Effectiveness	Access Control, Security	Location
Beginning of the cycle														
Mining														
Transport														
Miling														
Transport														
Conversion														
Storage														
Transport														
Uranium Enrichment														
Storage														
Transport														
Uranium Oxide Fabrication Facilities														
Production of Fuel Assemblies, Cast														
Storage														
Fresh fuel transport to NPP														
Operation at NPP														
Storage of fresh fuel														
Loading of fresh fuel into the core														
Reactor irradiation														
Unloading of irradiated fuel from the core														
On-site pool storage of spent fuel														
On-site dry storage of spent fuel														
Closed cycles														
Dissassembly of fuel assembly	H	H	H	M	H	I	I	I	M	I	VH	M	H	I
Separation of fissile materials	I	H	I	M	H	I	I	I	M	I	VH	M	H	I
Storage of highly-concentrated fissile material	I	M	I	M	H	I	I	I	M	I	L	M	H	I
Collection, processing and storage of actinide-containing waste														
Transport of separated plutonium	I	M	I	M	H	I	I	I	VH	I	VH	I	L	I
Transport of actinide-containing waste for burial														
Plutonium Oxide Fabrication	I	M	L	M	H	I	L	I	L	I	H	L	H	I
Production of MOX	I	M	M	H	H	I	L	L	L	I	H	L	H	I
Transport of MOX to NPP	I	M	M	H	H	I	I	L	VH	I	VH	I	L	I
End of fuel cycle (includes once-through)														
Off-site transport of irradiated spent fuel														
Temporary storage of irradiated fuel														
Processing of irradiated fuel for storage and disposition														
Storage of processed materials														
Long-term geolgical burial of irradiated fuel and actinide-containing waste														

KEY

I =Ineffective Barrier
L =Low Barrier
M =Medium Barrer
H =High Barrier
VH =Very High Barrier

4.2.4 Recommendations

Recommendation 1: PUREX reprocessing

Because the PUREX process was created specifically for production of a pure plutonium product, there should be no further geographic spread of PUREX reprocessing technology within the mid-century growth scenario. This recommendation does not exclude research on alternative reprocessing technologies, such as UREX, pyroprocessing. The US should work with the international community to promulgate this policy and to enforce it through export controls, diplomatic and other means.

Recommendation 2: Co-location

Separations and MOX fuel fabrication facilities should be co-located, thereby eliminating the need for transportation of separated plutonium.

Recommendation 3: Minimal working plutonium inventory

The US should work with nations engaged in the MOX fuel cycle to reduce separated plutonium inventories to the minimal working level needed for process operation. The current distribution of 345 GWe LWR-OT and 9GWe MOX worldwide would have a plutonium inventory of 6.3 MT[29]. That is, at any given point in time, no more than 6.3 MT of separated plutonium would need to be in storage. This is less than 5% of the current 200 MT separated plutonium inventory. For these calculations, the mass flow of separated plutonium needed to keep the system in equilibrium is 12.6 metric tonnes per year. The practical equilibrium minimal working inventory needs detailed analysis using process-specific information that may not be publicly available, and may be substantially larger than this amount; nevertheless, there may be an opportunity to substantially reduce stocks of separated plutonium without compromising fuel cycle operation. A first step towards the minimal working inventory would be to prevent further accumulation of separated plutonium, a goal that should be achievable in the near term (with the possible exception of certain British fuels).

Recommendations 1 and 3 deserve immediate attention for US engagement of the international nuclear community.

[29] Calculation done by Etienne Parent for the MIT Nuclear Energy Study. It assumes 1) that the time from the point where plutonium is separated in the PUREX process to the point where it is mixed back with uranium in the MOX fabrication plant is 6 months; 2) that the average plutonium content of the UOX fuel in the reactor is taken as 0.9% (the actual plutonium content goes from 0% to 1.33% during irradiation); and 3) that the average plutonium content of MOX fuel in the reactor is 6% (the plutonium content goes from 7% to 4.9% during irradiation).

4.3 High Temperature Gas Reactors

High temperature gas reactors (HTGR) have been developed, and even deployed, since the 1960's. Coated fuel particles and helium coolants are the common aspects of gas reactors being designed today. The fuel used in gas reactors has enrichment levels between 8 and 20% U-235, and the reactor will typically operate to burn-ups of about 100,000 MWD/MT.

There are essentially two fundamental HTGR design options under active consideration today. One is a small "pebble bed" core and the other is a large, annular prismatic carbon block core. Various countries are investing in active HTGR programs. For example, China (10MW_{th} pebble bed), South Africa (250 MW_{th} pebble bed) and Japan (40 MW_{th} prismatic) to name a few. Two gas reactors have operated in the United States; Peach Bottom-which was a small, experimental 40 MW_e HTGR and Fort St. Vrain-which was a 365 MW_e plant.

4.3.1 Modular Pebble Bed Reactor

MIT is currently doing research on a small modular pebble bed reactor (MPBR), which will be the HTGR model for this thesis, although our nonproliferation considerations are not sensitive to the specific choice. The diagram below is a schematic of the reactor. The figure below is an illustration of the MPBR design.

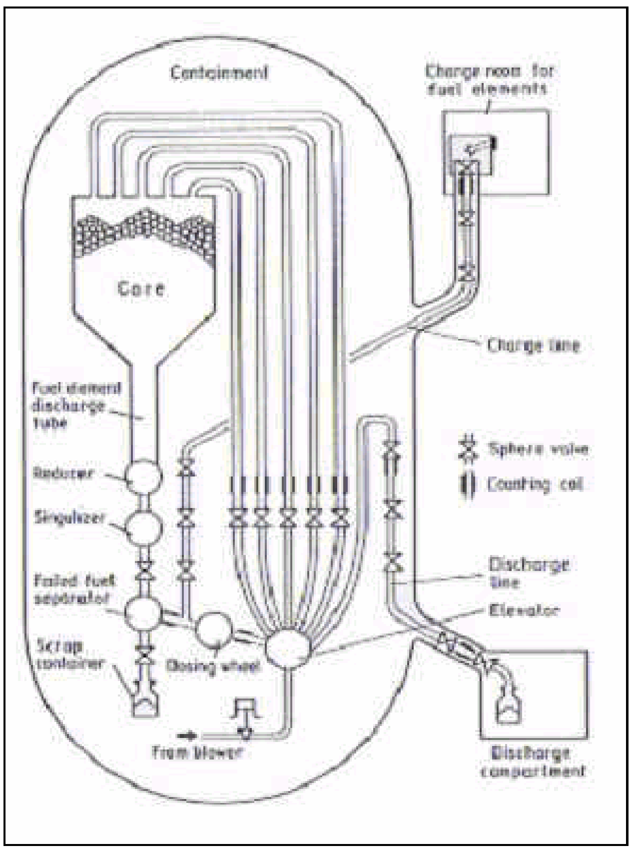

FIGURE 4-18: The Modular Pebble Bed Reactor[30]

[30] Diagram courtesy of MIT Department of Nuclear Engineering

The MPBR design has a thermal power of 250 MW. Its' core height and diameter are 10 and 3.5 meters respectively. There will be some 360,000 pebbles irradiated in the reactor core to burn-ups of up to 90,000 MWD/MT. Roughly 3,000 pebbles will be handled by the fuel handling system each day, with approximately one discharged every 30 seconds and about 350 pebbles discarded daily The average pebble will cycle through the core 15 times. Each pebble is 60mm in diameter with 11,000 microspheres (1mm diameter) inside a graphite matrix. There is 7-8 grams of uranium, enriched to 8-11% U-235, in each pebble. The uranium is in a UO_2 kernel inside the microsphere and covered by silicon carbide, pyrocarbon, and a porous buffer. The figures below show the TRISO[31] coated fuel pebble.

FIGURE 4-19: Fuel Pebble[32]

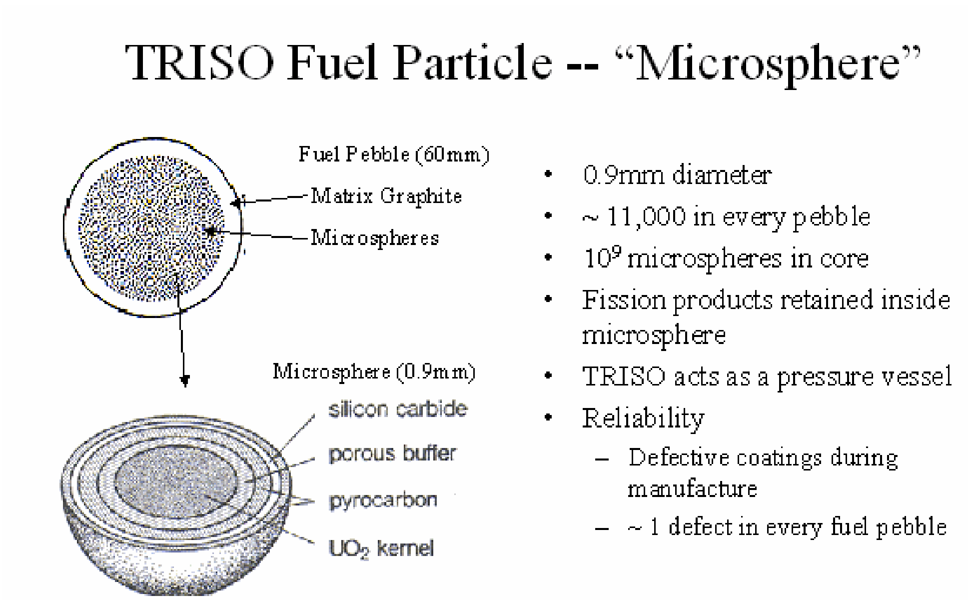

FIGURE 4-20: TRISO Fuel Particle[33]

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[31] The TRISO fuel particles contain a small kernel of nuclear fuel encapsulated by alternating layers of C and a barrier layer of SiC.

