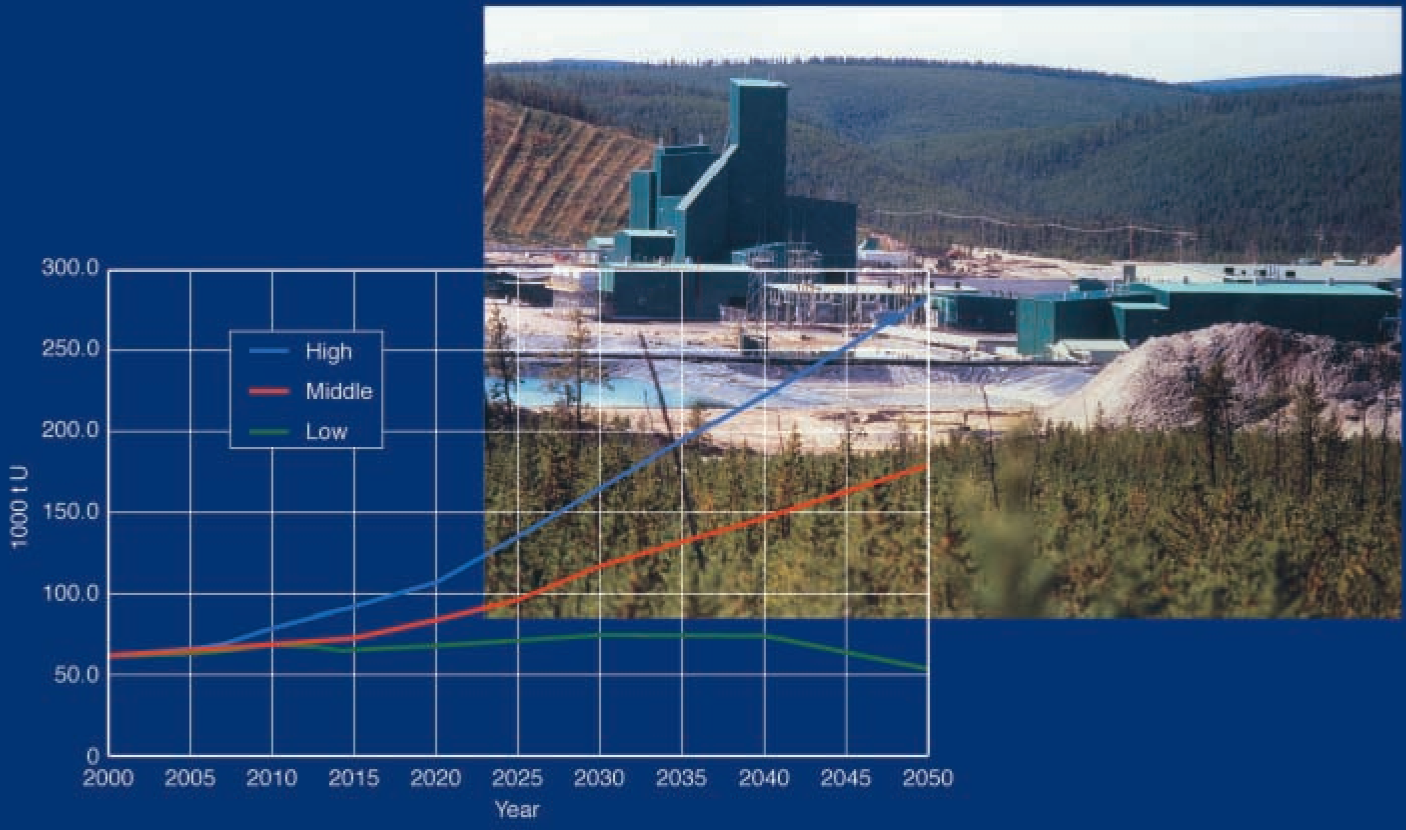
Analysis of Uranium Supply to 2050



INTERNATIONAL ATOMIC ENERGY AGENCY

ANALYSIS OF URANIUM SUPPLY TO 2050

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The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world’’.

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FOREWORD

A fuel supply is intrinsically fundamental to the sustainability of any energy system. Therefore it is essential that all stakeholders with an interest in understanding nuclear fuel supply have available a systematic analysis of the long term uranium supply. Compared with other fuels, the length of the time period of interest to the nuclear power industry is relatively long. The time span for a nuclear power plant from initial planning through to shutdown may be more than 50 years. The life cycle of a uranium mine and mill from the start of exploration through production and shutdown commonly extends from 20 to 40 years. Facilities with a very large resource base may have a life cycle of more than 50 years. It is therefore apparent that uranium supply forecasts looking forward 50 years are essential for long term planning.

It has been nearly a decade since the IAEA prepared its forecast of uranium supply to 2035. Since the preparation of that study uranium supply has become more complex, and the uranium mining and milling industry has changed dramatically. The importance of the secondary, or non-production, supply has increased, while becoming more diversified. Therefore it was essential that a new analysis be completed to provide the information required for making strategic decisions related to nuclear power and its fuel supply. This study should be useful for government and industry planners, policy and decision makers, and project managers. Potential users include both consumers and producers of nuclear fuel.

This report is part of the IAEA's programme on uranium supply and demand analysis. As it includes the first IAEA projection of uranium supply to 2050, it provides the reader with an understanding of how some alternative uranium supply scenarios could evolve over this period. The analysis is based on current knowledge of uranium resources and production facilities. It assumes that state of the art production technology will be used to produce uranium in the most economic (lowest cost) way. It takes into account the premise that uranium production facilities can operate with minimal environmental impacts when projects employ the best practices in planning, operations, decommissioning and closure. The analysis is based on published projections of uranium requirements. These projections cover a range from a very low to a very high level of utilization of nuclear power. While this analysis is not intended to be a prediction of utilization of nuclear power, it does provide users with an understanding of some of the possible future outcomes for uranium supply.

The IAEA acknowledges the work of all those who were involved in the drafting and review as listed at the end of the report, together with the respective organizations. It is particularly grateful to J. McMurray for his major contribution. The responsible officer at the IAEA was D. Underhill of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

SUMMARY

1. OBJECTIVE

Nuclear power is expected to be an important part of the worldwide energy mix at least for the next 50 years, and by most projections well beyond. That is, of course, provided an adequate supply of uranium is available to sustain the nominal growth rate for nuclear power of 1 to 3% per year that is projected by some analysts. The goal of this report is to evaluate the adequacy of supply to meet reactor uranium requirements (demand), and to characterize the level of confidence that can be placed in the projected supply.

2. ASSUMPTIONS OF DEMAND

Three demand cases (low, middle and high) are considered, covering a broad range of assumptions as to worldwide economic growth and related growth in energy and nuclear power. These cases are similar to the 'nuclear variants' in Key Issue Paper No.1 presented in Ref. [1]. The demand projections between 2000 and 2020 were compiled by the IAEA based on information available in late 1999. The long term portions of the demand cases (2020 to 2050) were developed by the International Institute for Applied Systems Analysis and the World Energy Council (IIASA/WEC) in Ref. [2]. The projections of nuclear generation for the six scenarios developed by IIASA/WEC are shown in Fig. 4 of this report. The cumulative uranium requirements to 2050 for the three demand cases addressed in this report, and the assumptions on which they are based, are shown in Table I.

The middle case of Table I is selected as the midrange of uranium demand between the low and high cases. The assumptions for the middle demand case are from the IIASA/WEC case C2. They are described as 'being rather optimistic and challenging', and assume that energy policies will explicitly integrate environmental protection objectives. The middle demand case of this report should not be confused with the IIASA/WEC case B, which IIASA/WEC also identify as their 'middle energy demand case'. They describe case B as 'more pragmatic' and containing more realistic features than cases A and C. The uranium demand for the IIASA/WEC 'middle energy demand case' (case B) would be much higher than the middle demand case of the present study.

TABLE I. THE THREE DEMAND CASES ADDRESSED IN THIS REPORT

Uranium demand case	Cumulative requirements, 2000 to 2050 (t U)	Assumptions
Low (IIASA/WEC case C1)	3 390 000	Medium economic growth Ecologically driven energy policies Low energy demand growth Phase-out of nuclear power by 2100
Middle (IIASA/WEC case C2) (This case is the midrange between the high and low uranium demand cases.)	5 394 100	Medium economic growth Ecologically driven energy policies Low energy demand growth Sustained development of nuclear power worldwide, including in developing countries
High (IIASA/WEC case A3)	7 577 300	High economic growth 'Rich and clean' energy future without recourse to stringent environmental policy measures Significant development of nuclear power

It also, however, falls below the high demand case of this study.

3. SECONDARY SUPPLY

Uranium supply is broadly classified into two categories — secondary and primary supply. Secondary supply includes high enriched uranium (HEU), natural and low enriched uranium (LEU) inventories, mixed oxide fuel (MOX), reprocessed uranium (RepU) and re-enrichment of depleted uranium (tails). Primary supply includes all newly mined and processed uranium. Secondary supply is projected to cover 42% of demand in 2000, provided it is supplied to the market in a systematic and timely manner. By 2025 this contribution is projected to drop to 6 and 4% of demand in the middle and high demand cases, respectively, and the percentage will continue to decline until 2050. Secondary supply is projected to contribute about 11 and 8% of cumulative demand to 2050 in the middle and high demand cases, respectively.

4. PRIMARY SUPPLY AND MARKET BASED PRODUCTION

The role of primary supply will expand as the contribution from secondary supply diminishes. Primary supply is divided into two broad categories — that which is not constrained or controlled by market conditions, such as production in the Commonwealth of Independent States (CIS), China and the small national programmes, and production that is market based. Market based production requirements are determined by adding secondary supply and primary supply from the CIS, China and the national programmes, and subtracting this total from annual demand.

5. PROJECTION OF THE CONTRIBUTION OF MARKET BASED PRODUCTION

For the middle demand case in 2000, market based production will be needed to cover about 46% of uranium requirements; by 2025 that requirement will grow to 86% of demand. In the high demand case, market based production will increase from 45% in 2000 to about 92% of demand by 2025. Market based production is projected to satisfy 77 and 85% of cumulative demand between 2000 and 2050 in the middle and high demand cases, respectively.

6. RESOURCE CATEGORIES

Assessing the adequacy of conventional uranium resources to satisfy market based production requirements is the main focus of this report. Conventional resources are those that have an established history of production where uranium is either a primary product, a co-product or an important by-product (e.g. gold). Conventional resources are categorized by confidence levels and relative production cost using definitions and cost ranges from Uranium Resources, Production and Demand (or the Red Book) [3], the joint report of the IAEA and the OECD Nuclear Energy Agency (OECD/NEA). The resources are identified starting with the highest confidence known resources (reasonably assured resources (RAR) plus estimated additional resources category I (EAR-I)), followed by lower confidence undiscovered (potential) resources (estimated additional resources category II (EAR-II) and speculative resources (SR)).

The definitions of the conventional resource categories are given below.

Reasonably assured resources (RAR) refers to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. RAR have a high assurance of existence.

Estimated additional resources category I (EAR-I) refers to uranium in addition to RAR that is inferred to occur, mostly on the basis of direct geological evidence, in extensions of well explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits and knowledge of the deposits' characteristics, are considered to be inadequate to classify the resource as RAR. Estimates of tonnage, grade and cost of further delineation and recovery are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best known parts of the deposit or in similar deposits. Less reliance can be placed on the estimates in this category than on those for RAR.

Estimated additional resources category II (EAR-II) refers to uranium in addition to EAR-I that is expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well defined geological trends or areas of mineralization with known deposits. Estimates of tonnage, grade and cost of discovery, delineation and recovery are based primarily on knowledge of deposit characteristics in known deposits within the respective trends or areas and on such sampling, geological, geophysical or geochemical evidence as may be available. Less reliance can be placed on the estimates in this category than on those for EAR-I.

Speculative resources (SR) refers to uranium, in addition to EAR-II, that is thought to exist, mostly on the basis of indirect evidence and geological extrapolations, in deposits discoverable with existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are speculative.

Very low grade resources, which are not now economic or from which uranium is only recoverable as a minor by-product, are considered unconventional resources (e.g. phosphates, monazite, coal, lignite and black shale). Only a small amount of phosphate by-product uranium (i.e. about 2% of the total) is included in the supply analysed in this report.

7. PRIORITY OF STARTUP OF PRODUCTION CENTRES

Production centres and their associated resources are also ranked by projected production costs. The order in which production centres are projected to begin operations to satisfy market based production requirements is based on a combination of confidence level and cost. It has been assumed that the lowest cost producer in the highest resource confidence category will fill the first increment of demand, followed by progressively higher cost producers until annual demand is filled.

The model used to project production and resource adequacy provides neither a prediction nor a forecast of precisely how the uranium production industry will develop during the next 50 years. Instead, it presents a number of scenarios based on current knowledge, each of which shows alternatives as to how the industry could unfold given changing sets of conditions.

8. ANALYSIS OF CUMULATIVE SUPPLY AND DEMAND TO 2050

The adequacy of resources to meet demand is measured in two ways. The first measure is a direct comparison of resources at different confidence levels with market based production requirements. The second measure takes into account the fact that not all resources will be utilized within the study period by comparing projected production with requirements. The importance of the difference between the two ways of measuring resource adequacy is indicated for the middle and high demand cases in Table II.

Production from high confidence RAR is projected to be adequate to meet all requirements in the low demand case. Therefore, deficits are not projected to be a factor in the low demand case. As we progress to the middle demand case, relatively high confidence known resources

TABLE II. COMPARISON OF THE TWO WAYS OF MEASURING RESOURCE ADEQUACY

Middle demand case (million t U)		
Known resources	RAR	RAR + EAR-I
Deficit between requirements and resources	(1.025)	(0.146)
Deficit between requirements and production	(1.540)	(0.845)
Known resources + EAR-II	RAR + EAR-I + EAR-II[a]	
Deficit between requirements and resources	+2.079	
Deficit between requirements and production	(0.307)	
High demand case (million t U)		
Known resources	RAR	RAR + EAR-I
Deficit between requirements and resources	(3.273)	(2.394)
Deficit between requirements and production	(3.734)	(2.950)
Known resources + EAR-II	RAR + EAR-I + EAR-II[a]	
Deficit between requirements and resources	(0.169)	
Deficit between requirements and production	(2.060)	

[a] It is important to emphasize that EAR-II are undiscovered resources. EAR-II will not become higher confidence level resources unless significant and timely exploration expenditures are performed to make discoveries.

fall short of market based production requirements by only 146 000 t U, or by less than the annual demand in each year from 2041 to 2050. With the addition of lower confidence (undiscovered) EAR-II, resources actually exceed requirements by about 2 million t U. However, a combination of timing when production centres will be cost justified and the size of their resource base precludes full utilization of resources, resulting in a projected shortfall of 844 500 t U between production from known resources and market based production requirements.

The deficits are even more dramatic in the high demand case. For example, known resources fall short of market based production requirements by 2 394 000 t U in the high demand case. A shortfall of 2 950 350 t U is projected between production from known resources and market based production requirements in the high demand case. The first deficit between production from known resources and requirements is projected to occur in 2026 in the high demand case, compared to 2035 for the middle demand case.

9. RESULTS OF ANALYSIS OF CUMULATIVE SUPPLY AND DEMAND TO 2050

As described above, lower cost (<US $130/kg U) conventional resources are not available to meet the uranium demand in the middle and high demand cases, even when EAR-II are taken into account. However, if very high cost (>US $130/kg U) conventional resources are taken into account, together with unconventional resources, sufficient resources are available to meet both the middle and high demand cases. For this to occur, significant increases in uranium prices would be inevitable. Based on this analysis, the projected trend of future production costs is discussed in the next section.

It is also estimated there are about 8.7 million t U of SR. They include the potential for discovering additional low cost resources. However, for such discoveries to be made from SR it is important that significant and timely exploration be undertaken. Therefore, in the final analysis, both the middle and high demand cases could be supplied by either very high cost conventional and unconventional resources, or by new lower cost conventional resource discoveries made from SR.

10. PROJECTED PRODUCTION COST

To ensure a supply of relatively low cost resources for the future, it is imperative that development of resources be started in a timely manner such that they will be available to satisfy requirements efficiently. Secondary supply and CIS production have, during the past decade, combined to reduce market based production requirements and to depress market prices, which in turn has been a deterrent to both exploration and new project development. As we look forward, the timing when production centres are projected to be cost justified to begin operations will be an indirect indication of market price trends. Table III provides a comparison for the middle and high demand cases of the approximate year that production centres with different cost ranges will first be cost justified, assuming production derived from different confidence level resources.

Based on the comparison in Table III, under the middle demand case and assuming availability of only known resources (RAR and EAR-I), production centres with costs exceeding US $52, US $78 and US $130/kg U will not be cost justified until about 2021, 2027 and 2034, respectively. In the high demand case, production centres with known resources in the same cost categories will not be cost justified until about 2015, 2022 and 2026, respectively.

TABLE III. COMPARISON OF YEARS WHEN PRODUCTION CENTRES WITH DIFFERENT COST RANGES WILL FIRST BE COST JUSTIFIED

	US $52–78/kg U	US $ >78–130/kg U	>US $130/kg U
Middle demand case			
RAR	2019	2024	2028
RAR + EAR-I	2021	2027	2034
RAR + EAR-I + EAR-II	2021	2029	2041
High demand case			
RAR	2013	2019	2023
RAR + EAR-I	2015	2022	2026
RAR + EAR-I + EAR-II	2015	2023	2031

11. SENSITIVITY ANALYSIS

Looking 50 years into the future is obviously accompanied by inherent uncertainties and requires broad assumptions. Every effort has been made to document all assumptions and to describe fully the methodology on which this report is based. Sensitivity analyses have been completed that help quantify the uncertainties by projecting the consequences of changes in availability of different supply sources.

The sensitivity analyses completed indicate that limiting secondary supply will have only a limited impact on supply–demand relationships and on the timing of when progressively higher cost production will be needed. For example, in the middle demand case significantly limiting the combined contribution of MOX, RepU and tails re-enrichment will only advance by two years, from 2021 to 2019, the year in which projects with production costs >US $52/kg U would be cost justified. Similarly, limiting the availability of Russian HEU to the current USA–Russian Federation agreement will only advance by two years cost justification of projects with production costs >US $52/kg U.

The middle demand case assumes that CIS production will continue to be constrained by capital limitations. However, an analysis was also completed in which production is assumed to increase to approximately the levels officially announced by the CIS producers. The net effect of increasing CIS production would be to reduce proportionately market based production requirements. Increasing CIS production would only reduce the cumulative deficit between production derived from high confidence RAR and requirements by about 174 000 t U and would have a minimum impact on market price trends.

12. DISCUSSION

There are a number of other factors that could change uranium demand projections. Concerns about longer term security of supply of fossil fuels and the heightened awareness that nuclear power plants are environmentally clean with respect to acid rain and greenhouse gas emissions could contribute to even higher than projected growth in uranium demand over the long term. For example, the World Energy Council [4] reports that “Nuclear power is of fundamental importance for most WEC members because it is the only energy supply which already has very large and well-diversified resources (and potentially unlimited resources if breeders are used), is quasi-indigenous, does not emit greenhouse gases, and has either favourable or at most slightly unfavourable economics. In fact should the climate change threat become a reality, nuclear is the only existing power technology which could replace coal in baseload. While it faces a public acceptance problem, the present evolution of safety, waste disposal and regulatory independence, should lower the existing concerns”.

Therefore the increasing importance of the debate on global warming points towards accepting nuclear power as a valid alternative within the framework of long term sustainable development. Conversely, the factors that could potentially reduce uranium requirements are development of reactor and fuel cycle technologies (i.e. enrichment, fuel reprocessing and fast breeder reactors) and lowering enrichment tails, if and when economically justified.