[32] Photo courtesy of ESKOM http://www.eskom.co.za/education/randdcenter/pebblebedmodularreactor_content.html

[33] Taken from A. Kadak "MIT/INEEL Modular Pebble Bed Reactor" presentation at Massachusetts Institute of Technology, Cambridge MA, March 22, 2000.

4.3.2 Proliferation Pathways

From a proliferation pathways point of view, the Modular Pebble Bed Reactor is qualitatively similar to the Light Water Reactor operated in Once-Through mode. Both nuclear fuel cycle systems follow identical processes from mining to waste disposal. The differences are found in enrichment levels, fuel forms, reactor operations (e.g., burn-up levels) and spent fuel isotopics.

As mentioned earlier, the MPBR will require uranium enriched to 8-11% U-235. This is more than twice the enrichment used in the LWR-OT. The higher enrichment levels present proliferation disadvantages because non-commercial enrichment technologies, that may be difficult to detect and monitor, can be used.

The MPBR fuel form (pebbles) offers some proliferation advantages over typical LWR-OT fuel. Each MPBR pebble only contains a tiny fraction of the total reactor fuel. Lebenhaft (2000, pp. 138, 139) did an analysis of a reference pebble bed core and found that a diversion of 258,000 first pass (on average it takes each pebble 73 days to pass through the core) pebbles is needed to obtain 6kg of Pu-239. Also, according to the same analysis, 157,000 spent fuel (discharged after being irradiated to 80 MWD/kgU) pebbles would be needed to obtain that same 6kg of Pu-239. Even if a proliferator were able to divert sufficient pebble quantities, removal of the graphite coating would leave an easily detectable signature.

The MPBR differs most from typical LWR's in enrichment required for its fuel. With enrichment levels reaching 8-11%, an even greater amount of work has been done to reach HEU than from LWR-OT's 4.5% enrichment. This difference is worth examining closer. The figure below sketches the principal proliferation pathway for MPBRs.

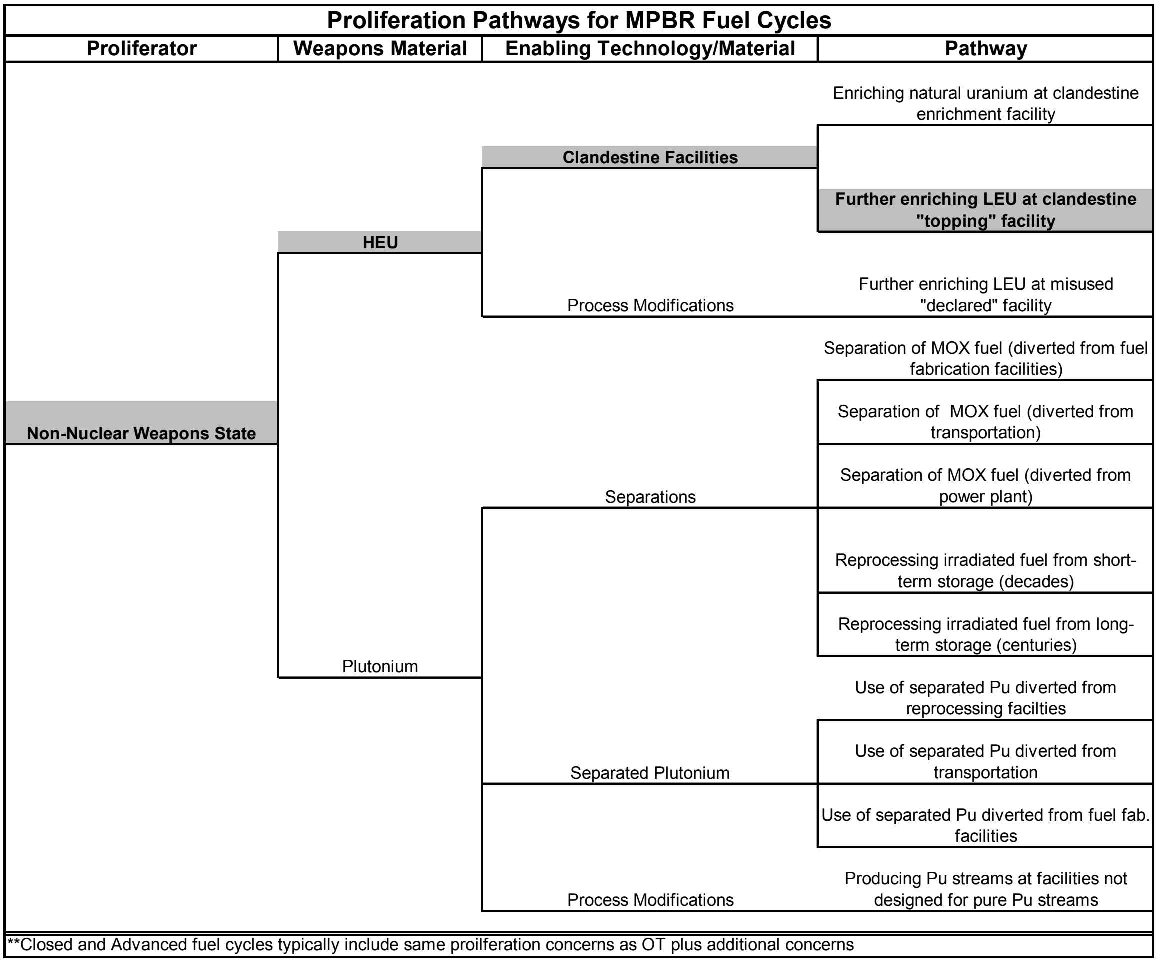

FIGURE 4-21: MPBR Pathway A: (HEU: Diversion of LEU)

In this pathway, a Non-Nuclear Weapons State (proliferator) desires to acquire HEU (weapons material) by enriching LEU at clandestine "topping" facilities. Qualitatively, this fuel cycle is the same as LWR-OT only due to the increased enrichment requirements it is somewhat more vulnerable to non-commercial enrichment technologies.

Pathway A: HEU

The MPBR nuclear fuel cycle does not present a qualitatively new proliferation pathway but, because of higher enrichment levels, it does increase the vulnerability of a previously discussed pathway. A potential proliferator could divert the 8-11% enriched uranium to topping plants for enrichment to HEU levels. These topping facilities could be developed from non-commercial enrichment technologies. For example, laser enrichment of uranium vapor has been under development for decades in many countries, with major unresolved issues remaining with respect to the continuous high-throughput operation needed for economic competitiveness; however, batch operation could suffice for a small number of weapons, and furthermore much of the needed technology (such as appropriate lasers) has developed dramatically since the early developments. Non-commercial enrichment technologies offer a unique challenge in that import/export controls of the component dual use items will often be very difficult. Further, civilian applications such as medical isotope separation can provide cover for a proliferator's intentions.

4.3.3 Assessments

Table 4-8 below gives an assessment of the proliferation resistance of the MPBR nuclear fuel cycle to this particular pathway and highlights the vulnerabilities mentioned above.

TABLE 4-8: MPBR Proliferation Assessment

MPBR Proliferation Pathway A: HEU (LEU diversion)														
Stages of fuel cycle	**Material Barriers**					**Technical Barriers**						**Institutional**		
	Isotopic	**Radiological**	**Chemical**	**Mass and Bulk**	**Detectability**	**Facility Unattractiveness**	**Facility Access**	**Available Mass**	**Facility Diversion Detectability**	**Skills, Knowledge, Expertise**	**Time**	**Safeguards Effectiveness**	**Access Control, Security**	**Location**
Beginning of the cycle														
Mining														
Transport														
Miling														
Transport														
Conversion														
Storage														
Transport														
Uranium Enrichment	L	I	M	M	L	I	I	I	VH	I	H	M	L	L
Storage	L	I	M	M	L	I	I	I	VH	I	M	M	L	L
Transport	L	I	M	M	L	I	I	I	H	I	VH	M	L	L
Uranium Oxide Fabrication Facility	L	I	M	M	L	I	I	I	H	I	H	M	L	L
Production of fuel (pellets,pebbles, etc.)														
Production of Fuel Assemblies, Cast														
Storage														
Fresh fuel transport to NPP														
Operation at NPP														
Storage of fresh fuel														
Loading of fresh fuel into the core														
Reactor irradiation														
Unloading of irradiated fuel from the core														
On-site pool storage of spent fuel														
On-site dry storage of spent fuel														
End of fuel cycle (includes once-through)														
Off-site transport of irradiated spent fuel														
Temporary storage of irradiated fuel														
Processing of irradiated fuel for storage and disposition														
Storage of processed materials														
Long-term geolgical burial of irradiated fuel and actinide-containing waste														

KEY
I =Ineffective Barrier
L =Low Barrier
M =Medium Barrer
H =High Barrier
VH =Very High Barrier

4.3.4 Recommendations

Recommendation 1: Enrichment technologies

The Nuclear Supplier Group, the IAEA, and other organizations charged with impeding nuclear proliferation should re-examine the control regime for a broader set of technologies applicable to non-commercial uranium enrichment approaches (i.e., beyond the centrifuge supply chain focus that is the principal concern today) that could be very effective and inconspicuous when starting with LEU to produce HEU.