As we look to the future, presently known resources fall short of demand. However, if significant and timely exploration is conducted and sufficient resources are discovered, there could be an adequate supply of lower cost uranium to satisfy demand. Nevertheless, if the exploration effort is insufficient, or is not implemented in a timely manner, it will become necessary to rely on very high cost conventional or unconventional resources to meet demand as the lower cost known resources are exhausted. Therefore, to ensure maximum utilization of newly discovered resources, exploration must begin relatively soon.

Lead times to bring major projects into operation are typically between eight and ten years from discovery to start of production. To this total, five or more years must be added for exploration and discovery and for the potential of completing even longer and more expensive environmental reviews. Therefore it would most likely be no earlier than 2015 or 2020 before production could begin from resources discovered during exploration started in 2000. On the other hand, longer delays will reduce the likelihood that the entire resource base of a large new project will be depleted by 2050. Put another way, discovery of a major deposit in 2030 will have much less impact on alleviating the projected shortfall between production and demand than will a project that is discovered in 2005.

Timely exploration is the best solution for ensuring the availability of low cost uranium resources to eliminate the projected deficits between production and market based production requirements. Over-reliance on an ever diminishing secondary supply could lead to a major supply shortfall in the future. Complacency resulting from overconfidence in the merits of impressive (but unproved) undiscovered resource totals could have the same effect.

1. INTRODUCTION

The role that nuclear power will play in the twentyfirst century is the subject of continuing debate, with disparate opinions offered by supporting and opposing camps. Although the issue is unlikely to be resolved soon, the debate has generated a multitude of reports and projections regarding nuclear power's future and the uranium requirements needed to fuel that future. Opponents and proponents alike have issued their forecasts of future requirements, as have a number of neutral and largely dispassionate experts such as the IAEA and the governments of countries that have nuclear power programmes.

The central theme of this report is to assess the adequacy of uranium resources to meet future requirements based on a range of opinions as to the future of nuclear power. The report begins by discussing three demand cases that project reactor uranium requirements from 2000 to 2050 (Section 3.1). The middle demand case, which represents the midrange between the low and high demand cases, assumes moderate worldwide economic growth, accompanied by a modest growth in nuclear power that averages between 1 and 2% per year. The high demand case envisions strong economic growth with accelerated growth in nuclear power averaging 5% per year, while the low demand case assumes that nuclear power will be phased out by 2100.

Section 3.2 reviews the supply sources that are expected to be available to meet reactor uranium demand through to 2050. The structure of the report accommodates the fact that some supply sources are not strictly tied to or constrained by market economics, and non-market based supply frequently displaces supply which is controlled by market conditions. Therefore, although the main focus of the report is adequacy of market based production to meet demand, the report first considers supply that is not strictly controlled by market economics, as its availability dictates market based supply requirements.

Supply is divided into two broad categories: secondary and primary supply. Secondary supply sources include high enriched uranium from nuclear weapons (Section 3.2.1), natural and low enriched uranium inventories (Section 3.2.2), mixed oxide fuels and reprocessed uranium (Section 3.2.3) and re-enrichment of depleted uranium stockpiles (tails) (Section 3.2.4). Primary supply, which includes all newly mined and processed uranium, is subdivided into four sources. Production from the CIS (Section 3.2.5.1), national programmes that produce uranium exclusively for internal use (Section 3.2.5.2) and the production from China (Section 3.2.5.3) is currently not controlled by economic market conditions. Production from these three sources is added to the secondary supply total, and that total is subtracted from reactor uranium demand to determine annual requirements for uranium produced at or below market costs, or market based production (Section 3.2.5.4).

The remainder of this report is largely devoted to assessing the adequacy of uranium resources to satisfy market based production requirements. Resources are subdivided according to three confidence levels (RAR, EAR-I and EAR-II); they are also ranked by estimated production cost into five cost categories. The potential contribution of SR is also considered. Section 3.2.5.4 describes the methodology used to project the timing when projects will be brought into production to satisfy requirements. Section 4 provides an analysis of the adequacy of resources in each of the three resource confidence categories to satisfy annual market based production requirements under the three demand cases. From the analyses, projections were made for the years when resources of successively lower confidence categories would be required to meet market based production requirements. Estimates also were developed for the year in which resources in the next higher cost category within each confidence category would be required to satisfy demand. Such estimates of resource utilization can be used as an indicator of general market price trends.

Section 5 first restates the adequacy of resources to satisfy market based production requirements for the three demand cases. Since production is projected to fall short of satisfying requirements in the middle and high demand cases, Section 5.1.3 discusses SR potential and Section 5.2 projects exploration requirements needed to develop that potential. Section 5.1.4 discusses high cost unconventional resources associated with phosphorite, black shale, lignite, coal deposits and sea water as potential supplements to SR. Section 5.1.5 examines the sensitivity of the balance between supply and demand to potential increases or decreases in the different supply sources and to the potential that projects could be abandoned because of environmental opposition to uranium mining, effectively reducing the resource base. Section 5.1.2 examines the savings in uranium and the accompanying decrease in market based production requirements that would accrue by decreasing enrichment tails assay.

The ultimate goal of this study is to determine the adequacy of supply from all potential sources to meet reactor uranium requirements, and to characterize the level of confidence that can be placed in the projected supply.

2. SCOPE OF THE STUDY

In 1996 the IAEA assembled a team of consultants to evaluate worldwide uranium resources and production capability to the year 2020. The results of that evaluation were published in 1998 under the title Critical Review of Uranium Resources and Production Capability to 2020 [5]. The uranium industry has continued to change since completion of that evaluation. Depressed market prices have resulted in industry consolidation, with fewer companies controlling a greater percentage of worldwide resources. Several high cost production centres have either closed or suspended operations, and many of the lower cost production facilities are operating at below their nominal annual capacity.

Another significant development affecting the industry was the implementation of programmes by the US and Russian Governments for commercializing surplus defence inventories, notably HEU. In 1993 an agreement between the USA and the Russian Federation was signed whereby the USA would purchase LEU derived from blending down 500 t of HEU from surplus nuclear weapons held by the Russian Federation. The US executive agent for the agreement, the United States Enrichment Corporation (USEC), pays the Russian Federation for the enrichment services content and markets the LEU generally through long term contracts. The natural uranium component (as UF_6) is to be sold by the Russian executive agent. Uncertainty regarding how the natural uranium component of the LEU derived from Russian HEU would come into the market has had a significant dampening effect on uranium market prices. However, much of the uncertainty was reduced when a consortium of three Western suppliers and the Russian Government signed a commercial agreement in 1999 to market the natural uranium component. In support of this commercial agreement, the US Government purchased the natural uranium component of LEU delivered by the Russian Federation to USEC in 1997 and 1998 and agreed to delay delivery of this material to commercial end users for 10 years. The US Government also agreed to delay delivery for 10 years of the uranium derived from certain inventories of US surplus HEU and commercial grade uranium (as UF_6) held by the US Department of Energy (USDOE).

As the industry has continued to evolve, uranium supply–demand relationships have also continued to change. In addition, most energy forecasts foresee a continued role for nuclear power well beyond 2020, the end point for the 1998 study. Therefore, the decision was made to update and expand the original report to cover the period from 2000 to 2050.

Uranium is somewhat unique among fuel resources in that non-traditional or secondary supply currently fills an important component of total reactor uranium requirements. Commercial and government inventories and commercialization of nuclear weapons originated

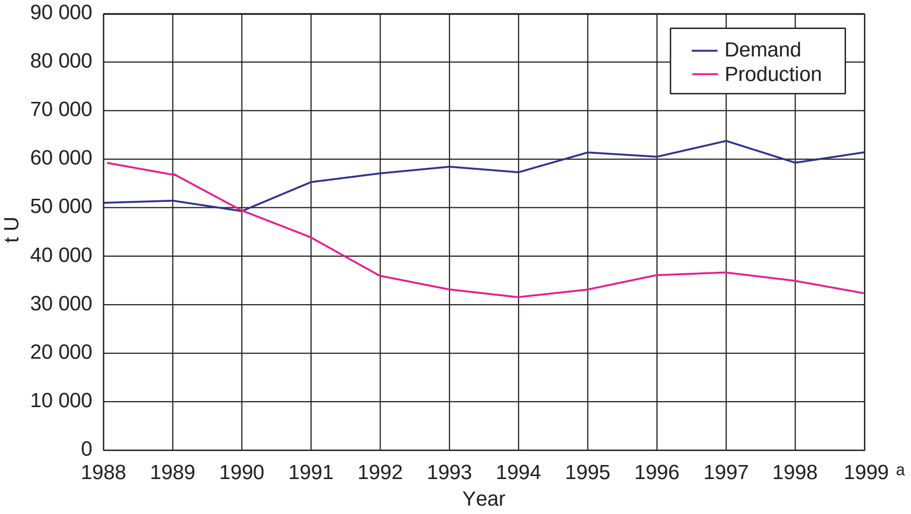

FIG. 1. Relationship between newly mined uranium and worldwide reactor requirements, 1988–1999. ^{a} Estimated.

material have been important secondary supply sources that have in effect displaced comparable amounts of newly produced uranium. Figures 1 and 2 show the importance of secondary supply. Figure 1 shows the relationship between worldwide reactor requirements and newly mined uranium between 1988 and 1998. As noted in Fig. 1, in 1990 newly mined and processed uranium and reactor requirements were approximately in balance. The balance in the market in 1990 was, however, short lived. By 1998 production satisfied only about 60% of requirements; the remaining requirements were filled by secondary supply.

Figure 2, which shows the relationship between Western production and reactor requirements, provides a broader historical perspective between supply and demand relationships from 1965 to 1998. Early forecasts predicting a dominant role for nuclear power were overly optimistic. As a result, in each year prior to 1983 Western production exceeded reactor requirements, leading to a significant inventory buildup. Since about 1983, however, Western reactor requirements have exceeded production; the deficit between requirements and production has been filled by a combination of secondary supply and imports from non-Western countries.

This historical perspective helps us to understand past supply–demand relationships and highlights the recent shortfall between uranium production and reactor requirements. The disparity between production and requirements obviously cannot continue indefinitely. Drawdown of secondary supply is expected to be important in the near term, but at some point this finite supply will be reduced to strategic levels, and newly produced uranium will once again become the dominant supply source. Therefore the objective of this report is to evaluate uranium supply and demand relationships on an annual basis to 2050. The following steps were taken in completing the study:

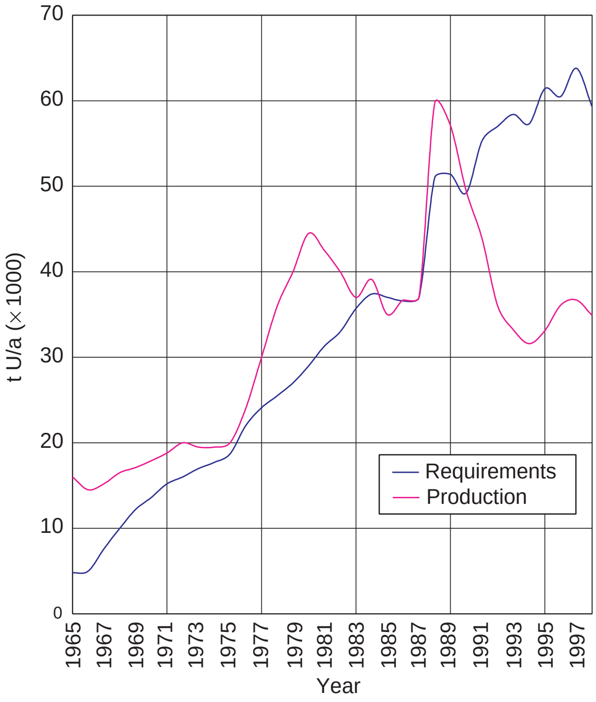

FIG. 2. Relationship between newly mined uranium and reactor requirements in Western countries, 1965–1998.

- —Establish annual worldwide reactor demand expressed in metric tonnes of uranium metal (t U);
- —Identify all sources of uranium potentially available to fill reactor demand, including both primary and secondary supply;
- —Determine the most likely contribution that each source will make toward satisfying annual demand;
- —Establish known uranium resources and evaluate exploration requirements to convert lower confidence resources to higher confidence categories;
- —Assess the adequacy of projected supply and broadly define market prices required to ensure supply availability.

3. METHODOLOGY AND ASSUMPTIONS

Uranium supply–demand projections must realistically account for a broad range of uncertainties. On the demand side of the equation, there is a wide range of opinions as to the future of nuclear power. Even when there is agreement on power projections, there may be considerable disagreement as to the mix of reactor types that will eventually fill those projections. Therefore high and low uranium demand cases have been selected based on a published international consensus study [6]. A middle demand case was selected based on the midrange between the high and low demand cases.

Similar uncertainties also characterize the supply side of the equation. One must first establish the respective roles that primary and secondary supply will likely play in satisfying uranium demand. Secondary supply is a broad term that includes the following subcategories.

- HEU,
- Western and Russian natural and low enriched uranium inventories,
- MOX,
- Reprocessing of spent uranium fuel (RepU),
- Re-enrichment of depleted uranium (tails).

These terms are discussed in detail in Sections 3.2.1 to 3.2.4; in addition, several of the terms are defined in the Glossary. Availability of each of these subcategories of secondary supply becomes a factor when establishing the annual contributions from total secondary supply.

Newly mined and processed uranium or primary supply is divided into four categories to reflect different levels of uncertainty and production economics:

- CIS production,
- National programmes,
- Chinese production,
- Market based production.

Market based production includes newly mined and processed uranium from all sources outside of the other three primary production categories. There is one exception to this distinction, that being CIS resources which become cost competitive in the future and will, therefore, be available to contribute to the market based production category. The distinction between market based production and the other three primary supply categories is made to recognize the fact that production statistics are either not publicly available or are available only from government sources, and, therefore, cannot be independently verified for all but the market based production category. Production capability of the first three primary sources is a key factor in determining the level of output required from market based production to satisfy demand. Supply scenarios based on contributions of both secondary and primary supply were established for three demand cases, starting with the middle demand case followed by the high and low demand cases. In addition, sensitivity analyses were completed to evaluate potential changes in the availability of different supply sources.

3.1. DEMAND

Projecting worldwide reactor uranium requirements (demand) for the next 50 years requires detailed analysis involving a number of uncertainties, and is far from an exact science. The process begins with estimates of total energy demand, followed by projections of the role that nuclear power will play in satisfying that demand. Once nuclear power's role in the total energy mix is established, there still remains the question of how to model the fuel cycle that will satisfy nuclear requirements. Issues such as numbers and types of reactors, load and burnup factors, and reprocessing–recycling strategies are only a few of the variables that must be resolved in modelling the nuclear fuel cycle. Once the fuel cycle is modelled, an estimate of uranium requirements can be established. Uranium requirements have been established assuming that enrichment tails assays will remain constant at 0.3% throughout the study period. However, the effect of lowering tails assays is also considered. The final step in the process is to project how requirements will be met. As previously noted, the ultimate goal of the study was to determine the adequacy of supply to meet reactor uranium requirements, and to characterize the level of confidence that can be placed in the projected supply.

This study benefited from a number of comprehensive analyses and projections of future energy trends and nuclear power's role in the total energy mix — and there is no lack of projections and opinions as to future uranium requirements. Figure 3 underscores the diversity of opinions regarding future uranium requirements and, indirectly, the future of nuclear power to 2020. This figure shows forecasts from five different sources, each of which provides a range of projected annual uranium requirements to 2020. As noted in Fig. 3, with the exception of the USDOE Energy Information Agency

(USEIA) low demand case, there is a relatively narrow range in the projections to about 2006. This general consensus in projected requirements reflects the relative near term inflexibility in global energy programmes. It takes time to change policy; therefore most nuclear programmes that are presently in place are essential to their respective countries' overall power mix, and it will take time to change that mix.

After 2006 the trends begin to diverge, and the divergence increases with time, reflecting the broad range of opinions regarding the future of nuclear power and the increasing flexibility to change nuclear policy over time. Table IV compares requirements in 2020 and the total or cumulative requirements from 2000 to 2020 projected for each of the forecasts shown in Fig. 3. The most negative assessment of nuclear power's future comes from the USEIA low demand case ('USEIA low'), which forecasts a requirement of only 26 550 t U in the year 2020. This total compares with the most optimistic forecast ('IAEA high') of 106 500 t U in 2020. Cumulative requirements between 2000 and 2020 for the high and low demand cases total 1 679 695 and 910 389 t U, respectively. This nearly twofold difference between the high and low demand cases again emphasizes the wide range of opinions regarding the future of nuclear power and the associated long term uranium requirements.

Most published forecasts of energy demand and the role of nuclear power end in 2020. There is, however, one notable exception — Global Energy Perspectives, published jointly by the International Institute for Applied Systems Analysis and the World Energy Council [6]. This study (hereafter referred to as the IIASA/WEC study) provides a comprehensive analysis of energy use to 2050, which is used in this report to provide the basis for the projection of long term uranium requirements. Appendix I provides an overview of six scenarios from the IIASA/WEC study for total energy demand, including the role that nuclear power is expected to play based

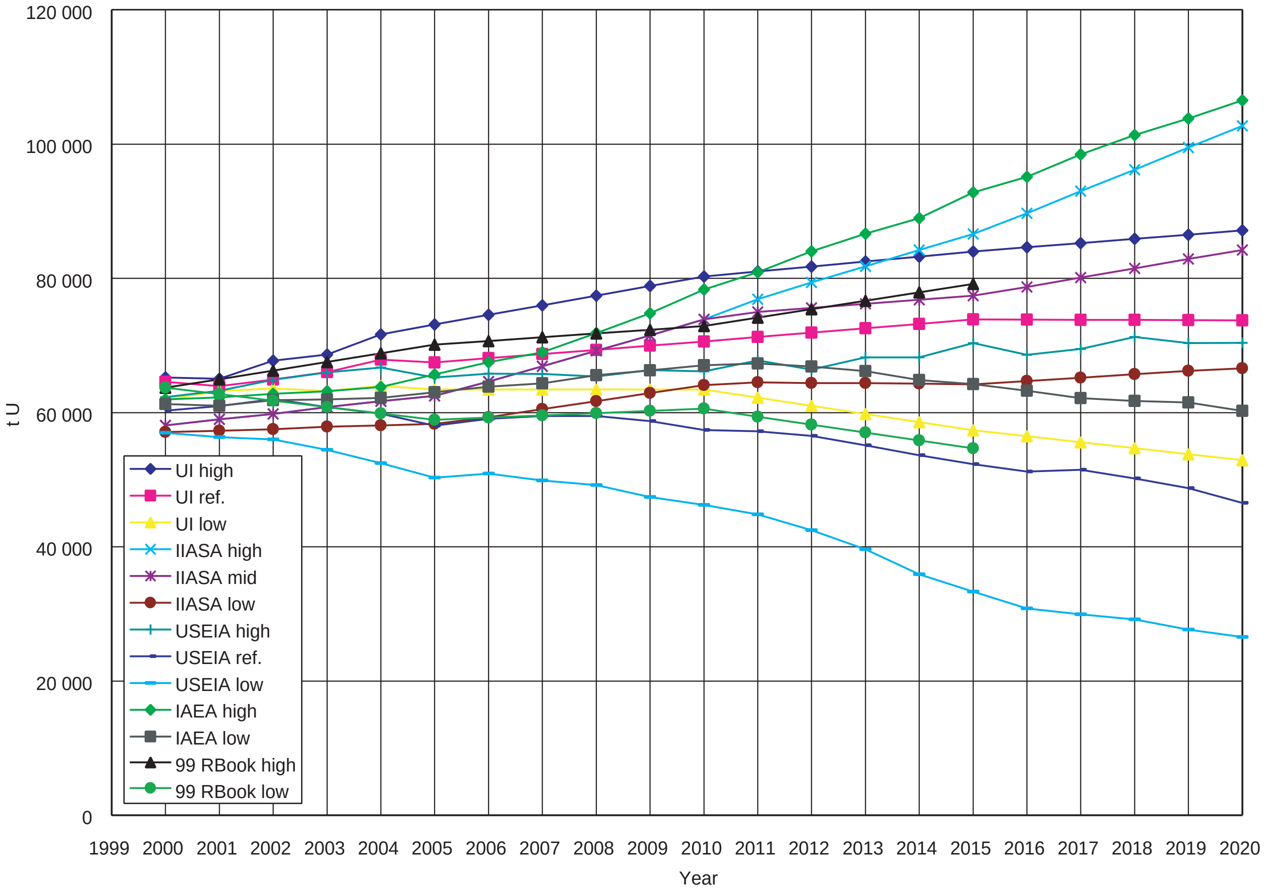

FIG. 3. Summary of previously published projections of annual uranium requirements to 2020.

on a diverse set of assumptions. The six scenarios discussed in the IIASA/WEC study are shown in Fig. 4.