4.4 Lifetime Core Reactors

There are many demands for small energy sources, especially in developing nations with relatively little energy infrastructure. These demands have led to research and design into reactors that are safe, simple, small, portable, have long-life and are proliferation-resistant. A key is that no fueling or fuels infrastructure is needed in the country of use. The Encapsulated Nuclear Heat Source, invented by David Wade, director of Argonne's Reactor Analysis Division, and Ehud Greenspan of the University of California at Berkeley, is one of these new reactor designed and is the basis for analysis below.

4.4.1 Encapsulated Nuclear Heat Source

The Encapsulated Nuclear Heat Source (ENHS) is a reactor concept that was selected in 1999 by the Department of Energy to be studied as one of the Generation IV reactors. It is a concept based on the idea of encapsulating the reactor core inside its own vessel as a module, with no external piping connections. The ENHS features modularity, it is to be factory fuelled, inserted into an in-place power reactor, run for 15 effective full power years without refueling, and replaced by another module (Greenspan, et. al., 2000). In the ENHS, the fission-generated heat is transferred from the primary coolant to the secondary coolant through the reactor vessel wall. This reactor type has never been built and is only a design concept.

There are many possible embodiments of the reactor concept. The figure below shows a schematic of one embodiment, having a single ENHS module.

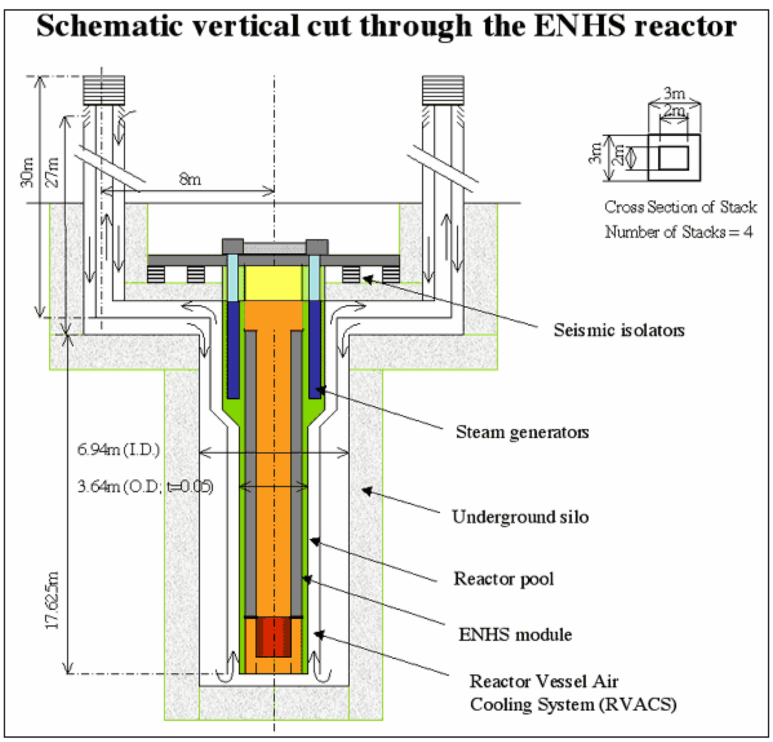

FIGURE 4-22: Single ENHS Module[34]

[34] Cited in D. Pescovitz, *Novel Nuclear Reactor (Batteries Included)* UC Berkeley Lab Notes Volume 2, Issue 8, October 2002.

The reactor consists of ten modules: one ENHS, three steam generators, three re-heaters and three secondary coolant loops. The concept features 100% natural circulation. Two structural walls and a confinement wall in between make up the three walls to the ENHS reactor vessel.

Figure 4-23 shows an alternate ENHS concept being considered. It uses a cover-gas lift-pump that circulates the cover gas from the plenum above the coolant level in the ENHS and injects it into the coolant in the riser through nozzles located at certain levels above the core. The cover-gas bubbles reduce the effective density of the coolant in the riser, thus increasing the head for coolant circulation.

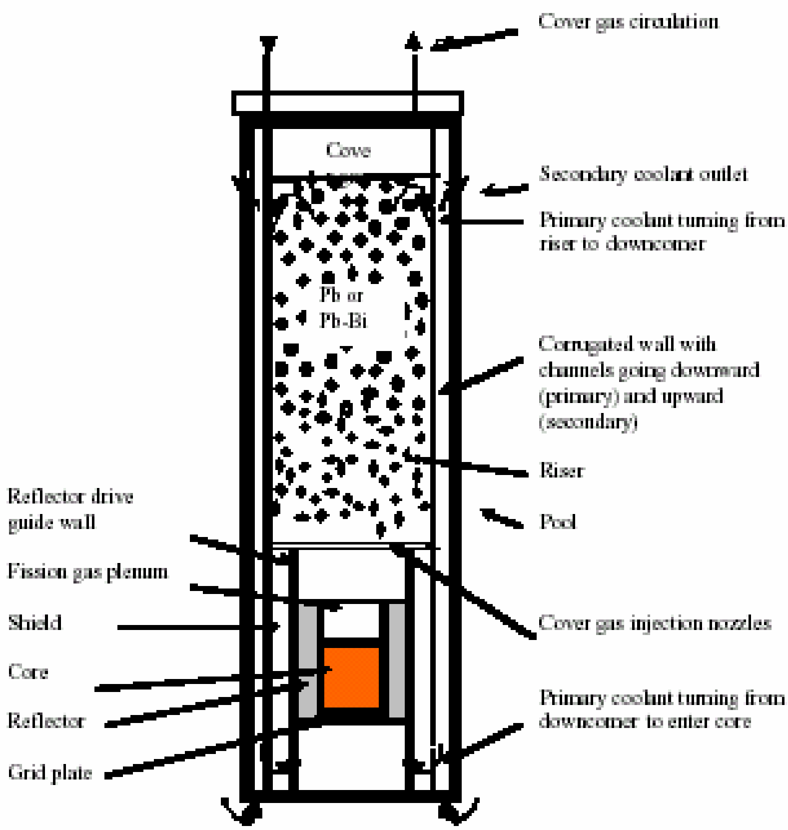

FIGURE 4-23: Cover-Gas ENHS design[35]

The ENHS does not include an intermediate heat exchanger, decay heat removal systems, and mechanical or electromagnetic pumps. Its confinement wall serves as the intermediate heat exchanger and the decay heat removal system. The ENHS will be manufactured and fueled in the factory. It will then be shipped, as a sealed unit, to the power plant site. The sealed unit will have Pb or Pb-Bi filling the vessel to the upper level of the fuel rods. Hot Pb or Pb-Bi will be pumped into the ENHS vessel upon insertion into the reactor pool. This hot Pb, along with the hot Pb in the pool, will melt the solid Pb at the lower part of the vessel.

[35] E. Greenspan, et. al., *The Encapsulated Nuclear Heat Source Reactor Concept for Developing and for Industrial Counties*

After the 15 effective full power years operation, the ENHS will be removed from the reactor pool and stored on-site until the decay heat drops to a level that will let the Pb or Pb-Bi solidify. The ENHS with the solidified Pb or Pb-Bi will then serve as the shipping cask.

The ENHS fuel is a metallic alloy of U-Pu (the uranium will range from depleted to 15wt% enriched and the plutonium initial composition is that of LWR spent fuel) with 10wt% Zr. Two power levels and two linear heat rates have been considered: 125 and 250 MW_{th}, and 80 and 120 W/cm. The peak burnup of these cores is approximately 100 GWD/tHM.

4.4.2 Proliferation Pathways

The Encapsulated Nuclear Heat Source was designed with proliferation issues as the primary motivation; therefore the proliferation pathways that exist for this fuel cycle are in the area of process modifications. The figure below (figure 4-24) highlights this pathway.

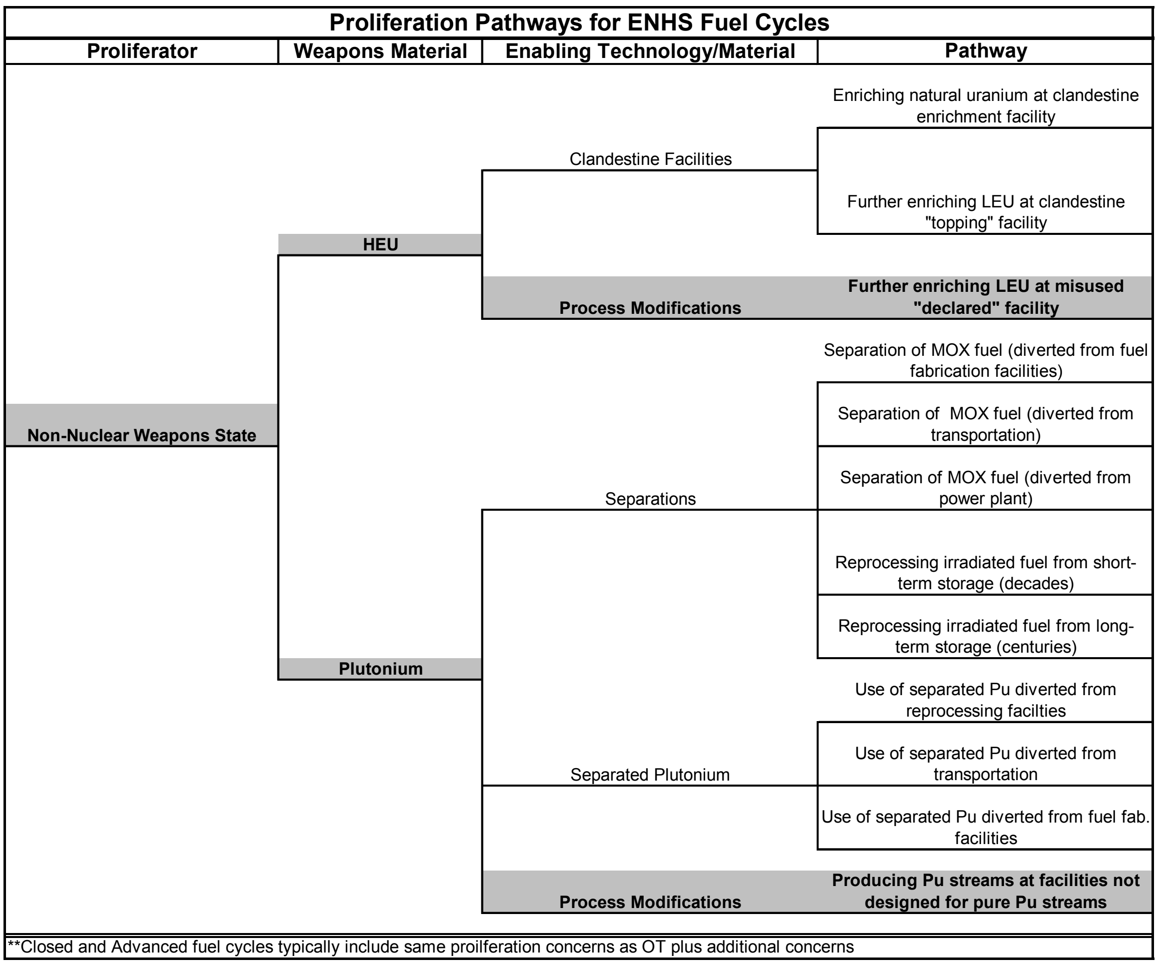

FIGURE 4-24: ENHS Proliferation Pathway
In this pathway, a Non-Nuclear Weapons State (proliferator) desires to acquire HUE or plutonium (weapons material) by process modifications.

The concept includes having all access to fuel (both fresh and spent fuel) only in the supplier state and/or at an internationally monitored nuclear park. Consequently, this reactor/fuel cycle has excellent nonproliferation characteristics. Unfortunately, it is likely to take a long time to make this approach economic.

4.4.3 Assessments

Table 4-9 below gives an assessment of the proliferation resistance of the ENHS nuclear fuel cycle to this particular pathway and highlights the vulnerabilities mentioned above.

TABLE 4-9: ENHS Proliferation Assessment

Encapsulated Heat Source Proliferation Pathway A: HEU (LEU diversion)														
Stages of fuel cycle	**Material Barriers**					**Technical Barriers**						**Institutional**		
	Isotopic	**Radiological**	**Chemical**	**Mass and Bulk**	**Detectability**	**Facility Unattractiveness**	**Facility Access**	**Available Mass**	**Facility Diversion Detectability**	**Skills, Knowledge, Expertise**	**Time**	**Safeguards Effectiveness**	**Access Control, Security**	**Location**
Beginning of the cycle														
Mining														
Transport														
Miling														
Transport														
Conversion														
Storage														
Transport														
Uranium Enrichment	L	I	M	M	L	I	I	I	H	I	H	VH	VH	L
Storage	L	I	M	M	L	I	I	I	H	I	M	VH	VH	L
Transport	L	I	M	M	L	I	I	I	H	I	VH	VH	VH	L
Uranium Oxide Fabrication Facilities	L	I	M	M	L	I	I	I	H	I	H	VH	VH	L
Production of fuel (pellets,pebbles, etc.)														
Production of Fuel Assemblies, Cast														
Storage														
Fresh fuel transport to NPP														
Operation at NPP														
Storage of fresh fuel														
Loading of fresh fuel into the core														
Reactor irradiation														
Unloading of irradiated fuel from the core														
On-site pool storage of spent fuel														
On-site dry storage of spent fuel														
End of fuel cycle (includes once-through)														
Off-site transport of irradiated spent fuel														
Temporary storage of irradiated fuel														
Processing of irradiated fuel for storage and disposition														
Storage of processed materials														
Long-term geolgical burial of irradiated fuel and actinide-containing waste														

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I =Ineffective Barrier
L =Low Barrier
M =Medium Barrer
H =High Barrier
VH =Very High Barrier

4.4.4 Recommendations

Recommendation 1: International nuclear fuel supply and waste disposal centers

A strong limitation on the number of countries dealing with fresh fuel and spent fuel infrastructures, as offered by the long-life core reactor, should be pursued in the growth scenario.

4.5 Fast Reactors

Breeder reactors provide full fuel reproduction in the core (core breeding ratio ≥ 1). These can be fast reactors with high-density fuel (U-Pu or Th-U cycle) and thermal reactors with Th-U cycle. The discussion below is based on the Integral Fast Reactor/pyroprocessing fuel cycle.

4.5.1 Integral Fast Reactor

The Integral Fast Reactor (IFR) reactor concept is a liquid-metal-cooled reactor using a sodium-bonded uranium-plutonium-zirconium alloy fuel capable of operating at very high fuel burnups. Beyond the traditional advanced reactor objectives of increased safety, improved economy and more efficient fuel utilization, the IFR is designed to simplify waste disposal and increase resistance to proliferation (Wade and Hill, 1997).

Separated plutonium is never present in normal operation of the IFR fuel cycle. Pyroprocessing is a fuel processing method that utilizes high temperatures, molten salt, and molten-metal solvents to produce a uranium-plutonium metal allow that is suitable for immediate fabrication into new fuel elements. This "fresh fuel" product is always highly radioactive and self-protective in the safeguards sense. (See figure 4-25 below)

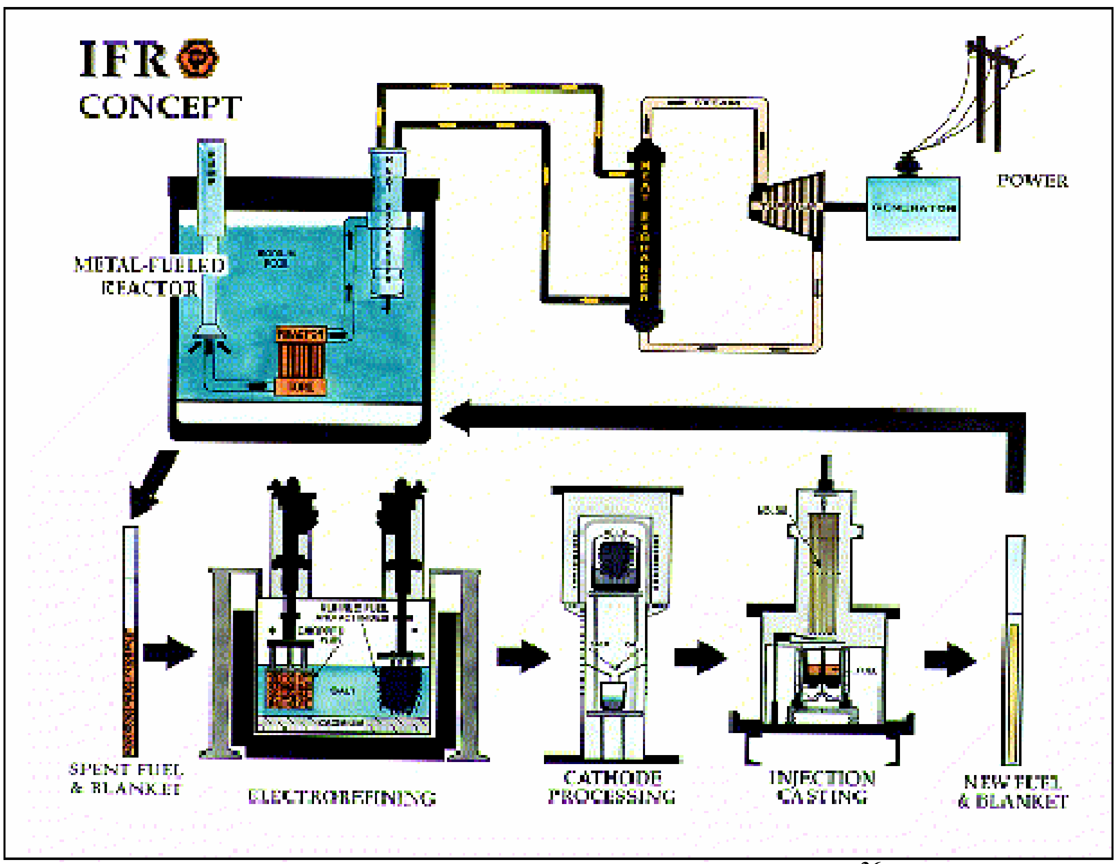

FIGURE 4-25: Integral Fast Reactor Concept[36]

[36] Diagram courtesy of University of California, Berkeley Department of Nuclear Engineering

The IFR is being designed such that it could be operated in a zero-release plant mode, where essentially nothing leaves the site except energy, heat and engineered waste products. Assessment was done assuming this mode.