The IIASA/WEC study projects nuclear generation capacity based on a broad range of assumptions. The IAEA [1] selected three of the IIASA/WEC scenarios and converted electricity generation capacity to reactor uranium requirements for these three scenarios. The IAEA conversions, which were used in this report to forecast uranium requirements between 2020 and 2050, utilized the IIASA/WEC scenarios summarized in Table V.

The data on which the IIASA/WEC projections were based were compiled for publication in 1995 [2]. We now have five additional years of established trends in the use of nuclear power that were not available to the IIASA/WEC analysts. Therefore, while the IIASA/WEC projections were been adopted for the period from 2020 to 2050, more up to date projections were utilized for the period from 2000 to 2020. These near term projections, which were completed by an IAEA working committee [9], are based on a country by country analysis of actual nuclear power programmes that are currently being implemented or planned. Figure 5 shows the high and low demand projections developed by the IAEA, with minor adjustment to ensure a common starting point in

TABLE IV. URANIUM REQUIREMENTS AS SHOWN IN FIG. 3

Data source	Fig. 3 designation	Annual requirements, 2020 (t U)	Total requirements, 2000–2020 (t U)
Uranium Institute high [7]	UI high	87 135	1 640 430
Uranium Institute reference [7]	UI ref.	73 738	1 473 316
Uranium Institute low [7]	UI low	52 904	1 268 942
IIASA high [1, 6 and this study]	IIASA high	102 700	1 598 000
IIASA mid [1, 6 and this study]	IIASA mid	84 200	1 496 400
IIASA low [1, 6 and this study]	IIASA low	66 600	1 304 900
USEIA high [8]	USEIA high	70 373	1 408 734
USEIA reference [8]	USEIA ref.	46 518	1 179 069
USEIA low [8]	USEIA low	26 549	910 389
IAEA high [9]	IAEA high	106 501	1 679 695
IAEA low [9]	IAEA low	60 233	1 336 690
OECD/NEA–IAEA 1999 Red Book high [3]	99 RBook high	[a]	[a]
OECD/NEA–IAEA 1999 Red Book low [3]	99 RBook low	[a]	[a]

[a] Data only available to 2015.

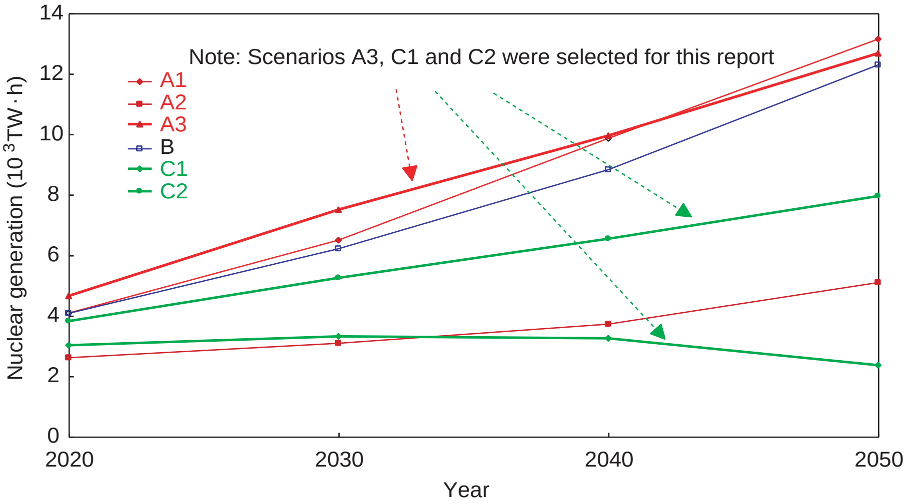

FIG. 4. IIASA/WEC scenarios to 2050. Source: Ref. [2].

TABLE V. SUMMARY OF IIASA/WEC DEMAND SCENARIOS

Terminology for this report	IIASA/WEC scenario	Basic characteristics/assumptions
High demand case	A3	Corresponds to high economic growth, limited impact of environmental concerns on energy policies and significant development of biomass and nuclear power. Note uranium requirements in the IIASA/WEC A1, A3 and B scenarios are similar to the A3 scenario and fall in the high demand range.
Middle demand case	C2	Corresponds to medium economic growth, ecologically driven energy policies and sustained development of renewable energy sources and nuclear power worldwide. The C2 scenario represents the midrange of the IIASA/WEC long term forecast. It is, however, not necessarily intended to represent the most likely demand scenario.
Low demand case	C1	Corresponds to medium economic growth, ecologically driven energy policies and phase-out of nuclear power worldwide by 2100.

FIG. 5. IAEA projections of annual uranium requirements to 2020.

2000. Each country’s nuclear power programmes and plans were reviewed on a ‘best case–worst case’ basis. The high demand estimate assumes that all plans will be implemented, while the low demand estimate factors in the potential impact of closure of all reactors at the earliest possible date and cancellation or deferral of all new reactors.

Since there is very little flexibility to change nuclear programmes in the near term, there is minimal variation in the high and low demand projections until about 2006. From that point on, however, the curves on Fig. 5 show steady divergence as the potential for change increases. By 2020 the high and low demand estimates show requirements of 106 500 and 60 233 t U, respectively. As shown in Table IV, cumulative requirements to 2020 for the IAEA high and low demand cases total 1 679 695 and 1 336 690 t U, respectively.

In summary, two data sources were used to project uranium requirements between 2000 and 2050: IAEA estimates were used for the period from 2000 to 2020

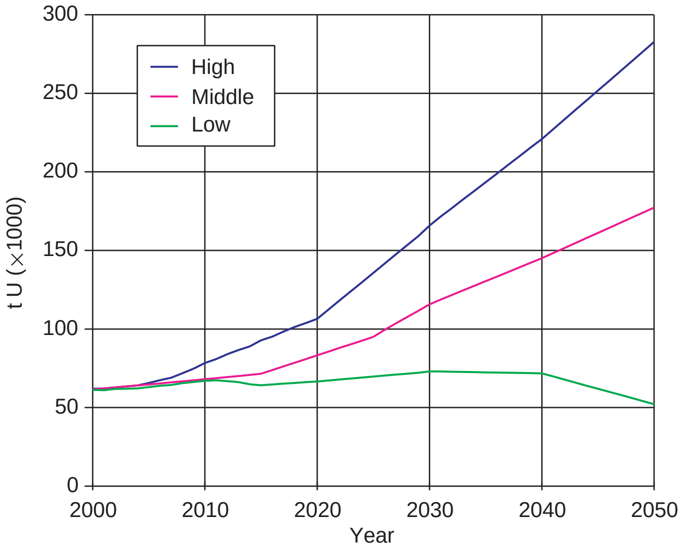

FIG. 6. Projections of annual uranium requirements, 2000 to 2050, for this study.

TABLE VI. SUMMARY OF URANIUM REQUIREMENTS FROM FIG. 6

Uranium demand case	Requirements in 2050 (t U)	Cumulative requirements, 2000 to 2050 (t U)
Low	52 000	3 390 000
Middle	177 000	5 394 100
High	283 000	7 577 300

and IIASA/WEC estimates from 2020 to 2050. Since the two data sources did not exactly match in 2020, minor adjustments were made in the data on either side of the 2020 join to ensure a smooth transition. Beyond 2023 requirements based on IIASA/WEC scenarios A3 and C1 (Table V) were used for the high and low demand cases, respectively. Similarly, IIASA/WEC scenario C2 served as the basis for the middle demand case. Figure 6 shows the result of merging the two data sources to present the projected high, middle and low demand requirements from 2000 to 2050. The three cases summarized in Fig. 6 are the foundation for the remainder of this report, as they define the total demand that must be satisfied under a broad range of assumptions/conditions. (With the exception of the updates discussed above, these projections are the same as in Ref. [1].) The task ahead is to forecast how that demand will be filled. Table VI quantifies this task.

3.2. SUPPLY

Newly mined and processed uranium, or primary supply, accounted for only about 60% of reactor demand in 1998. In the future, however, as secondary supply is drawn down to strategic levels, or in some cases entirely depleted, primary supply is expected increasingly to become the dominant supply source. During the early years of the study period supply sources expected to be available to satisfy reactor uranium demand include:

— Secondary supply (see Sections 3.2.1 to 3.2.4 for discussions of the secondary supply sources)
  - HEU,
  - The Western natural and low enriched uranium inventory (the commercial inventory),
  - The Russian natural and low enriched uranium inventory,

  - MOX (and other separated plutonium uses),
  - RepU,
  - Re-enrichment of depleted uranium (tails).
- Primary supply (see Section 3.4.5 for a review of primary supply sources)
  - CIS production,
  - National programmes,
  - Chinese production,
  - Market based production.

Estimates were first made of the annual availability of secondary supply from each of the six sources. Secondary supply was then subtracted from reactor demand to determine primary supply requirements. Projections were next made for the annual output from the CIS, Chinese and national programmes, and the sum of these projections was subtracted from total primary supply requirements to establish required output from the market based production category. Table VII summarizes the annual contributions that each supply category is projected to make towards filling demand for the middle demand case. These same relationships are shown graphically in Fig. 7. Below is a description of the assumptions used to establish the annual availability of each component of total supply.

3.2.1. HEU from surplus defence inventories

3.2.1.1. Background

Over half of historical uranium production has gone into producing fissile materials for government national defence programmes. For national defence purposes uranium has been used in manufacturing weapons and in fuelling reactors for naval propulsion and research. An arms race between the USA and the former USSR resulted in the accumulation of large stockpiles of fissile materials, especially HEU and plutonium. As a result of arms reduction treaties between the USA and the USSR and subsequently between the USA and the Russian Federation, large quantities of HEU and plutonium were declared as surplus for national defence purposes.

The two governments have recognized that significant financial and national security benefits would accrue by converting these surplus inventories to commercial reactor fuel for generating electricity. The Russian Government will gain billions of US dollars from the commercialization of HEU taken from dismantled nuclear weapons. From a national security perspective, the conversion of surplus defence inventories to civil reactor fuel reduces the likelihood that stocks of weapons usable material will be diverted for unauthorized use. Similarly, participants in the commercial market place recognize the importance of surplus defence inventories. The annual quantity of uranium supplied from current HEU commercialization programmes is anticipated to exceed output from the largest uranium mine. Thus an unexpected interruption of supply from surplus HEU inventories would have a major impact on the market place. With additional reductions in nuclear weapons by the Russian Federation and the USA, HEU could remain a significant source of uranium at least until 2030.

This section focuses on HEU from US and Russian surplus defence inventories as an important source of uranium supply. While HEU was also produced in China, France and the United Kingdom, the USA and the Russian Federation are estimated to hold over 95% of HEU stocks dedicated to nuclear weapons [10]. Plutonium, the other principal fissile material declared as surplus to national defence purposes, is treated in a subsequent chapter on MOX fuel. This discussion is divided into two sections: (1) the status of current and firm planned US and Russian HEU commercialization programmes; and (2) a discussion of the key availability and market penetration factors concerning HEU. In analysing the impact of HEU inventories on uranium supply to 2050, two cases are presented for the projected introduction of uranium derived from HEU into the market.

3.2.1.2. Status of the Russian HEU commercialization programme

The agreement between the Government of the USA and the Government of the Russian Federation Concerning the Disposition of Highly Enriched Uranium Extracted from Nuclear Weapons (Russian HEU agreement), signed in February 1993, established the world's first programme for converting weapons grade nuclear materials to civil reactor fuel. The Russian HEU agreement, popularly referred to as megatons to megawatts, stipulates that 500 t of Russian HEU derived from nuclear warheads would be converted to LEU over a 20 year period. The USA agreed to purchase 15 260 t LEU valued at US $12 000 million. HEU feed stock and slightly enriched uranium blend stock contained in the LEU is equivalent to 153 000 t of natural uranium.[1] In January 1994 an agreement for implementing the Russian HEU agreement was concluded between USEC and Techsnabexport (Tenex), the respective executive agents for the US and Russian Governments. The first LEU derived from HEU taken from dismantled Russian nuclear warheads was delivered to a US electric power

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[1] Assumes an LEU product assay of 4.4% ^{235}U derived from HEU feed stock containing 90% ^{235}U and a slightly enriched uranium blend stock containing 1.5% ^{235}U.

TABLE VII. SUMMARY OF URANIUM SUPPLY–DEMAND RELATIONSHIPS FROM 2000 TO 2050, MIDDLE DEMAND CASE (t U)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Demand	61 600	62 200	62 800	63 500	64 100	64 800	65 400	66 100	66 700	67 400	68 100	68 700	69 400	70 100	70 800	71 500	73 900
HEU	5 400	6 200	8 000	9 300	10 700	10 600	10 700	11 100	10 900	12 100	12 400	12 400	12 400	11 900	11 900	11 900	11 900
Supplier inventory	5 550	5 294	5 289	6 447	7 876	8 210	6 573	1 105	–2 064	–1 364	1 867	2 822	1 370	–1 869	–2 327	–1 373	160
Russian inventory	7 100	6 300	4 500	3 700	2 900	3 000	2 900	2 500	2 100	900	900	900	900	900	0	0	0
MOX	1 900	1 900	2 300	2 400	2 500	2 500	2 600	2 800	2 800	3 000	3 000	3 200	3 400	3 600	3 600	3 600	3 600
RepU	1 400	1 500	1 500	1 500	1 500	1 500	1 700	1 700	1 700	2 000	2 000	2 000	2 000	2 000	2 000	2 000	2 500
Tails reprocessing	4 500	4 500	5 200	4 850	4 250	3 650	3 300	3 000	2 800	2 650	2 350	2 350					
CIS production	6 300	7 300	7 500	8 500	9 300	10 400	10 500	10 600	10 800	11 000	11 200	11 200	11 200	11 200	11 200	11 200	11 200
National programmes	950	765	665	565	575	605	625	625	625	625	625	625	625	625	625	610	610
China	380	380	380	760	760	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380
Market based production	28 120	28 061	27 466	25 478	23 739	22 955	25 122	31 290	35 659	35 109	32 378	31 823	36 125	40 364	42 422	42 183	42 550

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Demand	76 200	78 600	80 900	83 300	86 000	88 000	90 000	93 000	95 000	99 000	104 000	108 000	112 000	116 000	119 000	122 000	125 000
HEU	11 900	11 900	11 900	11 900	11 900	9 900	300	0	0	0	0	0	0	0	0	0	0
Supplier inventory	–245	–1 804	–2 641	–2 092	–1 225	–1 222	–2 666	–8 700	–6 226	317	1 699	–2 413	–5 411	–4 668	–2 172	–337	–777
Russian inventory	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MOX	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600
RepU	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500
Tails reprocessing																	
CIS production	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200
National programmes	610	610	610	625	625	625	625	625	625	630	630	630	630	630	630	630	630
China	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380
Market based production	45 225	49 214	52 351	54 187	56 020	60 017	73 061	82 395	81 921	79 373	82 991	91 103	98 101	101 358	101 862	103 027	106 467

	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Demand	128 000	130 000	133 000	136 000	139 000	142 000	145 000	148 000	152 000	155 000	158 000	161 000	164 000	168 000	171 000	174 000	177 000
HEU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Supplier inventory	–2 294	–3 013	–1 814	–1 194	–1 588	–2 264	–2 452	–2 126	–1 784	–2 440	–2 438	–2 000	–1 709	–1 807	–2 727	–2 615	–1 926
Russian inventory	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MOX	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600	3 600
RepU	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500	2 500
Tails reprocessing																	
CIS production	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200	11 200
National programmes	630	630	640	640	640	640	640	640	640	640	640	640	640	650	650	650	650
China	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380	1 380
Market based production	110 984	113 703	115 494	117 874	121 268	124 944	128 132	130 806	134 464	138 120	141 118	143 680	146 389	150 477	154 397	157 285	159 596

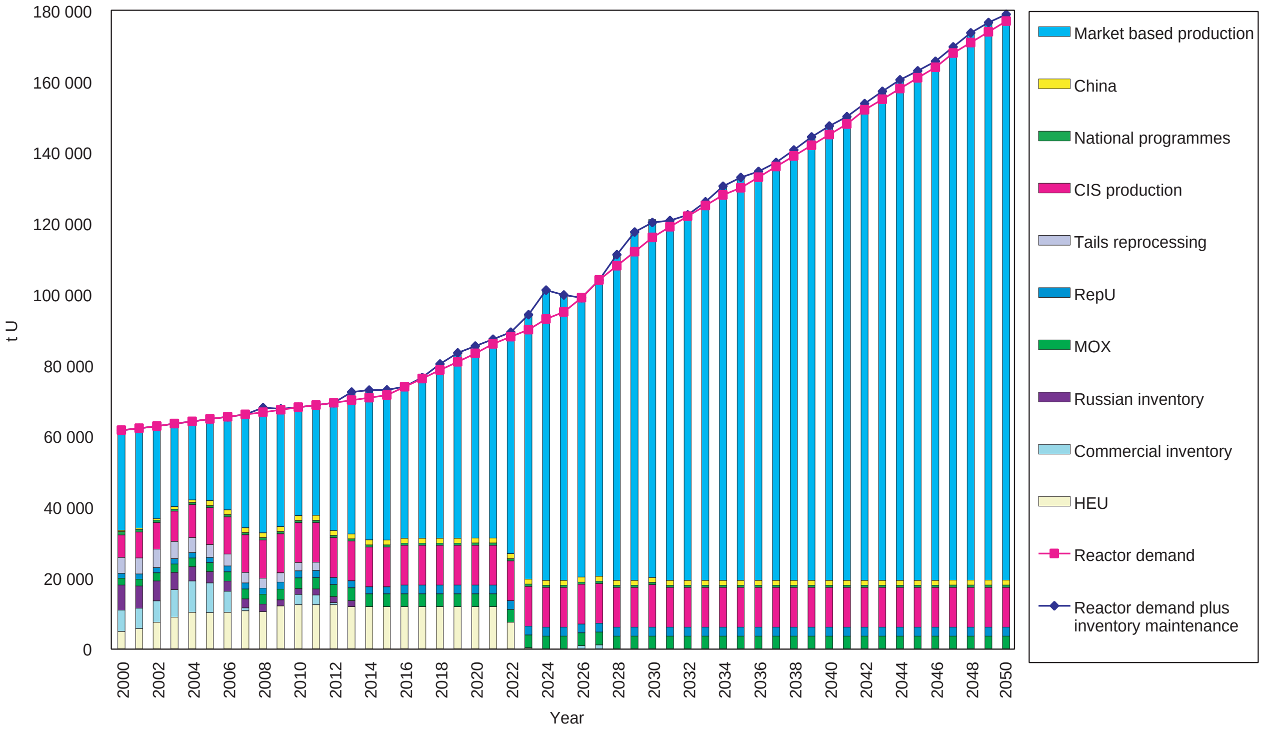

FIG. 7. Uranium supply–demand relationship, 2000 to 2050 — middle demand case.

utility in November 1995. An amendment to the implementing agreement, signed in November 1996, set the quantities and pricing for annual deliveries of LEU from 1997 to 2001.