It is not anticipated that advanced fuel cycles of this general type can be deployed for many decades, for both technical[37] and economic reasons. However, there is much discussion of aggressive international R&D programs to look at resolving the technical and economic challenges. Consequently, for the near and intermediate term, such R&D programs will the focus of proliferation concerns, as considerable facilities (hot cells,…) and expertise (actinide metallurgy,…) relevant to weapons production is developed.

4.5.2 Proliferation Pathways

Operated in zero-release plant mode, the IFR would primarily be susceptible to process modifications by a potential proliferator. This key vulnerability here is with misuse of know-how or process modifications. This is illustrated in the figure below.

[37] Technical feasibility was extensively explored in the Argonne IFR program that was stopped by Congress several years ago.

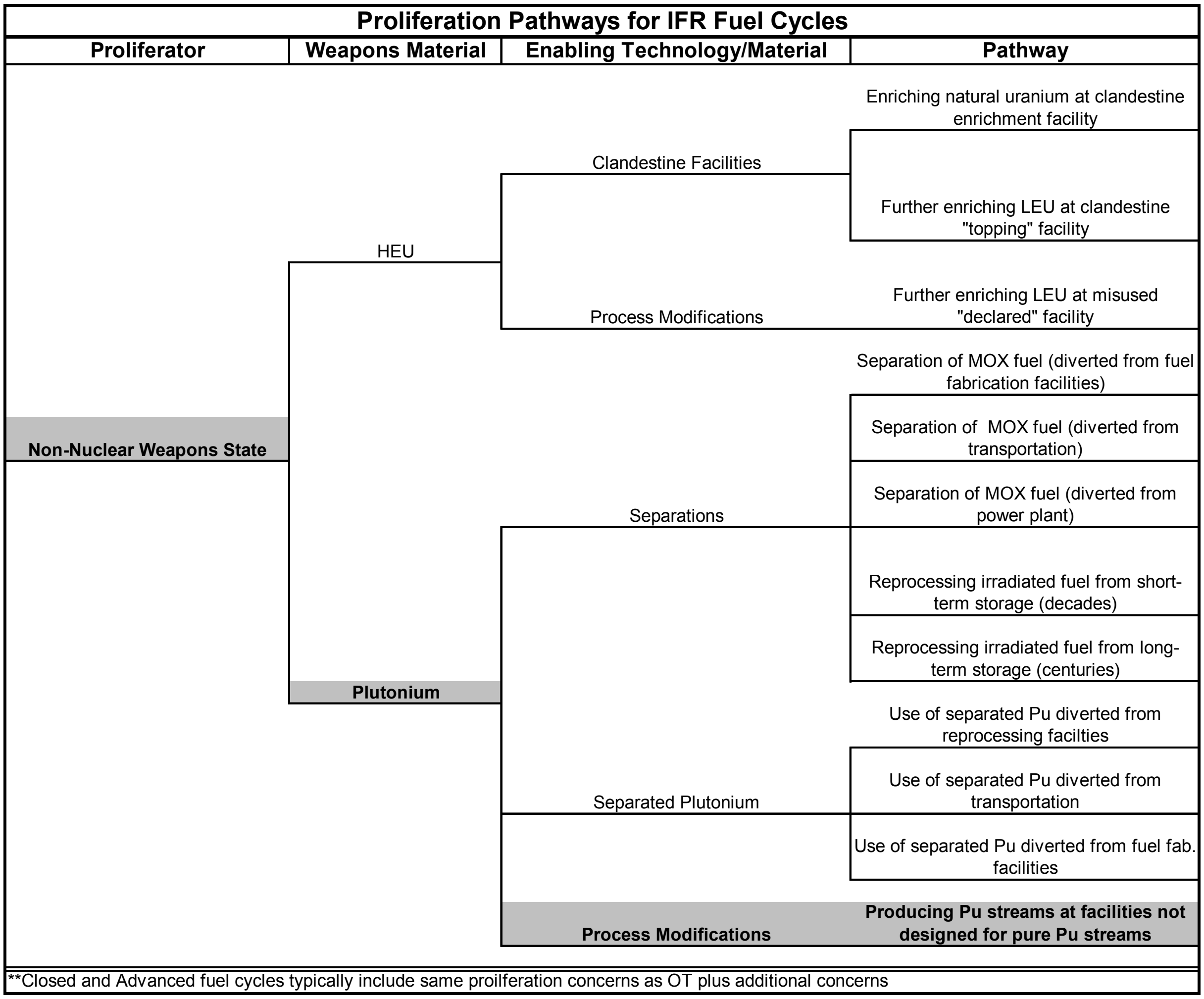

FIGURE 4-26: IFR Proliferation Pathway

In this pathway, a Non-Nuclear Weapons State (proliferator) desires to acquire plutonium (weapons material) by process modifications.

4.5.3 Assessments

Table 4-10 below gives an assessment of the proliferation resistance of the IFR nuclear fuel cycle to this particular pathway and highlights the vulnerabilities mentioned above.

TABLE 4-10: IFR Proliferation Assessment

IFR Proliferation Pathway A-1: Plutonium														
Stages of fuel cycle	Material Barriers					Technical Barriers						Institutional		
	Isotopic	Radiological	Chemical	Mass and Bulk	Detectability	Facility Unattractiveness	Facility Access	Available Mass	Facility Diversion Detectability	Skills, Knowledge, Expertise	Time	Safeguards Effectiveness	Access Control, Security	Location
Analysis and Research										I		I		
Design and Development										I		I		
Beginning of the cycle														
Mining														
Transport														
Miling														
Transport														
Conversion														
Storage														
Transport														
Uranium Enrichment														
Storage														
Transport														
Uranium Oxide Fabrication Facilities														
Production of fuel (pellets,pebbles, etc.)														
Production of Fuel Assemblies, Cast														
Storage														
Fresh fuel transport to NPP														
Operation at NPP														
Storage of fresh fuel														
Loading of fresh fuel into the core														
Reactor irradiation														
Unloading of irradiated fuel from the core														
On-site pool storage of spent fuel														
On-site dry storage of spent fuel														
Closed cycles														
Dissassembly of fuel assembly	L	I	H	H	VH	I	I	L	H	I	VH	L	VH	I
Separation of fissile materials	L	I	H	H	VH	I	I	L	H	I	VH	L	VH	I
Storage of highly-concentrated fissile material	L	I	M	H	VH	I	I	L	H	I	M	L	VH	I
Metallic fuel fabrication facilities	L	I	M	H	VH	I	I	L	M	I	H	M	H	I
Transport of recovered fuel	L	I	M	H	VH	VH	M	L	VH	VH	VH	H	H	VH
Collection, processing and storage of fission product waste														
Transport of actinide-containing waste for burial														
End of fuel cycle (includes once-through)														
Off-site transport of irradiated spent fuel														
Temporary storage of irradiated fuel														
Processing of irradiated fuel for storage and disposition														
Storage of processed materials														
Long-term geolgical burial of irradiated fuel and actinide-containing waste														

KEY

4.5.4 Recommendations

Recommendation 1: Integrated Safeguards for Advanced Separations Plants

The international safeguards community should be engaged in the design and cnstruction phases of fuel cycle separations plants for advanced closed fuel cycles (including pilot and demonstration plants). This will facilitate integration of safeguards and real-time surveillance with the process design so as to flag immediately any process modification aimed to producing pure plutonium streams.

Recommendation 2: Constraints on International Research and Development Cooperation

The near and intermediate term proliferation risk associated with advanced closed fuel cycles lies with the research facilities that may be built and the expertise developed in a variety of countries that take part in an international fuel cycle development program. Such a program should be guided jointly by government nuclear and nonproliferation experts.

The following tables summarize all the pathways and recommendations mentioned in this chapter.

TABLE 4-11: Summary of Proliferation Pathways

The letters in parenthesis indicate the corresponding recommendations

PROLIFERATION PATHWAYS	
1	Enriching Natural Uranium to HEU at a Clandestine Enrichment Facility *(B, D, E, L)*
2	Enriching LEU to HEU at a Clandestine "Topping" Facility *(B, C, D, K, L)*
3	Enriching LEU to HEU at a Misused "Declared" Facility *(A, B, C, L)*
4	Separation of MOX Fuel (Diverted from Storage) *(D, H, M)*
5	Separation of MOX Fuel (Diverted during Transport) *(D, H, M)*
6	Reprocessing Spent Fuel (Diverted from Short-Term Storage) *(D, G, L)*
7	Reprocessing Spent Fuel (Diverted from Long-Term Disposal) *(D, F, G, L)*
8	Use of Separated Plutonium (Diverted from Storage) *(H, J)*
9	Use of Separated Plutonium (Diverted during Transport) *(H, I, J)*
10	Producing Plutonium Streams at Facilities Not Designed for Pure Plutonium Streams *(N)*

TABLE 4-12: Summary of Recommendations

The numbers in parenthesis indicate the corresponding pathways

RECOMMENDATIONS	
A	Safeguarding against Reconfiguration of Enrichment Facilities *(3)*
B	Limiting Spread of Enrichment Technologies *(1, 2, 3)*
C	Containment and Surveillance of LEU*(2, 3)*
D	IAEA Authority to Seek Undeclared Facilities *(1, 2, 4, 5, 6, 7)*
E	IAEA Tracking of Material Flow from Country to Country *(1)*
F	Re-examination of Waste Retrievability as a Criteria *(7)*
G	International Spent Fuel Storage *(6, 7)*
H	PUREX Reprocessing Restrictions *(4, 5, 8, 9)*
I	Co-location of Separations and MOX Fuel Fabrication Facilities *(9)*
J	Minimal Working Plutonium Inventory *(8,9)*
K	Re-examine Control Regime for Enrichment Technologies *(2)*
L	International Nuclear Fuel Supply and Waste Disposal Centers *(1,2,3,6,7)*
M	Integrated Safeguards for Advanced Separations Plants *(4,5)*
N	Constraints on International Research and Development Cooperation *(10)*

5 SUMMARY AND CONCLUSIONS

The possible major expansion of nuclear power globally in response to climate change and electricity supply drivers re-opens the issue of nuclear weapons proliferation and the fuel cycle. There has been much discussion about advanced nuclear technologies that minimize the proliferation risk and about the participation of developing countries in a global nuclear power growth scenario. We have examined these issues so as to understand both what the pattern of nuclear power deployment would likely be at mid-century in a robust growth scenario and what technology pathways and associated proliferation concerns might be. This has led to a number of recommendations for near term consideration and action.

The nuclear power growth scenario starts with an examination of electricity demand. Our scenario is built in a somewhat unconventional way that we believe captures a rational strategy for national expansion of electricity supply. At its core, the strategy focuses on providing electricity supply aimed at a level that empirically brings individuals to a suitable quality of life as indicated by the Human Development Index/electricity consumption correlation; with overall growth constrained by limits associated with electricity supply expansion rates. Thus, per capita consumption together with the United Nations population and urbanization projections were central to development of the "demand map". The growth in global electricity production and use that emerges from this approach is consistent with various projections; for example, it lies between the "business-as-usual" and "low growth" results of the EIA. However, it also provides an important texture to the projections in various groupings of countries:

*Developed countries (such as the United States, Japan, Germany): In the aggregate, these countries have modest population growth. However, because of their current high per capita consumption of electricity, even modest growth rates in use lead to significant new electricity production capacity. These countries today have most of the world's deployed nuclear capacity.

*FSU: The former Soviet Union countries generally show little population growth, or even reductions. Thus they show relatively little growth in electricity use.

*Developing world – more advanced (such as China, Brazil, Mexico, Iran, Egypt, Turkey): These countries are projected to have modest population growth to mid-century (perhaps 25% or so). Electricity growth will be very considerable, drawing upon the rapidly increasing economic strength anticipated (for example, China's electricity production increased more than 10% last year). These countries will be major contributors to a nuclear growth scenario.

*Developing world – less advanced (such as India, Pakistan, Indonesia, Philippines, Vietnam): These countries are anticipated to have a much more significant increase in population by mid-century (more than 50%) and will strive to increase electricity production considerably. Some will have access to investment capital and may participate significantly (e.g., India) in expanding nuclear power deployment.

*Developing world – least developed (such as Nigeria, Bangladesh, Ethiopia, Tanzania, Afghanistan): These countries are predicted to have explosive population growth, approaching a factor of three. These nations have very little infrastructure or access to capital on the scale needed to develop nuclear power. We do not anticipate participation by these countries in the global growth scenario during this time period.

This categorization led to some important conclusions for our nonproliferation considerations. First is the leading role that must be played by the developed countries, generally not considered a major risk for fuel cycle-driven proliferation, if nuclear power is at least to retain its global market share and thereby contribute significantly to greenhouse gas emission mitigation. Further, the United States specifically must be the leader in that scenario. This is based not only on the size of the US economy and associated energy demand, but also on its unique position among large developed countries of having a major population increase projected by the UN. This is a significant conclusion from the scenario with obvious nonproliferation implications. This is the converse of the conclusion that the least developed countries are unlikely to develop nuclear power and are thus also not the focus of nonproliferation concerns.

Consequently, the principal focus falls upon the more advanced and less advanced countries in the categorization above. Among them, China, India and Pakistan already possess nuclear weapons and so also are of less importance to our considerations; indeed we anticipate that both China and India will need very substantial nuclear power expansions (following only that of the US) if the mid-century scenario is to be realized.

This finally takes us to the relatively small number of countries whose situations shape our thinking about the growth scenario and proliferation. A good example of the concerns is provided by the recent developments in Iran which, as an NPT signatory, has been actively pursuing nuclear power and nuclear fuel cycle development, despite its immense fossil fuel resources. They have been assisted most recently by Russia. However, recent revelations show that Iran has developed fuel cycle facilities, most importantly a centrifuge enrichment plant, alleged to be intended for commercial fuel production but nevertheless outside of IAEA oversight. Clearly such a capability, together with the domestic uranium mining industry being developed, provides a relatively straightforward path to nuclear weapons. This is the type of pattern of nuclear cycle development that needs to be addressed in the growth scenario.

Fuel cycle related proliferation pathways will be dependent on the reactor/fuel cycle technology, as well as institutional arrangements. We examined these pathways for five particularly relevant examples. For at least twenty years, the only credible candidates for substantial deployment are the reactor/fuel cycle combinations that dominate today; principally LWR's operated with once-through spent fuel disposal, or LWR's operated with MOX fuel. The former provides a nonproliferation resistance benchmark. The issues raised concern control of enrichment technology and "closing" the back end by implementing geological disposal. In contrast, the MOX fuel cycle has the distinguishing characteristic, quite negative from a nonproliferation standpoint, of making "directly usable" weapons material (i.e., separated plutonium) available during normal operations.

The envisioned deployment of nuclear power to developing nations within the robust growth scenario has been a motivation for modular reactor development. High temperature gas reactors and long-life core reactors are possibilities for the intermediate and long term, respectively. Both have attractive proliferation resistant features, with the latter aiming to remove all fueling operations from the nation employing the reactor. The only drawback with respect to the LWR once-through baseline is the higher enrichment of the LEU fresh fuel, which potentially allows for easier clandestine "topping off" to HEU.

For the long term, mid-century and beyond, there is the possibility of deployment of fast spectrum reactors in a closed fuel cycle that recycles plutonium along with minor actinides and/or fission products. Considerable R&D is needed to overcome both technical and economic barriers. Any closed fuel cycle raises the issue of plutonium diversion, although these approaches are superior to the MOX approach in that separated plutonium is not available in normal operation. Thus, appropriate process safeguards and international institutional arrangements could result in an adequate level of proliferation resistance in the overall system.

These five reactor/fuel cycle combinations by no means represent all possible technologies of interest. However, we believe that they capture the essential generic elements for moving on to a set of recommendations appropriate to the global growth scenario. Some of the key recommendations are:

1. The international safeguards regime needs strengthening in several ways in anticipation of robust growth and spread of nuclear power, such as
   a. IAEA access to undeclared sites for all states subject to IAEA safeguards
   b. Integration of safeguards surveillance and security functions with fuel cycle facility design and operation

2. Enhanced focus should be placed on tracking and control of enrichment technology, specifically including non-commercial technologies that can be used for batch operation and may now be enabled by the spread of technology (materials, lasers, design tools,…) and of industrial capacity. The difficult issue of strengthening cooperation between national intelligence agencies with the IAEA should be addressed.

3. Timely closure of the back end of the fuel cycle with respect to spent fuel management has important nonproliferation implications, both to support expansion of the once-through fuel cycle and to avoid significant degradation of the spent fuel radiation barrier that impedes access to plutonium. The long-term (several hundred years) retrievability criterion that has been imposed on geological repository design should be reexamined from a nonproliferation perspective.

4. International fuel cycle R&D collaboration and assistance for nuclear power development should be confined to reactor/fuel cycle combinations that support nonproliferation objectives. This should specifically exclude fuel cycles, notably the MOX fuel cycle, that make separated plutonium available in normal operation. This should be pursued energetically by US diplomacy. Any international R&D program on advanced reactors and fuel cycles should itself be subject to stringent constraints that minimize proliferation concerns due to research facilities and transfer of expertise. Nonproliferation experts in the government should have a strong role in framing and execution of such programs.