Since 1994 annual deliveries of Russian HEU derived LEU have not been consistent with the schedules set forth by the implementing agreement. For example, the final LEU delivery scheduled for 1998 was received by USEC in July 1999. A long standing issue affecting the delivery schedule was the timing of payments to the Russian Federation for the natural uranium feed component of the LEU derived from Russian HEU. Actual quantities of the natural feed component are acquired by substituting the LEU received from the Russian Federation for the equivalent natural uranium and the cost of enrichment services that would have been required if USEC had provided the enrichment services. The customer supplied natural uranium feed displaced by the Russian LEU is subsequently labelled ‘Russian HEU feed’. Initially, USEC was required to pay the Russian Federation only for the enrichment component of the LEU at the time of delivery. It would pay the Russian Federation after the HEU feed was either sold in the market or used for internal operations. Later, the Russian Government required payment for the full value of the LEU at the time of delivery. The USEC Privatization Act, enacted in April 1996, provided a legal remedy whereby USEC would be made responsible for paying only for the enrichment services component of the LEU. For deliveries of LEU derived from Russian HEU in 1997 and later years, the Russian Federation would take title to the HEU feed so that it could market the uranium on its own.

In March 1999 a commercial agreement was reached for marketing 138 000 t U equivalent of the Russian HEU feed from 1999 to 2013. The blending down of Russian HEU is expected to yield the equivalent of 9100 t U/a, of which three Western suppliers hold an option to purchase up to 6700 t U/a from the Russian Federation[2]. The remaining 2500 t U/a is retained by the Russian Federation for sales primarily in the USA. In the event that the three Western suppliers or the Russian Federation do not utilize their annual allocations, the unused uranium is to be placed in a monitored inventory. The extent to which the three Western suppliers and Russia are permitted to use their annual allocations or draw down the monitored inventory is specified by the commercial agreement and subject to applicable laws. Government to government

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[2] The three Western suppliers are Camero Corp., Cogéma and NUKEM Inc.

agreements were reached to permit the transport of the HEU feed from the USA to the Russian Federation.

To support the Russian HEU agreement, the US Government acquired Russian HEU feed in 1996 and 1999. From these acquisitions the USDOE currently holds 14 700 t U equivalent in its inventory. The first acquisition was made in December 1996 for the HEU feed stockpiled in 1995 and 1996. USEC purchased this uranium from the Russian Federation, but transferred this material to the USDOE pursuant to the USEC Privatization Act. The USDOE sold a portion of this stockpile to the Russian Federation in December 1996. The remaining 3700 t U is likely to be sold in 2001 for delivery to US utilities in 2002 and subsequent years as governed by the USEC Privatization Act. To facilitate the signing of the March 1999 commercial agreement, the US Government paid the Russian Federation US $325 million for 11 000 t of HEU feed that was stockpiled in 1997 and 1998. The US Government also agreed to delay selling this material for 10 years.

3.2.1.3. Status of the US HEU commercialization programme

The Energy Policy Act of 1992 (EPACT) directed the Secretary of Energy to identify all uranium owned by the Government of the USA, including HEU, for conversion to commercial use. The Non-proliferation and Export Control Policy, announced by the President in September 1993, commits the USA to seek elimination, where possible, of inventories of weapons usable fissile materials. Implementing this policy has been subject to a comprehensive regulatory process. For example, the National Environmental Policy Act of 1969 (NEPA) ensures that potential impacts on the environment will be considered for each US Government action. The USDOE assessments under NEPA also have taken into account costs, socioeconomic impacts and proliferation concerns. As a consequence, the start of commercializing US HEU has lagged that of Russian HEU.

In April 1995 the USDOE announced its intent to prepare an environmental impact statement on the disposition of US HEU. A nominal 200 t were considered to include HEU that has been declared as surplus or may be declared as surplus should future arms reduction treaties be enacted. The Secretary of Energy later identified 174 t of HEU as surplus. In contrast to material under the Russian HEU agreement, much of the surplus US HEU contains less than 90% ^{235}U [11]. In August 1996 the USDOE decided to implement a disposition programme whereby surplus HEU would be blended down to LEU, assaying between 4 and 5% ^{235}U for commercial use over a 20 year period. LEU that does not meet commercial specifications will be disposed of as low level waste after further blending down to 0.9% ^{235}U. Unlike conversion facilities in the Russian Federation, facilities in the USA do not have the capability to convert HEU metal or oxide into UF_6. Instead, the US HEU will be converted into uranyl nitrate hexahydrate (UNH). The blended UNH product will be delivered to fuel fabricators, where it will then be converted to uranium oxide powder, which can be pelletized for use in fuel rods.

As of 31 December 1999 ongoing and planned USDOE programmes described below have indicated 145 t of surplus US HEU for commercialization (compared with 174 t previously declared as surplus). Ongoing programmes involve 63 t in transfers to USEC and 37 t to be blended down to LEU for use in reactors of the Tennessee Valley Authority (TVA). In addition to ongoing programmes, the USDOE has plans in place to commercialize 45 t of HEU. The LEU derived from blending down 145 t of HEU from ongoing and planned programmes is equivalent to 21 400 t U of newly produced uranium.[3] The remaining 29 t of US HEU declared as surplus is likely to be disposed of as waste unless technological advances permit future utilization of off-specification fuels.

Transfers from the USDOE to USEC were made at no cost to USEC in fulfilment of certain USDOE statutory obligations. USEC sells the LEU derived from HEU in the commercial market. USEC already has completed the blending down of 14 t of HEU delivered under a 1994 Memorandum of Agreement between the USDOE and USEC. The blending down of an additional 48 t, the quantity of the transfer authorized by the USEC Privatization Act, began in late 1999. The blending activities are expected to continue to 2005. However, the USEC Privatization Act limits deliveries of transferred material to commercial end users in the USA to no more than about 1200 t/a.[4] Thus it is likely that deliveries of LEU derived from the 48 t of HEU will take place over much of the next decade.

The USDOE and the TVA signed a letter of intent in April 1999 whereby the TVA would utilize LEU derived from blending down US surplus HEU. This LEU is

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[3] Assumes LEU product assay of 4.95% ^{235}U derived from HEU feed stock containing a variety of assays. It is anticipated that slightly enriched uranium blend stock from USDOE inventories would be used to blend down a portion of the HEU. The remaining blend stock would come from natural uranium purchased on the market. Only the quantity of the natural uranium equivalent to the HEU feed stock and the slightly enriched uranium feed stock from the USDOE inventory are considered to displace newly produced uranium.

[4] Includes 7000 t of natural UF_6 transferred from the USDOE to USEC pursuant to the USEC Privatization Act.

considered ‘off-specification’ because it contains ^{236}U in excess of the specification established for commercial nuclear fuel. In May 1999 four lead test assemblies of the off-specification LEU were loaded into unit 2 of the Sequoyah Nuclear Power Plant. The TVA plans to fuel its nuclear reactors with the off-specification LEU derived from US HEU by 2003.

By the middle of the next decade the USDOE plans to commercialize 10 t of HEU metal currently under IAEA safeguards. The commercialization of an additional 35 t of HEU is subject to the agreement by the USA whereby the commercialization of additional USDOE inventories is delayed until 2009. This action was made to facilitate the commercial agreement concerning Russian HEU feed.

3.2.1.4. Projected HEU availability and market penetration factors

Achieving the goals for converting Russian and US surplus inventories of HEU into commercial fuel for generating electricity is dependent on timely implementation by the governments, trade and other national policies, and the dynamics of the commercial market place. The potential availability of additional quantities of HEU is dependent on the quantity and quality of remaining HEU inventories, national security requirements, budgetary demands, arms reduction initiatives and other international diplomacy and nuclear weapons non-proliferation objectives.

The Russian HEU agreement is a combination of complex government to government and commercial agreements that have evolved since the agreement was signed in 1993. Its implementation was made possible through co-operation between the Russian Federation and the USA, the two nuclear superpowers. Such co-operation serves the vital national interests of the two countries. The Russian HEU agreement is further complicated by the realities of a commercial nuclear fuel market. As described above, separate contracts have been negotiated for both the enrichment services and natural uranium feed components of the LEU derived from the Russian HEU. Because Russian law links deliveries with receipt of the full value of the LEU product, difficulties in executing the commercial contracts could cause a delay in uranium reaching the market place. However, for this analysis, it is assumed that the Russian and US Governments would intercede, if necessary, to ensure that no disruptions take place in the amount of uranium made available to the market. Nevertheless, uncertainties tied to political changes or the renegotiation of commercial contracts are likely to cause short term price volatility.

Implementation of the US HEU commercialization programme is strongly dependent on budgetary considerations and support of government policy. The availability of appropriated monies or the need to finance programmes internally may influence whether uranium sales are delayed or accelerated. In the interest of US Government policy, certain USDOE inventories were delayed for 10 years to support the Russian HEU agreement.

3.2.1.5. Potential for additional HEU supply

Limited availability of information makes it difficult to assess the potential supply of uranium from HEU inventories that have not yet been declared as surplus by the Russian or US Governments. Critical information concerning the quantity and quality of inventories and the extent of their requirements is highly sensitive to national security. Estimates of HEU inventories, published by Albright et al. [10] and Bukharin [12], serve as the basis for the analysis presented in this study. Estimates of national security requirements are speculative.

For this analysis the Russian Federation and the USA are assumed to implement bilateral reductions in nuclear weapons that would permit additional quantities of HEU to be commercialized. The implementation of the START II and START III treaties between the Russian Federation and the USA would reduce the number of strategic nuclear warheads that each country is permitted to maintain.[5] Each country also maintains other nuclear warheads not constrained by the START treaties. Should the number of nuclear warheads outside the scope of the START treaties eventually be reduced, the potential supply of HEU could be increased as national security requirements are further diminished.

The US HEU inventory, estimated at 749 t as of the end of 1993, is smaller than the Russian inventory. For this analysis, 200 t of US HEU would be commercialized from existing and potential US programmes. The equivalent uranium contained in 200 t of HEU is assumed to be 33 000 t of natural uranium.[6]

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[5] Implementation by the Russian Federation and the USA of both the START II and START III treaties would limit the number of strategic nuclear warheads held by each country to between 2000 and 2500 warheads. For reference, it is estimated that each country held over 10 000 strategic nuclear warheads as of 1990.

[6] No information is available for US HEU except for the 174 t identified to date. An average assay representing the midrange of values reported for HEU already identified is assumed for the potential HEU supply. The US Government is assumed to purchase stock from the market.

There is every reason to believe that the nuclear superpowers will continue disarmament dialogue that will ultimately lead to the availability of additional HEU for use in civilian reactors. In 1999 concerns regarding nuclear security prompted a task force organized by the Centre for Strategic and International Studies, a prestigious public research institute in Washington, DC, to recommend that the USA purchase additional Russian HEU. This and similar international pressure for nuclear disarmament is likely to ensure that more HEU will become available for eventual commercialization. To recognize this likelihood, two HEU scenarios are considered in this study (Fig. 8). The base case, which is used for the middle demand case in Fig. 8 and Table VII, includes 250 t of additional Russian HEU and 55 t of additional US HEU (i.e. in addition to the original 500 t of Russian HEU and 145 t of surplus US HEU). This additional material extends HEU commercialization to 2023, or 10 years longer than the original 500 t of Russian HEU would have provided for. The high HEU case provides for an additional 250 t of Russian and 200 t of US HEU, which will extend HEU commercialization to 2040. The potential impact of an increase or decrease in the availability of HEU is discussed in Section 5.1.5.1.

3.2.1.6. Trade restrictions and other national policies

The US Government considers Russian HEU feed to be Russian origin uranium. It has enacted legally binding quotas defining the extent by which Russian origin uranium can be sold to US utilities (Table VIII). The suspension agreement between the US and Russian Governments, amended in 1994, provides an annual quota whereby Russian origin uranium can be sold when matched with similar quantities of uranium produced in the USA. The suspension agreement runs to 2003 and is currently undergoing a review by the US International Trade Commission to determine whether it should be extended. A quota mandated by the USEC Privatization Act specifically addresses Russian HEU feed. The quota for Russian HEU feed is 1500 t U equivalent in 1999, 2300 t U in 2000, 3100 t in 2001 and rising incrementally to 7700 t in 2009 and subsequent years.

The availability of Russian HEU feed initially was also likely to be limited for end use in the European Union (EU). The Euratom Supply Agency (ESA) has enacted a policy designed to ensure a security of supply for its EU member states. To meet this objective, the ESA has sought to limit imports from the CIS, including the Russian Federation, to 25% of purchasing contracts. This policy is considered flexible in that it does not apply strict quotas by law. However, EU imports from the CIS in recent years have exceeded 25% of purchasing contracts [13]. The ESA is expected to continue carefully to monitor imports from the CIS. However, the ESA has announced that Russian HEU feed could be sold to EU end users without restrictions, subject to careful monitoring. This will provide a greater diversity in supply than if EU utilities purchased the uranium directly from the Russian Federation.

3.2.2. Inventory

Two broad categories of natural and low enriched uranium inventory are considered in this study: a commercial inventory and the inventory held by the Russian Federation. There is a great deal of subjectivity associated with estimates of inventory drawdown. The different entities that hold an inventory have varying policies as to what constitutes a strategic inventory compared to a discretionary inventory that can or should be sold, traded or otherwise disposed of. While some of these policies are a matter of public record, more typically they are protected by commercial confidentiality or are imprecise due to their reliance upon market conditions. Therefore analyst judgement and associated subjectivity characterize drawdown projections for the commercial inventory. In addition, there are neither firm estimates of the Russian Federation’s total non-military inventory, nor how much and at what rate that inventory is available for civilian use. According to official Russian statements, however, priority for the Russian Federation’s non-military inventory will go towards satisfying its internal reactor requirements as well as supply commitments to Russian built reactors in other CIS and eastern European countries.

In this report we have elected to follow the convention used by the Uranium Institute [7] whereby uranium in an inventory is in a form representative of the nuclear fuel cycle or stages involved in commercial contracts between suppliers and utilities. Material that would require considerable additional processing to make it suitable for reactor fuel is categorized as stockpiles. An inventory typically is in the form of natural uranium or low enriched uranium; it does not include enrichment tails, MOX or RepU.

3.2.2.1. Western natural and low enriched natural uranium inventory (commercial inventory)

A uranium inventory is held by a variety of entities for equally varied reasons, including minimizing supply disruptions (utilities), guaranteeing delivery schedules (producers), government policy and flexibility to participate in market fluctuations (producers and traders). The commercial inventory includes that held by the entities

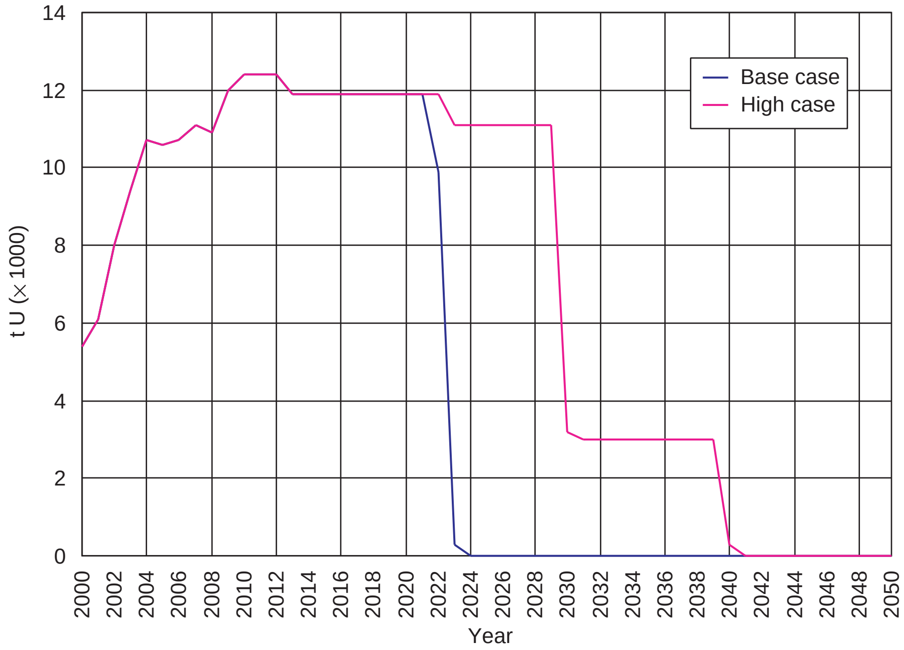

FIG. 8. Projection of uranium derived from HEU, 2000 to 2050.

TABLE VIII. US RESTRICTIONS ON SELLING THE NATURAL URANIUM FEED COMPONENT OF LEU PRODUCED FROM BLENDING DOWN RUSSIAN HEU, AFTER 1 JANUARY 1999

Delivery year	HEU (t)	Feed contained in LEU produced from HEU (t U equivalent)	USEC Privatization Act direct quota to US end users (t U equivalent)	Russian matching schedule (t U equivalent)
1999	30	9100	1500	1600
2000	30	9100	2300	1600
2001	30	9100	3100	1600
2002	30	9100	3800	1900
2003	30	9100	4600	1700
2004	30	9100	5400	—
2005	30	9100	6200	—
2006	30	9100	5500	—
2007	30	9100	6900	—
2008	30	9100	7300	—
2009 and beyond	30	9100	7700	—

given in Table IX along with their estimated inventory totals as at year end 1997 [7].

The producer inventory level is tied to sales commitments, which in turn indirectly control production requirements (demand). Accordingly, drawdown of the inventory fluctuates with future production requirements. In order to reflect this relationship, it has been assumed that producers will in the aggregate maintain annual inventory levels equal to two thirds of the previous year's market based production requirement.

Figure 9 shows the projected schedule for commercial inventory drawdown and/or requirements between 2000 and 2050. Negative totals indicate that the inventory is less than the required level (i.e. two thirds of the previous year's requirement). Therefore, in years with negative values, instead of a net inventory drawdown, market based production is assumed to be increased to return the inventory to desired levels. In the early years of the study, inventory drawdown by utilities and other non-producer suppliers helps offset the inventory requirements

TABLE IX. COMMERCIAL INVENTORY AS AT YEAR END 1997

	1000 t U
Utilities	113.0
Uranium producers	20.0
United States Enrichment Corporation	30.0[a]
United States Department of Energy	5.5[b]

[a] Approximately 5000 t U of this material has US HEU origin; down blending of this material will take several years.

[b] The USDOE holds 5500 t of natural uranium (as UF_6) that had been declared as surplus for defence purposes. In support of the commercial marketing agreement signed in 1999 between Western suppliers and the Russian Federation Government for the natural uranium component of LEU derived from Russian HEU, the US Government agreed to defer delivery of this commercial grade inventory to commercial end users for 10 years.

of the producers, and the total commercial inventory makes a positive contribution to secondary supply (Table VII and Fig. 7). However, as demand increases and as inventories from these three sources are drawn down to strategic levels, they are no longer sufficient to offset the assumption that producers will maintain two thirds of the previous year's production requirement, hence the negative numbers.

As shown in Fig. 9, in 2006 the producers' inventory levels no longer meet the required levels, but contributions from the other three inventory sources keep the total commercial inventory category in a positive range. By 2016, however, as demand continues to increase and contributions from other sources stabilize or decline, negative inventory totals persist throughout most of the remainder of the study. As previously noted, negative inventory totals are accompanied by a corresponding increase in market based production requirements.