5. Suitable international fuel cycle architectures will be essential in the global growth scenario, such as co-location of sensitive facilities in internationally supervised locations. Fresh fuel supply and spent fuel return to such sites would be a very positive nonproliferation step. International spent fuel storage facilities should be pursued in the near term, preparatory to global growth and spread of nuclear power.

Virtually all of these recommendations suggest the need for a fundamental reexamination of the nonproliferation framework established under the Nonproliferation Treaty if the robust global growth scenario is to be realized responsibly. That framework has already been taxed on many occasions in the very recent past. Thus, while such a reexamination is clearly a major complex undertaking, the magnitude of the challenges presented in the global growth scenario is equally significant.

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PROLIFERATION MATRIX APPENDIX

Attributes of Each Barrier

Barrier attributes must be assessed based on the same set of metrics. The system used by the TOPS task force to indicate the effectiveness of each barrier attribute, was adopted. Below is a brief description of the criteria used to determine barrier effectiveness, most of which was taken directly from information presented in the TOPS annex report.

MATERIAL BARRIERS

The civilian nuclear fuel cycle involves materials that either are, or could potentially be processed into weapons-usable[1] materials. Though all isotopes are capable of being assembled into a fast critical mass can be considered a proliferation concern, the principal isotopes considered here are those of uranium and plutonium.

The effort required to use any isotope is highly dependent upon the isotopic properties and the skills of the potential proliferator because the isotopes properties vary (half-life, neutron generation, heat generation, and critical mass). The nuclear properties, of fissile materials and fertile Th-233 and U-238 (which can produce U-233 and Pu-239 respectively), are listed in the table below.

[1] Materials that can be assembled into a fast critical mass and are capable of undergoing an explosive fissionable reaction). This does not include the dispersal of environmentally hazardous nuclear material.

TABLE A-1: Nuclear Properties of Fissile Isotopes

Table of Nuclear Properties				
Isotope	Half-life (y)	Neutrons/ sec-kg	Watts/ kg	Critical Mass[a] (kg)
Pa-231	32.8×10^3	nil	1.3	162
Th-232	14.1×10^9	nil	nil	infinite[b]
U-233	159×10^3	1.23	0.281	16.4
U-235	700×10^6	0.364	6×10^{-5}	47.9
U-238	4.5×10^9	0.11	8×10^{-6}	infinite[b]
Np-237	2.1×10^6	0.139	0.021	59
Pu-238	88	2.67×10^6	560	10
Pu-239	24×10^3	21.8	2.0	10.2
Pu-240	6.54×10^3	1.03×10^6	7.0	36.8
Pu-241	14.7	49.3	6.4	12.9
Pu-242	376×10^3	1.73×10^6	0.12	89
Am-241	433	1540	155	57
Am-243	7.38×10^3	900	6.4	155
Cm-244	18.1	11×10^9	2.8×10^3	28
Cm-245	8.5×10^3	147×10^3	5.7	13
Cm-246	4.7×10^3	9×10^9	10	84
Bk-247	1.4×10^3	nil	36	10
Cf-251	898	nil	56	9

[a]Bare sphere
[b]Not potentially weapons-usable material
*Taken from *Nuclear Energy Research Advisory Committee (TOPS) Annex* October 2000

The table indicates that several materials can be physically assembled into a fast critical mass and are therefore weapons-usable. Because of its high heat generation, plutonium with more than 80% Pu-238 is not weapons-usable.

More specifically, material barrier attributes are the qualities of materials that relate to the inherent desirability of the material by a potential proliferator. The barriers include the isotopic composition of the material, the radiation hazard and signature associated with each material, the difficulty of moving the mass and/or bulk of the material, and the inherent detectability of the material.

Isotopic

Attributes of the isotopic barrier indicate how difficult it may be to construct a weapon from a particular fissile material *once the material is available* in an acceptable chemical form. Determining the effectiveness of the isotopic barrier requires understanding the critical mass, degree of isotopic enrichment, spontaneous neutron generation, heat-generation rate, and radiation of the particular material. The **critical mass** is the minimum amount of material needed to achieve fast-neutron criticality. The barrier effectiveness is directly proportional to the size of the critical mass (larger critical masses represent a higher barrier than smaller masses). The **degree of isotopic enrichment** is inversely proportional to the size of the barrier effectiveness. Natural and low-enriched uranium (which are not directly weapons-usable, but can be converted into high enriched uranium) yield a high isotopic barrier. High enriched uranium and most plutonium isotopic mixes are considered "directly weapons-usable". **Spontaneous neutron generation** affects the design of a reliable explosive devise. Lower barriers have a lower spontaneous neutron generation. If the material is plutonium, then this is highly dependent on the concentration of the even numbered plutonium isotopes (see table A-1). Higher **heat generation rates** represent higher barriers. The heat produced complicates weapon operations and design (see table A-1). The **radiation** released by isotopes interferes with handling of nuclear devices. This deals with the difficulty of weapons design. For plutonium this depends on the even numbered isotope concentrations and for uranium it depends on the U-232 and U-233 concentrations.

The critical mass, for plutonium, varies less among the different isotopes than do those for uranium. "Weapons-grade" plutonium has a Pu-239 content of greater than 90wt%. Typical "reactor-grade" plutonium has approximately 60wt% Pu-239, and "very-high-burnup reactor-grade" plutonium has approximately 40wt% or less Pu-239.

Radiological

Radiation barriers affect the difficulty of theft or diversion and they can also complicate chemical processing. The characteristics that are included in the radiological attribute include: specific does rates, the time required to accumulate a significant dose, the degree of remote handling required (e.g., hand-on access, remote handling, fully shielded facilities). Some materials have a radiation barrier in their elemental form and others have it only as a result of mixtures. Because the radiological barrier decays with time, after a few decades, the barrier of spent fuel has decayed to a level where it may be reasonably handled with less sophisticated techniques[2].

Chemical

The chemical barrier refers to the extent and difficulty of chemical processing required to separate the weapons-usable materials from diluents and contaminants. The characteristics of chemical barriers relate to the degree of technical difficulty needed to refine materials into the appropriate form, the existence of admixtures, the number of separate processing steps needed to obtain materials of sufficient purity for weapons, and the general availability of the necessary processing techniques.

Mass and Bulk

This barrier refers to the amount and size of materials that have to be handled to obtain weapons materials. If the material is dilute, then the total amount of material to obtain, transport, and process is large, and the mass barrier is significant. If the material is concentrated, then less bulk is needed and the barrier would be much lower. Materials are also often contained in bulky items or configurations that are themselves not easy to obtain or transport.

[2] More detail about spent fuel decay characteristics in chapter 4.

Detectability

Nuclear material is inherently detectable, and this facilitates proliferation resistance through various arrangements. Some characteristics that contribute to detectability are: the degree to which materials can be passively detected (type and intensity of spontaneous emissions, the degree to which active methods (e.g., neutron stimulation) are necessary, the hardness of radiation signatures, the uniqueness of material signatures, and the uncertainties in detection equipment.

The table below summarizes the material barriers and their effectiveness. In the table, I represents an ineffective barrier, L a low barrier, M a medium barrier, H a high barrier and VH a very high barrier. This scale is not linear and some qualitative differences may exist between different rankings. The scale is also not comparable among the various barriers. That is to say, the effectiveness of an H for radiological barrier is not necessarily equivalent to a chemical barrier with an effectiveness of an H.

TABLE A-2: Classification of Material Barriers[3]

Material Barriers					
Barrier	**Classification**				
	I	**L**	**M**	**H**	**VH**
Isotopic	Weapons-grade HEU (80% or greater U-235)	HEU(50-80%), Weapons-grade Pu(>90%Pu-239), Typical Reactor-Grade Pu(60%Pu-239), HEU (35-50%U-235), very high burnup reactor-grade Pu (40%or<Pu239)	HEU (20-35%U235)	LEU	Natural, depleted U
Radiological	No significant radiation hazard, capable of unlimited hands-on access, includes natural, depleted, and enriched uranium		Moderate radiation hazards, normally requiring glove-box handling, includes separated plutonium	Dangerous radiation hazards, levels fall below "self-protection standard"(100R/hr @ 1meter)	Lethal levels of radiation meeting the self-protecting standard, includes most spent fuel and high-level wastes
Chemical	Pure metals	Single compounds (requiring relatively few and simple chemical steps to extract a pure metal)	Mixed compounds (MOX fuel, dilutents and burnable poisons, but not fission products or other radiation barriers)		Spent fuel and vitrified wastes
Mass/Bulk	Small amounts of weapons usable materials, easily concealed and transported, with sufficient concentrations that require few trips for accumulation	Similar to I, but significantly more difficult to conceal	Large quantities must be transported (multiple trips and/or several individuals)	Large quantities must be transported, requiring commonly used equipment and vehicles	Large quantities, specialized equipment and/or low concentrations requiring many trips
Detectability	No reliable signature for remote detection	Materials requiring active means of detection	Materials that can be reliably detected		Materials easily dected by passive means

[3] Adapted from TOPS report

TECHNICAL BARRIERS

Technical barriers are the intrinsic technical elements of the fuel cycle, its facilities, processes, and equipment that serve to make it difficult to gain access to materials and/or to use or misuse facilities to obtain weapons-usable material. The intrinsic technical barrier characteristics include: the unattractiveness (lack of utility for weapons use) of facilities, equipment, and processes for producing potentially weapons-usable material; the extent to which facilities and equipment inherently restrict access to fissile material; the amount of attractive material; facility detectability and material accountability; applicability of skills, knowledge and expertise; and timing.