3.2.2.2. *Russian natural and low enriched uranium inventory*

Uranium production in the former Soviet Union (FSU) and eastern Europe far exceeded military and civilian requirements, resulting in the buildup of a large stockpile of nuclear material. The total extent and availability of this stockpiled material for civilian use is uncertain. What is known, however, is that only a limited amount of the material conforms to international specifications and is thus suitable for immediate use in reactors. The remainder of the material would require considerable additional reprocessing to make it suitable for reactor fuel, and in fact some would probably never be commercially useful. The Uranium Institute [7] estimates that the Russian inventory at the end of 1997 totalled approximately 58 000 t U. The Russian Federation's inventory is thought to be largely LEU.

The starting point for projecting the drawdown schedule for the Russian inventory relies on an estimate by the Uranium Institute [7] that material entering the Western commercial market from the Russian Federation totalled 12 000 t U in 1998, including uranium from Russian HEU and its inventory. In this study, future Russian contribution to the market from HEU and its inventory was held constant at 12 000 t U/a through the primary term of the HEU agreement. Uranium projected

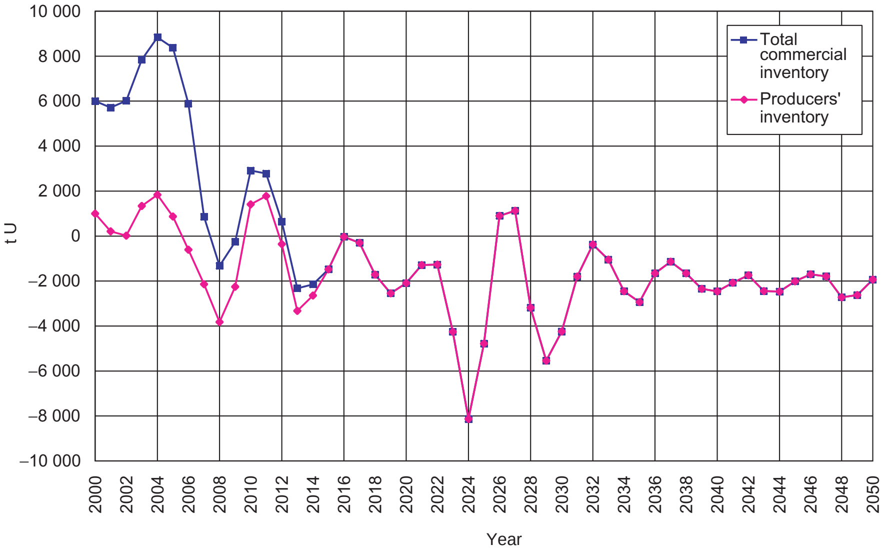

FIG. 9. Projection of annual commercial inventory drawdown/requirements to 2050 — middle demand case.

to be derived from HEU was subtracted from 12 000 to determine the contribution from the Russian inventory. Figure 10 shows the projected inventory drawdown schedule for the Russian inventory. As the contribution from HEU increases, inventory drawdown steadily decreases, finally ending in 2014, after a cumulative contribution of 47 000 t U.

3.2.3. MOX and RepU

Spent nuclear fuel can be reprocessed to separate the remaining uranium and plutonium formed during irradiation from waste products. Uranium and plutonium recovered during reprocessing can be recycled and used in new fuel assemblies, and therefore they become a secondary supply source and can effectively displace equivalent amounts of primary supply. Six countries currently have established reprocessing–recycling programmes: Belgium, France, Germany, Japan, Switzerland and the United Kingdom. Sweden is also considering recycling its separated plutonium. Three Western countries currently have reprocessing facilities: Belgium, France and the United Kingdom. The Russian Federation also has reprocessing facilities, but their current operational status is uncertain. It has also indicated its intent to recycle uranium and plutonium in the future, although the schedule for such plans is indefinite.

Plutonium from reprocessing is used to manufacture fuels that contain a mixture of plutonium and uranium dioxides, hence the name mixed oxide fuel. Plutonium replaces ^{235}U as the major source of energy in MOX fuels, which can be loaded in most reactors in place of conventional enriched uranium fuel. Figure 11 shows the projected uranium equivalent that would be displaced by the use of MOX fuels. Two cases are shown in Fig. 11 — the base case which projects MOX use to 2050 and the ‘stop MOX’ case which assumes that MOX use will terminate in 2005–2006. The base case, which is used in the middle demand scenario (Table VII), assumes steady growth of MOX fuel use to 2012, after which usage stabilizes to 2050 at 3600 t U equivalent per year, which approximately equals the capacity of the three plants currently in operation. Refurbishment of existing plants and/or investment in new plants will be required to sustain the base case projection. It is unlikely that MOX usage will exceed that considered in the base case unless fast breeder reactors stage a comeback as an alternative to very high uranium prices.

In January 2000 the USDOE announced a record of decision to build a MOX fuel fabrication plant for converting 33 t of plutonium declared as surplus to US defence purposes. The MOX fuel would be irradiated in US civilian nuclear power reactors over the period 2008 to 2022. Similarly, the Russian Federation has developed plans to burn plutonium declared surplus to its defence requirements. These plans include a joint venture between Russia and Western nuclear fuel companies to build and operate a MOX fabrication plant that will use weapons grade plutonium. At present, the quantities of MOX fuel envisioned for the US and Russian Government programmes would displace a relatively small amount of natural uranium — probably less than 1000 t U/a.

The ‘stop MOX’ or low case assumes that MOX usage will be phased out in 2005 in response to environmental and/or anti-plutonium opposition. This opposition could come both from the USA, where there is strong opposition to a ‘plutonium economy’, or from Europe where the Green environmental movement is opposed to MOX. The Green movement could potentially win anti-MOX concessions as part of formation of political coalitions.

Reprocessed uranium can be used as a direct substitute for newly produced uranium in reactor fuel fabrication. Consequently, a utility’s decision whether to use reprocessed uranium is generally driven by the comparative cost of fuel manufactured using the two different sources of uranium. Therefore projections of RepU use are directly tied to uranium market price projections; as the market price increases, RepU becomes more competitive. Figure 12 shows the projected uranium equivalent that would be displaced by the use of RepU. The base case scenario, which is used in the middle demand case (Table VII), shows a gradual stepwise increase which is capped at 2500 t U equivalent per year in 2016 for the remainder of the study period. The base case assumes a continuation of current reactor burnup practices and access to spent fuel from non-reprocessing countries.

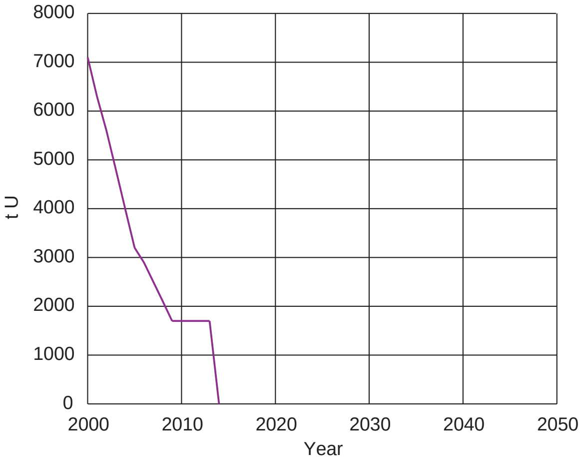

FIG. 10. Projection of annual drawdown from the Russian inventory to 2050.

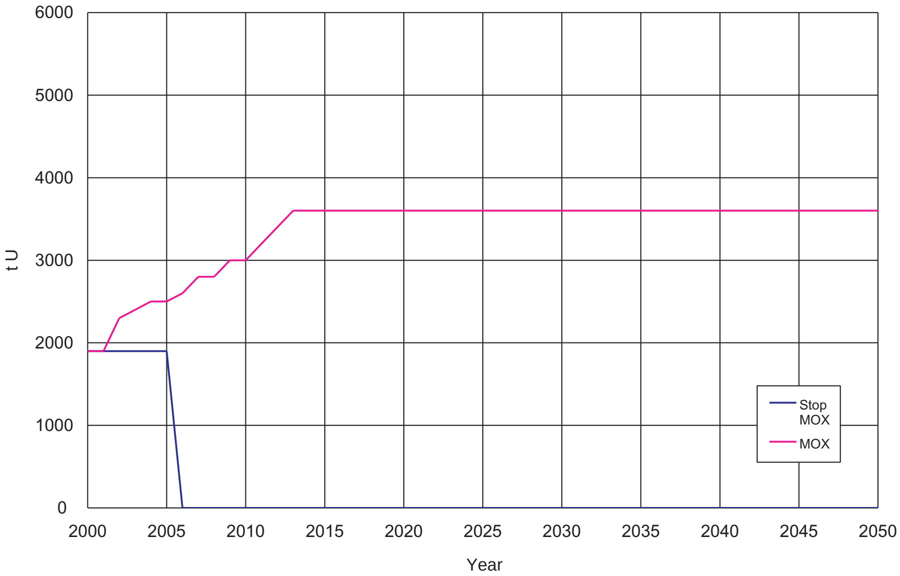

FIG. 11. Projection of uranium equivalent displaced by the MOX contribution to 2050.

With the current trend toward higher burnup, economically attractive spent fuel in countries currently using reprocessing techniques could be depleted by 2010. Therefore, without the assurance of the availability of spent fuel from non-reprocessing countries, the low RepU case in Fig. 12 shows RepU going to zero in 2010. The affects on the balance between supply and demand of the low MOX and RepU scenarios is discussed in Section 5.1.5.2.

3.2.4. Depleted uranium stockpiles (tails)

3.2.4.1. Background

Nuclear power is mainly produced in reactors fuelled with enriched uranium. In the enrichment process, for each kilogram of enriched uranium produced, an average of 8 kg of depleted uranium (range 5 to 10 kg) is produced. Consequently, more than three quarters of the total uranium devoted to fuelling reactors is now in the form of depleted uranium (or tails), and the accumulated stockpiles of tails represent a significant quantity of uranium. Whether the depleted uranium stockpiles represent a valuable energy source or a waste to be disposed of has been debated for three decades.

The answer to this question has evolved over time, and will most likely continue to change. In the 1970s and 1980s the answer was clearly that depleted uranium is potentially a valuable energy source for the future. At that time uranium prices were high, development of fast breeder reactors was considered by many to be unavoidable within one or two decades and transforming fertile ^{238}U into fissile Pu was considered as the appropriate answer to the lack of uranium. Today the answer is more controversial and less certain. Low uranium prices and the economic burden of tails management have altered the equation so that depleted uranium is now more often considered to have no current use at present Western enrichment costs.

However, re-enrichment of tails to recover more fissile uranium is still being conducted, and this activity is likely to continue as long as low cost enrichment capacity is available and there remains a supply of tails with a sufficient ^{235}U residual content. In addition, the Russian Federation is reportedly using tails to downgrade weapons grade HEU into commercial grade material. Furthermore, when addressing supply issues 50 years into the future, potentially lower cost enrichment technologies and new reactors such as fast breeder reactors could once again elevate depleted uranium tails from a waste to a potentially valuable energy source. This change in philosophy could be accelerated by a significant uranium price increase over time, which can be expected if nuclear power remains a significant option in the energy mix. Since depleted uranium storage does not represent a significant hazard when de-converted to a stable form such as U_3O_8, storage costs are likely to remain low, thus ensuring their availability for future needs. Appendix II provides an example of tails re-enrichment economics that helps put the remainder of this discussion in an economic context.

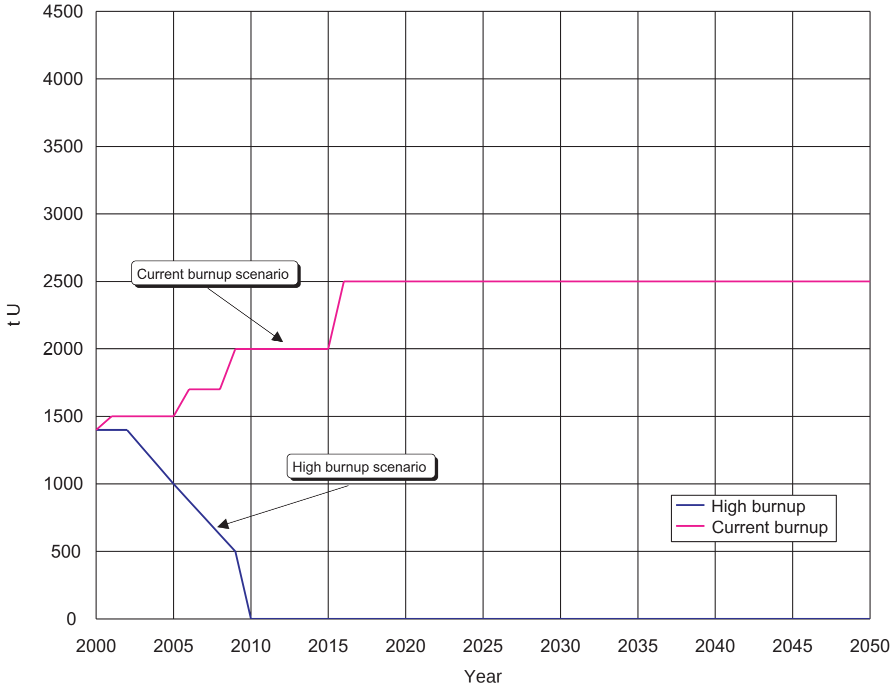

FIG. 12. Projection of uranium equivalent displaced by the RepU contribution to 2050 — current burnup and high burnup scenarios.

3.2.4.2. *Current uses of depleted uranium*

Depleted uranium is suitable for fuelling reactors, assuming re-enrichment or mixing with other fissile material (e.g. Pu for MOX, HEU for dilution). Other non-fuel uses involve only small amounts of depleted uranium, mainly for radiological shielding. Uses of depleted uranium for fuelling reactors include the following.

- Re-enrichment. From a purely economic point of view, depleted uranium can be reused as feed for a further enrichment step if the ratio between the enrichment unit cost and natural uranium prices allows such a recovery. To some extent this is currently the case for limited quantities.
- MOX matrix. The quantities involved are small but still constitute about 94% of MOX heavy metal content.
- HEU dilution. The quantities of depleted uranium tails presently being used for dilution of HEU are reported to be significant as a result of the Russian HEU deal. They are already counted in the HEU impact figures, and should be deducted from the tails stockpile totals.
- Core blankets. Pellets made with depleted uranium are quite often used peripheral to the reactor core as neutron shielding. This is a potentially important use assuming the development of fast breeder programmes, but its current use is very limited in LWRs and CANDUs (5 to 10 t/a).

3.2.4.3. *Existing stockpiles of depleted uranium*

The total quantities of depleted uranium tails have been estimated at approximately 1.1 million tonnes at year end 1995 [14]. Assuming an average ^{235}U content of 0.3% and a re-enrichment tails assay of 0.15%, this total could provide 294 000 t of natural uranium equivalent (or more than one and one half times the resources of the McArthur River deposit). However, the true content is probably lower, because the Russians have been operating at low tails assays for a considerable period of time, and even the Western gaseous diffusion plants (GDPs) were operating at lower tails assays before the 1980s.

The estimate of the allocation among the various forms of tails is: 365 kt of uranium in depleted uranium hexafluoride (DUF$_6$) at an average of 0.32% ^{235}U (Table X); 730 kt of U in DUF$_6$ at an average of 0.25% ^{235}U; 131 kt of uranium in other forms at an average of 0.25% ^{235}U.

TABLE X. DEPLETED URANIUM STOCKPILES AT YEAR END 1998

Enricher	Total depleted U (t U)	U/DUF$_6$ (t U)	Estimation of U/UF$_6$ supply 0.3% (t U)
USDOE–USEC	47 000	47 600	120 000
Eurodif	168 000	37 000	25 000
Urenco	29 000	29 000	25 000
British Nuclear Fuels Limited	30 000	30 000	25 000
Russian Minatom	495 000	495 000	150 000
China	20 000	20 000	15 000
Other	8 000	8 000	5 000
Total	1 226 000	1 095 000	365 000

Table XI shows that the readily available natural uranium equivalent content of tails stockpiles worldwide is limited compared to some published reports. In addition, the effect of the yet to be announced decision regarding the fate of the USDOE and USEC tails could have a significant negative impact on the future availability of the more than 40% of tails having a significant ^{235}U residual content.

3.2.4.4. Scenario for depleted uranium use to 2050

A large part of the ongoing use of depleted uranium is already accounted for within other supply components, including HEU down blending and use as a MOX matrix. Therefore the related quantities of depleted uranium must be deducted from the stockpiles potentially available in the future. Because of these uses and the low residual tails assays currently in use in the Russian Federation, the ^{235}U content of the world's depleted uranium stockpiles has been significantly reduced. For the purposes of this discussion, it is assumed that only tails at or above 0.3% ^{235}U could be commercially attractive for re-enrichment. It is also assumed that MOX matrix and other uses will come from depleted uranium with a content of less than 0.3% ^{235}U.

Strictly commercial re-enrichment of depleted uranium depends mainly upon the availability of very low cost (marginal) separative work unit (SWU) capacity. US and western European GDPs have relatively high marginal SWU costs and are unlikely candidates for tails re-enrichment. The capacities at western European centrifuge plants are currently committed to normal enrichment contracts. Future expansion of these plants could free up some capacity for tails re-enrichment, but by the time these expansions are completed the supply of economically attractive tails (>0.3%) is likely to be largely depleted. Therefore, until the market price of uranium reaches US $65/kg U, significant expansion of tails re-enrichment in the West seems very unlikely.

In the near term, re-enrichment of tails will probably be limited to Russian centrifuge plants, which reportedly have available marginal capacity and thus can offer fuel contracts on a marginal cost basis. In order to supply Soviet design reactors, the Russian Federation has to supply fuels with a content of 8300 t U equivalent assuming 0.3% tails assay and 4400 kSWU. These totals are expected to increase to 9900 t U equivalent and 5100 kSWU by 2010. [Note: the Russian Federation reportedly runs their enrichment plants at 0.15% tails. However, the effect of lower tails is not included in the tails usage scenario, in order to achieve a more global perspective.]

In addition to satisfying its traditional markets, down blending of HEU requires about 3500 kSWU (assuming feed tails of 0.3% and residual tails assay of 0.15%). The Russian Federation also currently exports 3600 kSWU/a, which could increase to 4000 kSWU by 2010. Table XII projects the allocation of Russian SWU and, assuming a stable enrichment capacity of 20 000 kSWU/a, the remaining capacity available for tails re-enrichment.

Based on the above assumptions, the available capacity for tails re-enrichment is projected to total 6500 kSWU/a in 2000, diminishing to 5100 kSWU/a by 2010. The base case for tails re-enrichment, which was used as a component of secondary supply in the demand cases, is constrained by: (1) the availability of low cost SWUs; and (2) safeguards related limitations on transferring large quantities of depleted uranium in the form of UF$_6$ to Russian enrichment plants and leaving the secondary tails in the Russian Federation. Therefore, as shown in Table XIII, tails re-enrichment is scheduled to end in 2011 after having contributed 43 400 t U equivalent.

The base case scenario will by no means utilize all depleted uranium tails with a content of 0.3% or greater. The 365 000 t U as UF$_6$ listed in Table X represent 110 000 t U equivalent, although the near term availability of the USDOE–USEC tails is uncertain. In addition, if uranium prices remain at less than US $52/kg U, assum-

TABLE XI. ECONOMICALLY RECOVERABLE NATURAL URANIUM EQUIVALENT CONTENT OF EXISTING TAILS

Tails stockpile	Estimation of U/UF_6 supply 0.3% (t U)	Natural uranium equivalent content (t U)	Likely to be available (t U)
USDOE–USEC	120 000	36 400	20 000
Eurodif	25 000	7 600	7 600
Urenco	25 000	7 600	7 600
British Nuclear Fuels Limited	25 000	7 000	7 000
Russian Minatom	150 000	40 000	
China	15 000	5 000	5 000
Other	5 000	1 500	
Total	365 000	105 100	47 200

ing current SWU prices, new tails totalling 17 000 t U/a in the form of UF_6 will be produced through enrichment of newly mined and processed uranium. To re-enrich these tails totally would yield 4545 t U equivalent/year, which would significantly extend the lifetime for tails as a secondary supply source. It would, however, also require enrichment capacity comparable to the Russian Federation's capacity currently available for the re-enrichment of tails. The potential of these tails assumes that tails storage technology will allow their retrievability in the future. It also assumes significantly higher uranium prices, lower SWU costs or expansion of low marginal cost SWU capacity to realize full utilization of the re-enrichment of tails.

3.2.5. Natural uranium production

Newly mined and processed uranium (primary production) is divided into four categories: CIS production, national programmes, Chinese production and market based production. Individual projections for the first three categories are made based on knowledge of current and consensus estimates of future production capability. The sum of these three production categories is added to the total secondary supply, and that total is in turn subtracted from the reactor requirements (demand) to project market based production requirements.

One underlying assumption applies to all of the primary production scenarios — the uranium production industry worldwide is gradually adopting market based economic principles. Accommodation is made for the transition to market conditions by existing national programmes, as well as those in the CIS and China, by assuming that these programmes will continue to produce at current rates throughout the study period. In addition, provision for near term growth has been made where existing expansion plans are considered likely to be implemented. However, it is assumed that future expansions of these programmes to meet increasing internal reactor requirements will depend on their economic viability and ability to compete with the worldwide industry. Increases in production beyond current levels will only take place in those countries where such increases can be economically justified. Otherwise, it has been assumed that countries will cover their increased requirements by purchases on the open market. Future increases in production, if and when economically justified, are included in the market based production category to emphasize their economic competitiveness. There is in fact increasing evidence to support this approach. Several

TABLE XII. RUSSIAN ENRICHMENT CAPACITY AVAILABLE FOR TAILS RE-ENRICHMENT (kSWU/a)

	Year 2000	Year 2010
Supply commitments to Soviet designed reactors	6 400	7 400
Tails re-enrichment for HEU dilution	3 500	3 500
Russian LEU exports	3 600	4 000
Available for tails re-enrichment	6 500	5 100
Natural uranium equivalent potential (t U/a) assuming 0.3% residual content and 0.15% secondary tails assay	6 232	4 890
Related tails consumption (t DU/a)	23 308	18 288

TABLE XIII. TAILS USE IMPACT, 2000–2012 (t U)

Tails use impact	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Maximum potential	6100	6000	5900	5700	5500	5300	5100	5000	4900	4800	4700	4700	0
Base case	4500	4500	5200	4850	4250	3650	3300	3000	2800	2650	2350	3500	0

countries with national programmes are cutting back or suspending operations in favour of purchasing uranium, and there is every reason to believe this trend will continue.

3.2.5.1. The CIS

Uranium is currently produced in four CIS countries: Kazakhstan, the Russian Federation, Ukraine and Uzbekistan. Both the Russian Federation and Ukraine have nuclear power programmes and, therefore, potentially have an internal use/need for most of their production.[7] Neither Kazakhstan nor Uzbekistan currently has nuclear power programmes, so all of their production is available for sale. Figure 13 shows middle case projected annual production from these four countries to 2050. These projections represent only output from existing operations, with minimal consideration given for project economics. Uranium is an important source of hard currency for the CIS countries, so they are likely to continue their programmes at least at current or perhaps slightly higher levels, even though they may not be strictly cost competitive on a worldwide basis. As previously noted, however, beyond the growth shown in Fig. 13, when a major expansion of existing facilities or a start of new operations is economically justified, they will be accounted for in this study as part of the market based production category. Similarly, resources not required to satisfy the CIS production category requirements are considered to be available to be utilized as market based production.

There is sufficient uncertainty regarding CIS production plans and capability that a second production scenario is also considered. The more conservative scenario depicted in Fig. 13 is based on the assumption that CIS production will continue to be constrained by capital limitations. These limitations will result in equipment and supply shortages which in turn will slow expansion of production. The second scenario is more in line with official forecasts of the CIS producers and projects more rapid near term growth. Table XIV is a comparison of the two scenarios between 2000 and 2014, after which their respective annual totals continue at the 2014 level. The accelerated scenario results in cumulative CIS production to 2050 of 708 900 t U, while the conservative total is 551 400 t U. Therefore the net effect of the accelerated scenario would be to reduce market based production requirements by a total of 157 500 t U during the study period.

Although referred to as the accelerated scenario, this projection of accelerated growth of CIS production is still less than official government forecasts, which indicate that CIS production could total 13 500 and 18 500 t U in 2005 and 2010, respectively [3]. These totals compare with 11 000 t U in 2005 and 13 500 t U in 2010 in the accelerated scenario.

Below is a summary of the underlying assumptions on which the production projections for the four CIS countries are based. Additional details about each country’s uranium production industry are provided in Appendix III.

Kazakhstan. All of Kazakhstan’s production comes from in situ leach (ISL) operations in the southern part of the country, and it is assumed that will continue to be the case until the restart of conventional uranium production operations which were shut down in the early 1990s can be cost justified. Figure 13 shows that under the conservative production scenario, Kazakhstan’s production is projected to increase to 2600 t U by 2005 and to remain at that level to 2050. The near term increase in production is supported by two joint ventures with Western companies, both of which could begin operations in 2000 and add a total of between 700 and 800 t U each to current production capability by 2005. Under the middle demand case scenario, market price increases could support expansion of Kazakhstan’s current ISL operations beginning in about 2021. This increase, which would be accounted for under the market based production category, could increase total output from Kazakhstan’s ISL operations to 3370 t U by about 2022. Additional cost justified capacity increases could ultimately lead to an annual output from Kazakhstan’s ISL operations of

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[7] Russian uranium production is currently exported to Western countries. Russian reactor requirements and commitments to eastern European and CIS countries operating Soviet designed reactors are largely filled from the drawdown from its inventory.

4100 t U, assuming the conservative CIS production scenario.

The accelerated scenario envisions a more rapid increase in near term production to 5000 t U by 2013, all of which is accounted for in the CIS production category. Even with the accelerated production, Kazakhstan's RAR recoverable at <US $80/kg U could accommodate cost justified ISL production (in the market based production category) in about 2022. The market based production increment could increase total ISL output to 6500 t U by 2035. Restart of conventional operations in the Kokchetav and Pribalkhash districts and uranium recovery from organic phosphate deposits at the Kaskor (Pricaspian) operation could potentially be economically justified by 2023 under both the conservative and accelerated scenarios. Production from the conventional operations would be accounted for under the market based production category.

The Russian Federation. The Russian Federation currently has only one uranium production centre, the Priargunsky conventional mine–mill complex near Krasnokamensk, in southeastern Siberia. However, pilot tests using ISL technology have been ongoing in the Trans-Ural region (the Dalmatovsk deposit), with production scheduled to start in 2001 to 2003. Extensive exploration drilling has been completed in two other areas with ISL potential, western Siberia and Vitim. Table XV is a projection of Russian production included under the broader category CIS production, from 2000 to 2010, based on the conservative CIS production scenario. After 2010 production attributable to the CIS production category is capped at 3800 t U/a for the remainder of the study period.

It is important to note that the RAR reported by the Russian Federation for all cost categories is insufficient to fulfil its portion of the CIS production category (185 600 t U in the CIS production category compared to 140 900 t U of RAR reported in the Red Book). Even the total of RAR + EAR-I reported in the Red Book (177 400 t U) is not sufficient to satisfy the Russian portion of the CIS production category. However, the Red Book resources are conservative in that they do not include any RAR or EAR-I in the US $80–130/kg U category. In addition, they do not include RAR and EAR-I totalling about 52 000 t U in the Vitim area that were reported in the 1997 Red Book. The Vitim resources, although well defined by drilling, are still under review and hence are not included as RAR or EAR-I in the 1999 Red Book [3]. The Russian Federation acknowledges that its lower cost resources are only adequate to satisfy requirements for about 20 years. However, it has ongoing exploration programmes

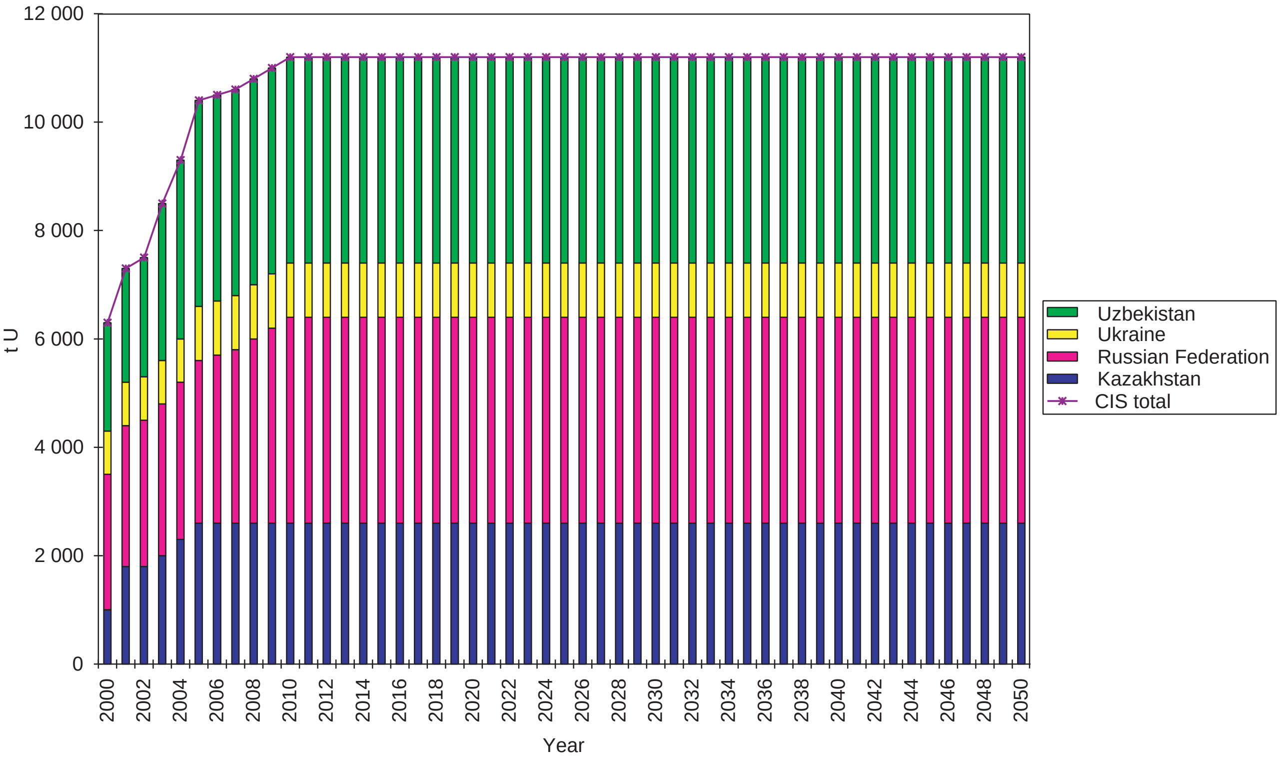

FIG. 13. Projection of annual CIS production to 2050 — conservative scenario.

TABLE XIV. COMPARISON OF CONSERVATIVE AND ACCELERATED PRODUCTION SCENARIOS IN THE CIS PRODUCTION CATEGORY (t U)

Scenario	2000	2001	2002	2003	2004	2005	2006	2007
Conservative	6 300	7 300	7 500	8 500	9 300	10 400	10 500	10 600
Accelerated	7 600	8 300	9 000	9 800	10 400	11 000	11 500	12 000

Scenario	2008	2009	2010	2011	2012	2013	2014
Conservative	10 800	11 000	11 200	11 200	11 200	11 200	11 200
Accelerated	12 500	13 000	13 500	13 900	14 300	14 600	14 700

designed to move resources into progressively higher confidence categories. With the inclusion of higher cost resources, the Russian Federation has sufficient known resources to satisfy its requirements in the middle demand case CIS production category, with significant EAR-I available to contribute to the market based production category.

Table XVI summarizes annual output from the Russian Federation under the accelerated production scenario, which foresees a more rapid buildup of production before it stabilizes at 5000 t U/a in 2015. All Russian RAR + EAR-I will be required to implement the accelerated scenario, leaving no resources available for later cost justified expansion.

Ukraine. Ukraine’s production is currently limited to conventional underground mines in the Kirovograd district. Ore from the Kirovograd mines is hauled by rail to the conventional mill in Zheltiye Vody. Ukraine’s contribution to the CIS production category is capped at 1000 t U throughout the study period. However, official Ukrainian projections indicate that production could increase to 1500 t U by 2005, with a further increase to 2000 t U/a beginning in 2010. There is also the potential that market prices could increase sufficiently to justify economically based expansion in about 2023 under both the conservative and accelerated production scenarios. In addition, Ukraine has a large nuclear energy programme, and requirements to fuel this programme could increase uranium production in excess of the totals used in this report. This increase would, however, probably not be cost justified according to the methodology of this study.

Uzbekistan. Uzbekistan’s uranium industry is similar to that of Kazakhstan in that production is currently limited to ISL operations. It is assumed that this will continue to be the case for the CIS production category throughout the report period. Part of Uzbekistan’s increase in production between 2000 and 2005 (Fig. 13) is predicated on successful implementation of a joint venture with a Western company to develop the ISL potential of the Sugraly deposit. Implementation of either the conservative or accelerated production scenarios will require development of lower confidence EAR-I and EAR-II to supplement RAR. Under the conservative scenario, ISL amenable RAR will be exhausted in 2019, EAR-I in 2029 and EAR-II in 2043. Therefore, based on Red Book data, additional resources totalling 36 194 t U will have to be discovered before Uzbekistan can satisfy the projected requirements of its portion of the CIS production category solely based on ISL operations. The other alternative is to assume that conventional mining operations, which were shut down in 1994, will be called upon to supplement ISL production in order to satisfy Uzbekistan’s requirements in the CIS production category.

3.2.5.2. National programmes

Several countries have small uranium production programmes dedicated to meeting domestic reactor requirements. While these programmes typically have high production costs, they are maintained either because of their importance to the local economy or for reasons of national security. Countries that historically maintained national programmes include Argentina, Brazil, Bulgaria, the Czech Republic, France, Germany, Hungary, India, Pakistan, Romania and Spain. Increasingly, however, national programmes are being shutdown as their host countries turn to the market to supply reactor demand. France, which has the largest of the national programmes, will have shut down uranium production by the end of 2001. Bulgaria and Hungary suspended uranium production in 1994 and 1997, respectively, and Spain and the Czech Republic are scheduled to stop production in 2000 and 2003, respectively (subject to periodic government review).

Requirements that production costs be based on market economics are expected to play an increasingly important role in the worldwide uranium production industry. Government support for maintaining uneconomic

TABLE XV. PROJECTION OF THE RUSSIAN FEDERATION’S PRODUCTION BETWEEN 2000 AND 2010 BASED ON THE CONSERVATIVE SCENARIO (t U)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Conventional	2500	2500	2600	2600	2700	2800	2800	2800	3000	3000	3000
ISL	—	100	100	200	200	300	400	400	400	600	800
Total	2500	2700	2800	2900	3000	3200	3200	3400	3600	3800	3800

TABLE XVI. PROJECTION OF THE RUSSIAN FEDERATION’S PRODUCTION BETWEEN 2000 AND 2015 BASED ON THE ACCELERATED SCENARIO (t U)

	2000	2001	2002	2003	2004	2005	2006	2007
Conventional	2500	2600	2700	2800	2900	3000	3100	3200
ISL	—	100	200	300	400	500	600	700
Total	2500	2700	2900	3100	3300	3500	300	3900
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Conventional	3300	3400	3500	3500	3500	3500	3500	3500
ISL	800	900	1000	1100	1200	1300	1400	1500
Total	4100	4300	4500	4600	4700	4800	4900	5000

production is likely to come under increasing scrutiny. Although there may be exceptions to this expectation, they are few and constitute only a very small percentage of total uranium requirements. Accordingly, as shown in Fig. 14, it has been assumed in this study that output from national programmes will stay at approximately their current levels. The decline in national programme production between 2000 and 2003 reflects the gradual winding down of the programmes in Spain and the Czech Republic.

3.2.5.3. China

There is still sufficient uncertainty about the current and future uranium production industry in China that it is treated as a separate category of primary supply. Part of the uncertainty stems from China’s laws prohibiting release of resource estimates and annual production totals. Emphasis within China’s uranium production industry has historically been on satisfying its internal requirements, both military and more recently civilian reactor demand. It has, however, also exported minor amounts of uranium to satisfy sales commitments signed in the 1980s. Although China has emphasized a policy of self-sufficiency in its uranium industry, it is increasingly faced with high production costs and lack of known resources as it struggles to satisfy the increasing demand of a growing civilian nuclear power industry. In this study it has been assumed that China will continue to maintain its uranium production capacity at current levels, and that it will increasingly turn to the international market to satisfy the perceived shortfall between growing uranium requirements and domestic output. Accordingly, as shown in Fig. 15, China’s production could potentially increase from current levels of about 400 t U to 1380 t U by 2005, after which it has been capped at that level for the remainder of the study period. China’s known resources have not been updated since the 1995 edition of the Red Book. It continues to report 64 000 t U distributed among seven different provinces, although the total associated with current and planned operations may only be about 22 000 t U. All of China’s known resources are allocated to fulfilling the Chinese production category and none are projected to be available to contribute to market based production.

3.2.5.4. Market based production

Market based production as used in this report consists of uranium produced at or below market costs to satisfy reactor requirements (demand) not covered by secondary supply and primary supply from the CIS, national programmes and China. A bottom-up approach has been used to determine market based production required to satisfy the gap between demand and all other supply sources. The previous sections describe the approach used to determine secondary supply and non-market based primary supply. For this study it is assumed that for reasons of economics (low cost) or policy these supply sources will be available more or less independently of the market based production category. What remains, therefore, is to determine market based production requirements in order to complete the supply–demand picture.

The first step in this process is to determine potential supply sources outside of those included in the other three primary supply categories. Three main sources were used in compiling this information:

- — The Red Book,
- — The International Uranium Resources Evaluation Project (IUREP) (Appendix IV),
- — The collective knowledge of the consulting specialists who contributed to this study.

One of the primary objectives of this study is to assess the adequacy of worldwide resources to meet projected reactor demand. Reliability of information on resources covers a broad spectrum, from hard fact (e.g. information publicly released by mining companies on specific deposits under legal obligations and financial reporting standards) to speculative assessments of the relatively untested potential of large geographic subdivisions ranging from mining districts to entire countries. Resource totals have very little meaning without an understanding of the reliability of the information on which they are based. Therefore the starting point in assessing resource adequacy is to establish the level of confidence or reliability of the resources. Towards that end, the IAEA/NEA resource terminology used in the Red Book has been adopted for this study. Resource categories that will be referred to are as follows (in order of decreasing confidence level):

- — Reasonably assured resources (RAR);
- — Estimated additional resources category I (EAR-I);
- — Estimated additional resources category II (EAR-II);
- — Speculative resources (SR), also referred to as potential resources.