Facility Unattractiveness

The extent to which facilities, equipment, and processes are resistant to the production of weapons-usable materials is an important technical barrier. Those that can directly produce weapons-usable material have a negligible barrier to proliferation and those that cannot be modified have a high barrier. Among the characteristics involved in this barrier are: the complexity of modifications needed to obtain potentially weapons-usable material; the cost of modifying the facility or process; the safety implications of such modifications; the time required to perform the modifications; facility throughput; and the existence and effectiveness of observables (e.g., environmental signatures that can be remotely sensed or observed) associated with facility modification and misuse.

Facility Access

The extent to which facilities and equipment inherently restrict access to fissile material represents an important barrier. This barrier is considered independent from institutional barriers including security and access controls. The characteristics that are involved with this barrier include: the difficulty and time required to perform operations leading to access to materials, equipment, and processes of concern (e.g., time required to remove a reactor head for refueling); the need for an availability of specialized equipment, skills, and knowledge to gain access; the extent of manual vs. automatic, remote or autonomous operations; and the frequency of operations potentially supporting a proliferator's goal (e.g., refueling-which may provide access to fuel).

Available Mass

At least a critical mass of appropriate weapons-usable material must be available in order for a proliferator to construct nuclear weapons. Insufficient materials represent a larger barrier to proliferation. Although, material availability is affected by the physical characteristics of the process, technology, and facility, and also by the security and safeguards measures implemented, these aspects are discussed under other barriers. The available mass barrier specifically deals with the amount of material in existence at a point in the nuclear fuel cycle, expressed in terms of critical masses (see Table A-1).

Facility Diversion Detectability

Diversion detectability is a measure of the extent to which diversion of materials from processes and facilities can be detected. Facility detectability describes the extent to with undesirable modification to the facilities can themselves be detected. The characteristics involved include: the type of material and processes involved and the extent to with the process supports accurate materials accountability; the uncertainties in detection equipment, including screening for dummy items; and the whether or not the form of the material is amenable to item counting.

Skills, Knowledge and Expertise

Nuclear fuel cycle activities involve varying degrees of skills, knowledge and expertise that may be applied to support a nuclear weapons program. Characteristics important to determining the extent to which such information could support a program include: the level of specialized skills and knowledge necessary to support specific elements of the fuel cycle (i.e., the availability of "dual-use" skills—skills that serve both civilian and weapons programs); the extent to which such information is directly applicable to weapons development; the extent to which such information is generally available; the time required to achieve some level of expertise from available sources; and the general availability and alternate sources of applicable skills.

Time

The time that materials are available to potential proliferators is also a determinant to the overall effectiveness of the barriers to proliferations. In general, the storage of materials and equipment represents the greatest time-related proliferation threat (long storage times for materials and equipment typically provide potential proliferation plenty of opportunities for access).

Table A-3 summarizes the technical barriers and their effectiveness.

TABLE A-3: Classification of Technical Barriers[4]

Technical Barriers					
Barrier	**Classification**				
	I	**L**	**M**	**H**	**VH**
Facility Unattractiveness	Facilities that routinely use, handle or produce significant quantities of directly weapons-usable materials	Facilities that can be modified quickly, safely and easily. With observables difficult to detect prior to accumulation of significant quantities of materials	Facilities that require expertise, expense and time (~month) to modify	Facilities capable of modification given substantial time (months to years), money and expertise. Safety and throughput issues involved	Facilities with little appeal for modification
Facility Access	Access to sensitive materials is quick and easy. Frequent hands-on access		Access is normally accomplished via automated, remote processes. Manual operations are limited		Access is extremely difficult, requiring highly specialized skills and equipment
Available Mass	Very large quantites (multiple critical masses) of potentially weapons-usable materials present	A significant quantity (on the order of a critical mass) of potentially weapons-usable material is present		Small quantities (<10% critical mass) of potentially weapons-usable materials present	Very small quantities (<1% critical mass) of potentially weapons-usabe materials present
Facility Diversion Detectability	Facilities with no or minimal detection equipment. Procedures that allow materials to easily move with detection				Facilities with detection equipment. Procedures that make it very difficult for material to move without detection]
Skills, Knowledge, Expertise	Process, technology, or facility provides significant and unique technical expertise having direct weapons-development application. "Dual-use skills"		Existence of skills, knowledge and expertise provide support valuable to weapons-development programs, but is not directly applicable		Only general industrial skills are needed to support the technology or facility. These skills are well known and readily available
Time	Long storage time (decades) with oportunity for access to materials and/or equipment	Long storage time but with low access opportunity	Intermediate storage time (years) and low opportunity for access	Short to intermediate storage times with high opportunity for access	Short or no storage time (days to months) and low opportunity for access

INSTITUTIONAL BARRIERS

Institutional barriers are those practices, controls, and arrangements designed to protect against various threats, compensating in whole or in part for weaknesses of material or technical barriers, or for the potential of other aspects of the nuclear energy system to contribute to proliferation. These practices, controls, and arrangements include international safeguards, MPC&A[5], highly effective and well-integrated safeguards measures based substantially on real-time monitoring, and other measures such as controls over sensitive information, export controls, etc. Institutional barriers may also include the economic and political stability of the region or nation where the nuclear system (or certain parts) is located.

Safeguards

Safeguards are those extrinsic measures implemented to assist in the monitoring, detection, and deterrence of facility misuse and/or of material diversion or theft. Safeguards specifically relate to extrinsic measure and therefore they are materially different from the intrinsic

[4] Adapted from TOPS report

[5] Complex measures known as material protection, control, and accounting

"diversion detection" and "materials detectability" barriers. Safeguards are effective to the extent that they can: provide a credible and effective deterrent to proliferation; provide effective transparency; and reliably detect illicit activities as early as possible. The barrier characteristics include: availability of and access to relevant information; minimum detectability limits for materials; existence of conspicuous signatures and the ability to detect illicit activities; response time of detectors and monitors; existence, precision, and frequency of material and process inventory and control procedures; and incorporation of safeguards measures into facility and process design and operation.

Access Control and Security

Access-control and physical-security measures are different from facility access in being institutional additions not inherent to the system. The characteristics of this barrier include: administrative steps necessary to obtain access; physical protection and security arrangements; existence of effective backup support; and how effective access control and security are implemented and supported if needed (e.g., whether the technology supports co-location of sensitive activities).

Location

Location represents a problematic barrier in many ways. For example, in that site remoteness may make a facility harder to attack, but it can also make it difficult to defend and increase the defenders' response time. Operations at widely dispersed locations require transport of materials between them, and transport involves increased risk. Oppositely, co-located facilities may only require on-site transport. The effectiveness of the location barrier requires careful evaluation of the threat and location implications to determine the net value of the location barrier. This makes characterization of the barrier difficult to impossible. The characterization in the following table is a zero to first order approximation of the necessary evaluation of the location barrier.

Table A-4 summarizes the institutional barriers and their effectiveness.

TABLE A-4: Classification of Institutional Barriers[6]

Institutional Barriers					
Barrier	**Classification**				
	I	**L**	**M**	**H**	**VH**
Safeguards Effectiveness	Safeguards monitoring parameters are limited and complex. Uncertainty in materials status increases rapidly if monitoring is delayed or restiricted. Margins for error in meeting timeliness of detection goals are small				Multiple monitored parameters provide easily interpreted data. Uncertainty in material status increases slowly with delays or restrictions. Margins for error are large and robust
Access Control, Security	Materials could be easily moved without detection.	With some prior planning, materials could be removed with a small probability of detection. Could be stolen by a small group of lightly armed outsiders	At most times, theft attempts by a single insider would be detected. System vulnerabilities to circumstances (emergencies/power outages) are high. Theft by outsiders would require well-trained, well-armed individuals properly equiped	Theft by a single insider or small group of armed outsiders (or both) can be blocked with good confidence. Design basis threat includes possible use of equipment brought in by vehicles	Theft attempts by multiple insiders or large groups of armed outsiders (or both) can be blocked with high confidence. Design basis threat also includes the possible use of helicopters
Location	Proliferation threat is highly dependent upon facility location				Facility location poses no additional threat to proliferation

[6] Adapted from TOPS report

DON'T QUIT

When things go wrong
As they sometimes will
When the
Road you're trudging
Sees all uphill,
When the funds are low
And the debts are high,
And you want to smile,
But you have to sigh,
When care is pressing you
Down a bit,
Rest if you must
But don't you quit.
Life is queer
With its twist and turns,
As every one of us
Sometimes learns,
And many a
Failure turns about,
When you might have won
Had you stuck it out.
Don't give up,
Though the pace
Seems slow-
You may succeed with
Another blow.
Success is failure turned
Inside out—
The silver tint of the
Clouds of doubt.
And you never can tell
How close you are;
It may be near when it seems so far.
So stick to the fight
When you're hardest hit
It's when things seem worst
That you must not quit.
-Author Unknown