Definitions of these resource categories are provided in Appendix V. It should be emphasized that, even among the different resource categories, the quality of the information varies widely. As previously noted, the major Western mining companies are required to list reserve and resource information in their annual reports. Therefore the level of confidence in such projects as McArthur River and Cigar Lake in Canada, Ranger/Jabiluka and Olympic Dam in Australia and Highland and Smith Ranch in the USA is very high. For other deposits the information is much less definitive. Nevertheless, they have been classified as RAR because they are known to be based on sufficient exploration drilling and radiometric logging and/or chemical analysis for at least a first phase feasibility study. All resource estimates are expressed in metric tonnes of recoverable uranium (t U).

Another key factor in assessing resource potential or adequacy is an estimate of production costs, without which the term resource has no practical meaning. RAR

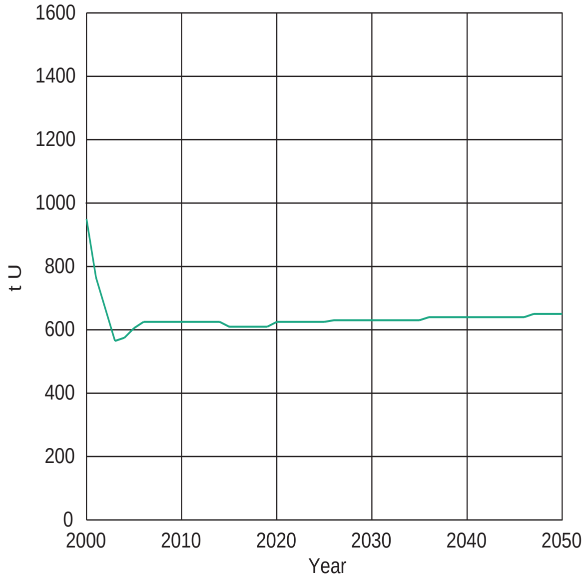

FIG. 14. Projection of annual production by national programmes to 2050.

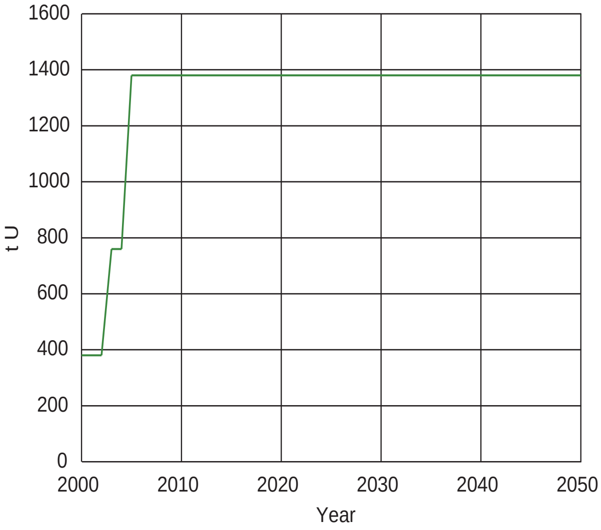

FIG. 15. Projection of annual production in China to 2050.

production costs are based on a pre-feasibility or feasibility analysis. Table XVII shows the cost categories that were adopted for this study.

All resource categories are defined in terms of forward costs of uranium recovered at the ore/solution processing plant. Sunk costs were not normally taken into consideration. When estimating the cost of production for assigning resources within these cost categories, the following costs are taken into account:

- The direct costs of mining, transporting and processing the uranium ore;
- The costs of associated environmental and waste management during and after mining;
- The costs of maintaining non-operating production units;
- In the case of ongoing projects, those capital costs which remain unamortized;
- The capital cost of providing new production units, including the cost of financing;
- Indirect costs such as office overheads, taxes and royalties;
- Future exploration and development costs wherever required for further ore delineation to the stage where it is ready to be mined.

For this analysis, once the guidelines for resource confidence levels and production cost categories were established, a preliminary list of known deposits and their respective resources was compiled, based on information provided by the consulting specialists, IUREP and Red Book data. Known deposits are emphasized to underscore the fact that these contain relatively high confidence resources directly attributable to known deposits. Table XVIII lists the deposits and their respective countries. In some cases individual deposits in close geographic proximity and with similar geology and production costs are grouped into mining districts or areas, and their resources are consolidated under a single district name. For example, the listing Yilgarn calcrete deposits in Australia includes seven individual deposits. Every effort was made to determine whether resources were reported as in situ (in place) or recoverable. Where that information was not available, a conservative approach was taken, and a recovery factor was applied to the resources to account for mining and processing losses. Recovery factors vary depending on the type of deposit and the extraction method. They typically range from 65 to 92%.

Table XVIII was compiled by country in order to compare RAR that was directly associated with known deposits by consultants contributing to this study (hereafter referred to as study RAR) with RAR reported in the 1999 Red Book [3]. RAR listed in the Red Book that are not accounted for in the study RAR are termed non-attributed RAR. RAR was reduced in this report for projected 1999 production, which accounts for the minor discrepancies with 1999 Red Book RAR [3]. For most countries, the comparison between study and Red Book RAR is very close. In other cases, however, there is a significant disparity between RAR listed in the Red Book and study RAR. In most cases there is a ready explanation for the difference, with Niger being a good example. RAR listed in the Red Book for Niger are restricted to the current operations at Akouta and Arlit, perhaps because the other resources are not considered viable under near term market conditions. Taking a longer term perspective, however, this is a conservative approach, because there are significant other resources that have been defined by extensive drilling, which can clearly be assigned to the RAR category. A good example of RAR not included in the Red Book section on Niger are those associated with the Imouraren deposit, which is currently being tested for its amenability to ISL extraction. The Imouraren resources may in fact not be economically viable at today’s market price, but they certainly should be considered when looking ahead 50 years.

The deposits on the study RAR list were next ranked by their relative forward production costs. This ranking process was not based on a rigorous production cost analysis of each individual deposit, but instead was a consensus based subjective comparison of production costs for each project relative to other projects. In the final analysis it matters very little whether one project ranks slightly above or below another, because most if not all study RAR will eventually be needed to satisfy long term reactor demand.

In addition to the production cost ranking, each project was assigned an estimated production capacity. Capacities based on published plans for production were used where available. Otherwise, capacities were estimated based on resource size and/or projected length of operation, extraction method, deposit type/geology and grade of the ore. Table XIX shows the projected annual capacities for production centres included in the study RAR category.

In the final step, production capacity was combined with cost ranking to project the order in which deposits will fill market based production requirements. The lowest cost producer operating at or near capacity was assumed to fill the first increment of demand. Remaining demand will be filled by progressively higher cost producers until annual demand is filled. Production from higher cost projects is deferred until they are projected to be cost competitive. Flexibility was introduced into the analysis to accommodate higher cost

TABLE XVII. PRODUCTION COST CATEGORIES

Cost category	US $/kg U	US $/lb U_3O_8	(US $/kg U_3O_8)
Low	≤34	≤13	(≤29)
Low medium	>34–52	>13–20	(>29–44)
High medium	>52–78	>20–30	(>44–66)
High	>78–130	>30–50	(>66–110)
Very high	>130	>50	(>110)

projects that may continue to operate because of contractual obligations or other special circumstances. Estimated lead times were factored into when a project could come on stream. Even though justified by a lower cost to begin operating earlier, a project was delayed until sufficient time would have lapsed to complete environmental assessment, licensing and construction. In some cases this is estimated to be as much as 15 years. It should be emphasized that this analysis is neither a prediction nor a forecast of precisely how the uranium production industry will develop during the next 50 years. Instead, it presents a number of scenarios based on current technology, each of which shows alternatives as to how the industry could unfold given changing sets of conditions. The analysis does not take into account new technology, innovations or changing circumstances that could result in unforeseen major changes in project resources, capacity, licensing or production costs.

Evaluation of the adequacy of uranium resources to meet demand was begun by first determining the extent to which study RAR could satisfy market based production requirements. Study RAR are considered to have the highest probability to be brought into production because of their size and the detailed feasibility studies on which production plans are based. Deposits already in production or under development of course have the highest confidence level, followed by those on which economic feasibility studies, mine design and test mining have been completed, and lastly by deposits defined only by limited drilling and preliminary feasibility studies. The next lower confidence level are non-attributed RAR that could not be specifically identified and located due to lack of information available to the specialists preparing this report. For example, as shown in Table XVIII, Red Book RAR in Australia exceed study RAR by about 125 600 t U. Although the consultants involved in this study could not directly relate the non-attributed RAR to specific deposits, they nevertheless are considered legitimate, high confidence resources recognized by experts in their respective countries. These non-attributed RAR are added as the next confidence layer of production, followed by EAR and finally by SR. There is no assurance that study RAR are not in some cases included in the non-attributed RAR category. However, the approach used in this study precludes double accounting of resources, because only the difference between Red Book and study RAR is included in the non-attributed RAR category. Section 4 provides details on the various categories of resources identified for use in this study.

The bottom-up evaluation of adequacy of resources provides a projection of how the uranium production industry could potentially change over time. For example, Fig. 16, which projects production by cost category, indicates that production derived from study RAR will be adequate to satisfy middle demand case market based production requirements to approximately 2026. The gap shown in Fig. 16 between market based production requirements and study RAR available at all cost levels starting in 2027 will have to be filled by utilizing lower confidence resources. Figure 16 also projects that low and low medium cost resources could fill middle demand case market based production requirements to 2018, suggesting that spot market prices may not rise above US $52/kg U (US $20/lb) (year 2000 US $) before 2018 under the most likely (middle demand case) demand scenario. It should be emphasized that Fig. 16 presents an overly simplified picture of a single demand scenario (production derived from study RAR matched against middle demand case market based production requirements). In the more comprehensive analyses presented in Section 4, lower cost resources, even though they are in a lower confidence category, are typically assumed to come into production before higher confidence but higher cost resources.

Identifying resources is only the first step in developing a comprehensive analysis of resource adequacy. In addition, production cost is not the only criterion that must be considered in evaluating if and when resources will be developed. Mining in general, and uranium mining specifically, continues to be opposed in some locations. If, as expected, economic standards continue to improve throughout the world, this resistance may in fact grow. Even people in areas with a tradition of mining can over

TABLE XVIII. COMPARISON OF STUDY RAR WITH RED BOOK RAR (1000 t U)

Country	Year 2000 resources	1999 Red Book RAR
Algeria		
Hoggar	26.0	26.0
Argentina		
Cerro Solo	3.5	
Sierra Pintata	4.0	
Total Argentina	7.5	7.5
Australia		
Angela	6.8	
Ben Lomond/Maureen	6.6	
Beverley	17.7	
Bigrlyi	2.0	
Crocker Well	3.8	
Honeymoon	6.8	
Kintyre	24.4	
Koongarra	10.3	
Manyingee	7.9	
Mount Painter district	5.6	
Mulga Rock	8.4	
Olympic Dam	281.3	
Ranger/Jabiluka	123.8	
Valahalla/Mount Isa	14.0	
Westmoreland	17.8	
Yeelirrie	40.8	
Yilgarn calcrete deposits	12.4	
Total Australia	590.4	716.0
Brazil		
Itataia	80.8	
Lagoa Real	52.0	
Poças de Caldas	22.8	
Total Brazil	155.6	162.0
Bulgaria		
Bulgaria — various	16.3	7.8
Canada		
Blizzard	3.8	
Cigar Lake	135.8	
Cluff Lake	8.7	
Dawn Lake	8.6	
Eastern Canada — quart–pebble conglomerates	100.0	
Kiggavik–Sissons Schultz	38.5	
Kitts–Michelin	7.2	
McArthur River	184.2	
McClean Lake/Midwest Lake	34.5	
Rabbit Lake	14.4	
Total Canada	535.7	326.4
Cameroon		
Kitongo	5.0	No report
Central African Republic		
Bakouma — shallow	8.0	
Bakouma — deep	8.0	
Total Central African Republic[a]	16.0	16.0
China		
Conventional and ISL	60.0	60.0
Czech Republic		
Stráž	22.0	
Rozhna	7.0	
Total Czech Republic	29.0	7.0
Democratic Republic of the Congo		
Copper process	3.5	1.8
Finland		
Various	3.4	1.5
France		
Coutras	6.0	14.2
Gabon		
Gabon	4.3	4.8
Greenland (Denmark)		
Illimaussaq[a]	11.0	27.0
Hungary		
Mecsek	15.8	0.0
Indonesia		
West Kalimantan	6.3	6.3
Italy		
Novazzo	4.8	4.8
Japan		
Tono/Ningyo Toge	6.6	6.6
Kazakhstan		
Economic ISL	179.1	
ISL lower cost	128.5	
Kokchetav district	99.0	
Pribalkhash district	10.0	
Pricaspian district	15.0	
Total Kazakhstan[b]	431.6	450.9
Mexico		
Las Margaritas[a]	7.6	1.7
Mongolia		
Dornod	51.0	
ISL	22.0	
Total Mongolia[a]	73.0	61.6
Namibia		
Langer Heinrich	11.3	
Rossing	112.0	
Total Namibia	123.3	180.5
Niger		
Afasto	25.2	
Akouta	40.5	
Arlit	22.2	
Imouraren	100.5	
Madaouela	5.1	
Total Niger	193.5	71.1
Portugal		
Nisa	1.9	
Urgeiriça	5.6	
Total Portugal	7.5	7.5

TABLE XVIII. (cont.)

Country	Year 2000 resources	1999 Red Book RAR
Russian Federation		
Far east	4.0	
Onezhsky (other production)	2.0	
Streltsovsk—RAR	130.7	
Trans-Baikal (incl. Vitim)	6.0	
Trans-Ural	10.2	
Total Russian Federation	161.3	140.9
Slovenia		
Zirovsk	2.2	2.2
South Africa		
Nufcor — lower cost	79.0	
Nufcor — higher cost	160.0	
Palabora	4.9	
Total South Africa	243.9	292.8
Spain		
Ciudad Rodrigo area	6.7	6.7
Ukraine		
Dnepr-Donets (lower cost)	9.3	
Dnepr-Donets (higher cost)	6.6	
Kirovograd	62.2	
Krivorzh	2.2	
Pobuzhy	15.0	
Total Ukraine[a]	95.7	81.0
USA		
Alta Mesa	1.6	
Ambrosia Lake mine water	2.2	
Arizona Strip breccia pipes	25.4	
Big Red	2.3	
Borrego Pass	5.8	
Bull Frog	5.0	
Canon City	2.6	
Charlie	1.3	
Christensen Ranch	6.0	
Church Rock	4.8	
Crow Butte	14.7	
Crown Point	9.7	
Dalton Pass	4.9	
Dewey Burdock	2.4	
Gas Hills	28.8	
Grants mineral belt	12.7	
Green Mountain	19.2	
Hansen	8.0	
Highland/Ruby Ranch	7.3	
Kingsville Dome/Vasquez	6.0	
L Bar	3.0	
Marquez	5.8	
McDermitt Caldera	5.5	
Moore Ranch	1.3	
Mount Taylor	16.2	
New Wales	19.7	
North Butte	4.0	
Nose Rock	10.0	
Red Desert	11.3	
Reno Creek	2.3	
Reynolds Ranch	3.1	
Shootering Canyon	2.6	
Smith Ranch	21.5	
Sundance	1.4	
Swanson	7.3	
Taylor Ranch	3.9	
Uncle Sam/Faustina	18.0	
Uravan (uranium and vanadium co-products)	4.7	
West Largo	3.8	
Total USA	316.1	355.0
Uzbekistan		
Conventional (other production)	17.5	
ISL	63.0	
Total Uzbekistan	80.5	83.1
Viet Nam		
Viet Nam	7.5	1.3
Zambia		
Copper processing	6.0	No report
Zimbabwe		
Kanyemba	1.8	1.8
Totals	3276.1	3128.2

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[a] Data from previous Red Book.

[b] In situ resources adjusted to estimate recoverable resources.

TABLE XIX. PROJECTED PRODUCTION CAPACITIES AND RESOURCES — STUDY RAR

Country/uranium district/ production centre	Production capacity (t U/a)	Resources (1000 t U)	Comments
Algeria			
Hoggar	1359	26.0	Currently high political risk; development of water supply critical to production.
Argentina			
Cerro Solo	385	3.5	Approximately 1 million lb U_3O_8 (0.43 million kg U_3O_8).
Sierra Pintata	385	4.0	Currently operating, but output nil. Expected to shut down in 2000.
Australia			
Angela	385	6.8	
Ben Lomond/Maureen	1000	6.6	
Beverley	770	17.7	Approximately 2 million lb U_3O_8 (0.9 million kg U_3O_8).
Bigrlyi	385	2.0	
Crocker Well	385	3.8	
Honeymoon	385	6.8	
Kintyre	1270	24.4	
Koongarra	855	10.3	
Manyingee	580	7.9	
Mourt Painter district	770	5.6	
Mulga Rock	770	8.4	
Olympic Dam	3880	281.3	Expansion of capacity to 6540 t/a projected for 2017.
Ranger/Jabiluka	6000	123.8	Assumes Jabiluka ore will be milled at Ranger, although this option is still uncertain.
Valhalla/Mount Isa	770	14.0	
Westmoreland	1150	17.8	
Yeelirree	2110	40.8	
Yilgarn calcrete deposits	1000	12.4	Seven deposits; assumes processing of ore at a central mill.
Brazil			
Itataia	600	80.0	
Lagoa Real	600	52.0	
Poças de Caldas	600	22.8	
Bulgaria	385	16.3	
Canada			
Blizzard	385	3.8	
Cigar Lake	6920	135.8	Ore to be processed at Rabbit Lake and McClean Lake mills.
Cluff Lake	1500	8.7	Scheduled to shut down in 2002; restart when cost justified.
Dawn Lake	770	8.6	
Elliot Lake/Blind River	4225	100.0	Risk of environmental opposition.
Kiggavik/Sisson Schultz	1350	38.5	
Kitts–Michelin	1350	7.2	
McArthur River	6920	184.2	Ore processed at Key Lake mill.
McClean Lake/ Midwest Lake	2310	34.5	
Rabbit Lake	4615	14.4	
Cameroon			
Kitongo	385	5.0	
Central African Republic			
Bakouma	770	16.0	
Czech Republic			
Stráž ISL	1000	22.0	Scheduled to shut down and restart when cost justified; risk of environmental opposition.
Rozhna	385	7.0	

TABLE XIX. (cont.)

Country/uranium district/ production centre	Production capacity (t U/a)	Resources (1000 t U)	Comments
Democratic Republic of the Congo	200	3.5	By-product of copper operations.
Finland	385	3.4	
France			
Coutras	500	6.0	Risk of environmental opposition.
Gabon	385	4.3	Existing mill being decommissioned; resumption of production will require a new mill.
Greenland (Denmark)			
Illimaussaq	770	11.0	Refractory ore; technical risk.
Hungary			
Mecsek area	750	15.8	
Indonesia			
West Kalimantan	770	6.3	
Italy			
Novazza	385	4.8	Significant political and environmental opposition risks.
Japan			
Tono/Ningyo Toge	385	6.6	
Kazakhstan			
Economic ISL	1500	179.1	
ISL CIS production	4000	128.5	Includes Stepnoye, Central and Ore Co. No. 6 and Inkay and Moynkum joint ventures.
Kokchetav district	2500	99.0	Ore will be processed at the Tselliny/Stepnogorsk mill.
Pribalkash district	1000	10.0	
Pricaspian district	770	15.0	
Mexico			
Las Margaritas	300	7.6	
Mongolia			
Dornod	1000	57.0	Assumes heap leach and conventional processing.
Gobi Basins (ISL)	770	22.0	
Niger			
Afasto	1690	25.2	
Akouta	2000	40.5	
Arlit	1540	22.2	
Imouraren	1150	100.5	Currently being evaluated for ISL amenability.
Madaouela	385	5.1	
Namibia			
Langer Heinrich	770	11.3	
Rossing	3845	112.0	
Portugal			
Nisa	150	1.9	
Urgeiriça	170	5.6	
Russian Federation			
Aldan			Insufficient information on which to base resource and production capacity.
Far east	385	4.0	
Onezhsky	200	2.0	
Streltsovsk/Priargunsky	3500	130.7	
Trans-Baikal (incl. Vitim)	770	6.0	

TABLE XIX. (cont.)

Country/uranium district/ production centre	Production capacity (t U/a)	Resources (1000 t U)	Comments
Slovenia			
Zirovsk	385	2.2	
South Africa			
Nufcor	2000	243.9	Includes production from Palabora.
Spain	800	6.7	
Ukraine			
Dnepr-Donets	385	15.9	
Kirovograd	1000	62.6	
Krivorzh	385	2.2	
Pobuzhy	770	15.0	
USA			
Alta Mesa	300	1.6	
Ambrosia Lake	150	2.2	Mine water treatment.
Arizona Strip breccia pipes	1155	25.4	Assumes ore will be processed at White Mesa mill.
Big Red	385	2.3	
Borrego Pass	385	5.8	
Bull Frog	385	5.0	
Canon City	385	2.6	Projected to shut down in 2002 and restart in when cost justified.
Charlie	290	1.3	Assumed to be satellite ISL operation to Christensen Ranch.
Christensen Ranch	385	6.0	
Church Rock	580	4.8	Risk of environmental opposition.
Crow Butte	385	14.7	
Crown Point	580	9.7	Risk of environmental opposition.
Dalton Pass	770	4.9	Risk of environmental opposition.
Dewey Budock	385	2.4	
Gas Hills	1345	28.8	Assumes ISL resin will be processed at Highland.
Grants mineral belt	770	12.7	Risk of environmental opposition.
Green Mountain	1540	19.2	Ore will be processed at Sweetwater mill.
Hansen	580	8.0	Risk of environmental opposition.
Highland/Ruby Ranch	385	7.3	
Kingsville Dome/Vasquez	385	6.0	Placed on standby in 1999.
L Bar	385	3.0	Risk of environmental opposition.
Marquez	385	5.8	Risk of environmental opposition.
McDermitt Caldera	385	5.5	
Moore Ranch	200	1.3	
Mount Taylor	770	16.2	Risk of environmental opposition.
New Wales	810	19.7	
North Butte	385	4.0	Assumes ISL resin to be processed at Christensen Ranch.
Nose Rock	770	10.0	Risk of environmental opposition.
Red Desert	580	11.3	
Reno Creek	385	2.3	
Reynolds Ranch	385	3.1	Could be operated as satellite to Smith Ranch or as standalone operation.
Shootering Canyon	385	2.6	Mill on standby status.
Smith Ranch	770	21.5	
Sundance	385	1.4	
Swanson	580	7.3	Risk of environmental opposition.
Taylor Ranch	385	3.9	
Uncle Sam/Faustina	600	18.0	
Uravan	385	4.7	Assumes ore will be processed at White Mesa.
West Largo	385	3.8	Risk of environmental opposition.
White Mesa	385		Non-uranium ore alternative feed.

TABLE XIX. (cont.)

Country/uranium district/ production centre	Production capacity (t U/a)	Resources (1000 t U)	Comments
Uzbekistan			
Conventional	770	17.5	Black schist.
ISL	3400	63.0	Kyzylkum Basins and Navoi central processing plant.
Viet Nam	770	7.3	
Zambia	200	6.0	By-product of copper operations.
Zimbabwe			
Kanyemba	200	1.8	

time develop anti-mining attitudes, so the risk of environmental opposition has to be considered in resource viability. This has been done to a certain extent in this study by assuming that projects will not begin production until adequate time has lapsed fully to address and mitigate environmental concerns. Where the risks of environmental opposition are considered to be very high, costs should and have been increased to at least partially address this opposition and the resulting stringent environmental regulations. In addition, for the comprehensive supply–demand analyses in Section 4, lower confidence resources are in some cases brought on line before projects that have a higher confidence and/or lower cost, but which are perceived to have a very high risk of environmental opposition.

In addition to the risk of environmental opposition, political risk must be considered. Political risk is admittedly subjective, but, like environmental opposition, it can be partially addressed by increased production cost. There is yet a third risk associated with the resources,

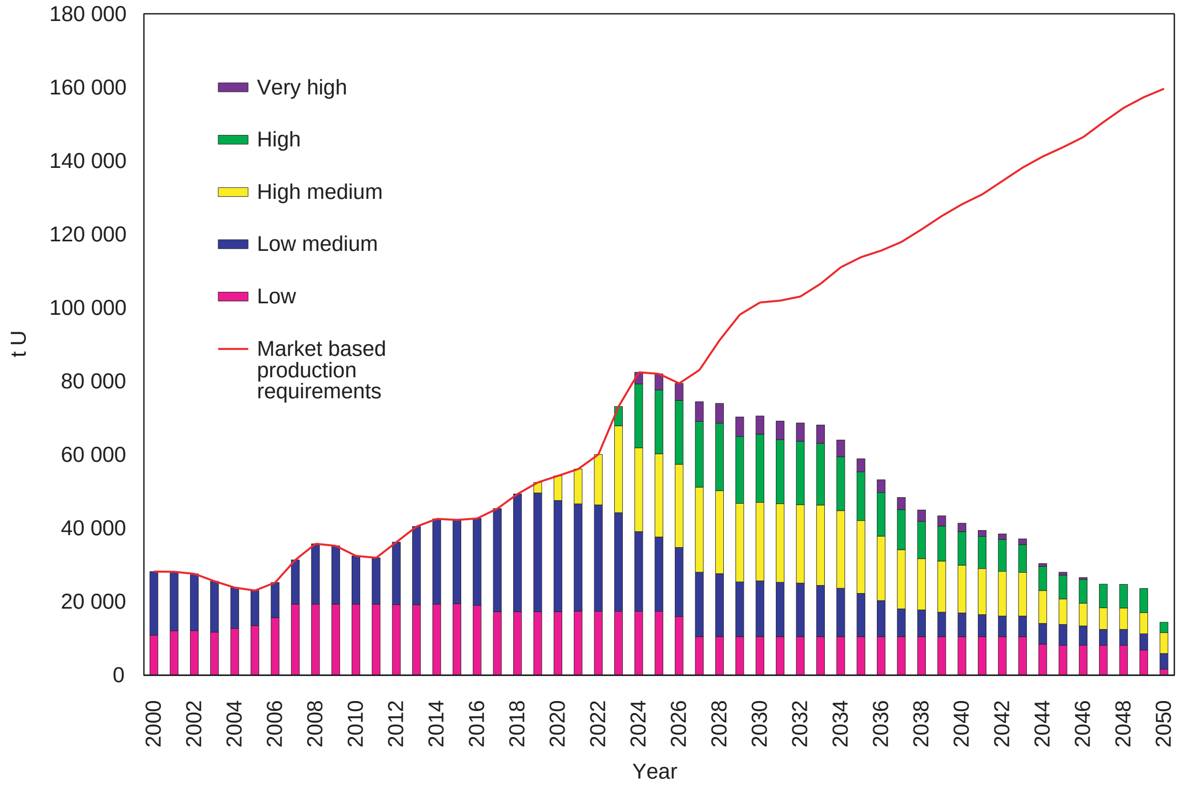


FIG. 16. Projection of market based production from study RAR by cost category — middle demand case.

that of technical uncertainty. Assumptions have been made regarding the extraction methods that will apply to each deposit. However, most of the deposits have not had the benefit of test mining, and their amenability to a given extraction method bears some uncertainty. This is particularly true of ISL projects, in which groundwater chemistry, host sand mineralogy and inhomogenities in the host sand can affect the recovery rate and even viability of a deposit to ISL extraction. Bench testing of host sand core cannot always detect potential leaching problems in the natural aquifer setting. There are also study RAR attributable to deposits in which the uranium occurs in refractory minerals. High processing costs are assumed for these deposits, but there is the risk that recovery factors will be so low that the deposits will not be commercial within the framework of this report.

In the final analysis, every effort has been made to arrive at realistic production scenarios that fully consider all aspects of uranium production, including cost, technical feasibility, and environmental and political risk. As previously noted, these production scenarios are intended to characterize the uranium production industry (market based production) throughout the next 50 years based on a range of potential demand scenarios. They address adequacy of supply at different confidence levels, and they can indirectly be used broadly to project market price trends. They should not, however, be considered as absolute forecasts of the future. Section 4 provides details of the buildup of market based production scenarios for the low, middle and high demand cases. Total projected market based production requirements to 2050 for the three demand cases are as given in Table XX.

TABLE XX. PROJECTED MARKET BASED PRODUCTION REQUIREMENTS TO 2050

	Market based production requirements (t U)
Low demand case	1 917 990
Middle demand case	4 158 280
High demand case	6 406 190

Appendix III provides details on the uranium production industries of the leading worldwide producing countries and the resources each is expected to contribute to these total requirements. Appendix III also includes maps on which are located major deposits and/or important production centres. Space limitations preclude showing the locations of all production centres and deposits. Typically only one deposit is included in major districts; inclusion or exclusion of deposits on these maps is not meant to imply their overall importance.

4. ANALYSIS

As discussed in the previous section, resources are broadly subdivided by confidence level as determined by the reliability of the data on which they are based. Three main sources were used to determine resources, including personal knowledge of the consultants participating in the study supplemented by mining company reports and publications, the 1999 Red Book [3] and the International Uranium Resources Evaluation Project (IUREP) (Appendix III). Obviously there is a broad overlap among the three sources, but every effort has been made to eliminate duplication of resources. Four distinct resource categories are used, each with a very precise definition. While the definitions are precise, however, in practice defining where one resource category stops and the next one begins is less precise when utilizing published data. Therefore an analyst's judgement frequently determines whether resources belong to one category or the other, which can lead to inconsistencies in allocating resources to specific categories.

The Red Book is used as the key reference in this study, and resources are compared to the Red Book on a country by country basis (Table XVIII). It is important to remember, however, that the Red Book is based on data submitted by government institutions from each contributing country. Despite the best efforts of the IAEA and NEA, inconsistencies are inherent in a data collection process that depends on such a diverse information source. Some countries limit reported resources to those shown by feasibility studies to be viable under near term uranium prices. Others take a broader perspective and fully report resources recoverable at up to US $130/kg U, or nearly five times the current uranium spot market price. Still other countries have not reported resources to the Red Book for several years. Therefore resources used in this study exceed those listed in the Red Book for some countries, while for other countries the opposite is true. Every effort was made to document data sources for resources used in this study and to reconcile differences between the study resources and those in the Red Book. In the final analysis, however, resource calculation is not an exact science. It relies on a set of geological assumptions to define the characteristics of an ore body such that grade, thickness and continuity of the resources can be predicted within a specified confidence level. Resources calculated by two analysts given the same geologic data can differ dramatically. Therefore it is not realistic to expect complete reconciliation of all differences between the Red Book resources and those used in this study, which come from a variety of sources, not all of which are necessarily available to the Red Book contributors.

The following sections describe the details of the bottom-up approach to evaluating resource utilization based on a combination of confidence category for the resources and projected production costs. The ultimate goal is to assess the adequacy of resources to fill market based production requirements, starting with the lowest cost, highest confidence resources and progressively adding higher cost and/or lower confidence resources until demand is satisfied. Each subheading is divided into two sections: one discusses data synthesis, the other discusses caveats and limitations to the use of the data.

4.1. URANIUM RESOURCES AVAILABILITY AND UTILIZATION — MIDDLE DEMAND CASE

4.1.1. Study RAR — data synthesis

RAR that consultants contributing to this study were able to attribute to specific deposits (study RAR) are accorded the highest level of confidence. More specific information is publicly known about the geology, mining methods and production costs for these resources than the others, and this knowledge was used as the first step in assessing resource adequacy and for modelling projected changes in the uranium production industry over time. As described in Section 3.2.5.4, production cost ranking was used to determine the order in which production centres will be brought on line in order to fill annual market based production requirements. Once this process was completed, projected changes in the structure of the uranium production industry over time became apparent. As previously noted, these projections should not be considered to be absolute forecasts of the future, but as overviews of how the industry structure could change over time based on a variety of different input parameters.

Figure 16 projects production cost trends as output expands to meet growing requirements for market based production. As projected in Fig. 16, study RAR will be adequate to satisfy market based production requirements to 2026, after which lower confidence resources will play an increasingly important role. This is the case under both the conservative and accelerated scenarios for CIS production, which is potentially the most uncertain of the supply sources, except for market based production. There is in fact only minimal practical difference between the two CIS scenarios as far as study RAR utilization is concerned. Table XXI compares the deficit between production based only on study RAR and market based production requirements for the two CIS production scenarios.

Since the difference between the two scenarios is relatively small, future discussions and comparisons will relate to the conservative scenario. Not surprisingly, as projected in Fig. 16, requirements for higher cost production increase over time, but even so, low and low medium cost resources are projected to be adequate to meet market based production requirements to about 2018. Therefore market prices could remain at or below US \$52/kg U (US \$20/lb U_3O_8, US \$44/kg U_3O_8) to 2018, provided future supply and demand relationships are similar to the middle demand case.

The remainder of this section will focus on the period from 2000 to 2026, because it is during this time that study RAR, about which considerable data are available, are projected to be adequate to satisfy market based production requirements. Figure 17 shows a portion of the spreadsheet that was used to balance production derived from study RAR and market based production requirements. Each line represents an individual production centre; however, the names of the production centres have been deleted to eliminate unnecessary controversy associated with the cost ranking. Figure 17 illustrates how the next higher cost production centres are added as needed to satisfy annual increases in market based production requirements. The numbers on the spreadsheet represent the production (t U) that each production centre will contribute towards satisfying a given year's requirements. Figure 18 tracks the number of production centres that are projected to be in operation in any given year. To 2007 the industry will be relatively stable, with between 17 and 19 production centres, all but one of which are currently in operation; two facilities are projected to shut down and one (Cigar Lake) is expected to start up. During this time the industry will be dominated by the large capacity operations in Canada and Australia. In 2007 the five largest production centres will account for 72% of the total nominal capacity of all active operations; 13 production centres will account for the remaining 28%. Between 2007 and 2017 the number of production centres is projected to grow in a stepwise fashion. The number increases steadily between 2008 and 2022, followed by a dramatic increase between 2022 and 2025. The actual number of production centres that will be required will depend on the capacities of the next lowest cost producers. Cigar Lake will be the last of the very large production centres to come on line for the foreseeable future. The next group of lower cost producers will be dominated by ISL projects that inherently have relatively small capacities, ranging between 385 and 770 t U annually. Therefore it would take between 9 and 18 ISL projects to equal the capacity of one Cigar Lake. This difference partly explains why the projected number of production centres is expected to increase by 400% between 2000 and 2026 to cover a 180% increase in market based production requirements during the same time frame.

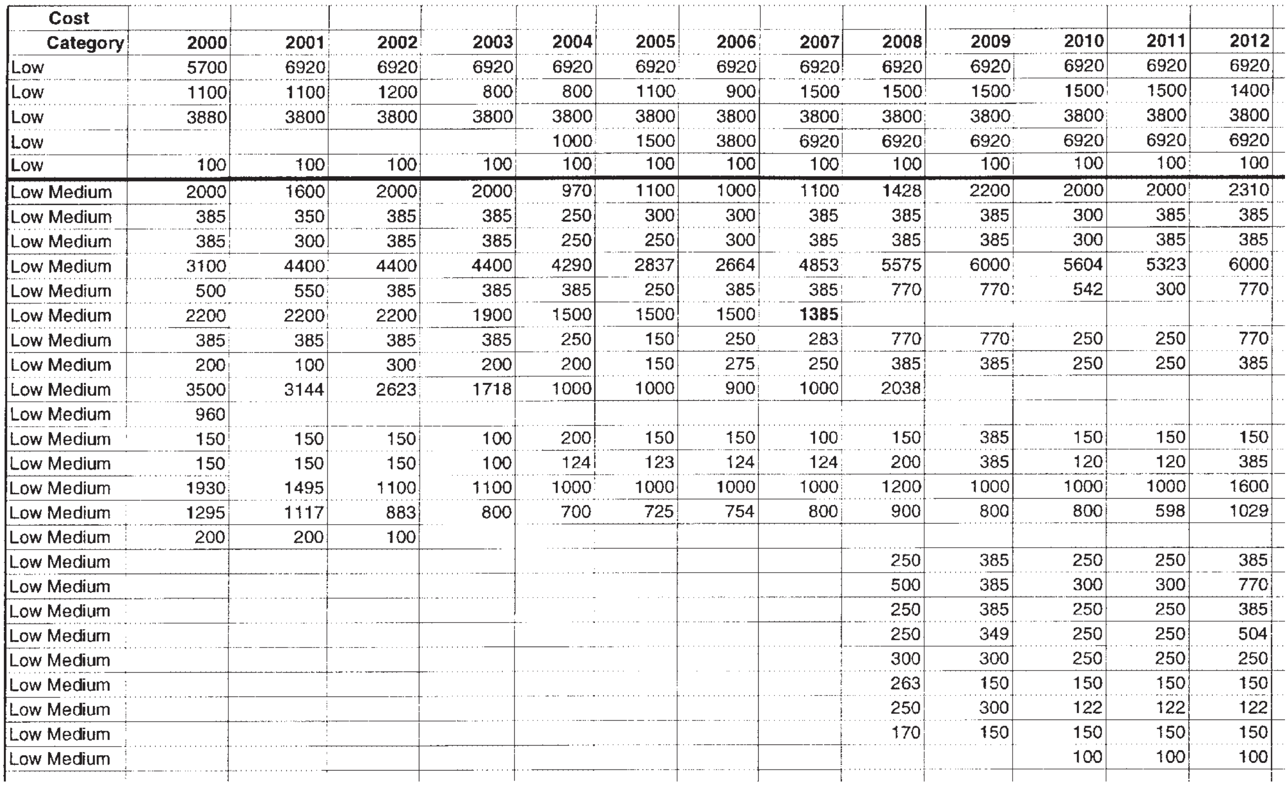
Table VII can be used to help explain the events leading to the trend of ever increasing numbers of production centres through time, shown in Fig. 18. For example, the increase between 2007 and 2008 is attributable to an increase in reactor demand and a reduction in supplier inventory drawdown. The dramatic increase between 2022 and 2025 coincides with the projected end of the current Russian and US HEU sales programme (middle demand case) and the need to increase production to ensure that suppliers' inventories are maintained at a strategic level.

Table XXII shows the role that different mining and extraction methods are projected to play in the market based production category throughout the next 25 years. ISL output is expected to triple between 2000 and 2015, mostly at the expense of open pit mining. After 2020, however, resurgence in production from open pit operations is projected, as lower cost ISL amenable resources

TABLE XXI. COMPARISON OF DEFICITS BETWEEN PRODUCTION AND MARKET BASED PRODUCTION REQUIREMENTS ASSUMING CONSERVATIVE AND ACCELERATED CIS SCENARIOS — BASED ON STUDY RAR (t U)

	Conservative scenario	Accelerated scenario
Deficit in 2027	(8 620)	(4 740)
Deficit in 2050	(159 600)	(139 290)
Cumulative deficit 2027 to 2050[a]	(1 839 070)	(1 665 050)

[a] Deficit between market based production requirements and cumulative production.



Cost Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Low	5700	6920	6920	6920	6920	6920	6920	6920	6920	6920	6920	6920	6920
Low	1100	1100	1200	800	800	1100	900	1500	1500	1500	1500	1500	1400
Low	3880	3800	3800	3800	3800	3800	3800	3800	3800	3800	3800	3800	3800
Low					1000	1500	3800	6920	6920	6920	6920	6920	6920
Low	100	100	100	100	100	100	100	100	100	100	100	100	100
Low Medium	2000	1600	2000	2000	970	1100	1000	1100	1428	2200	2000	2000	2310
Low Medium	385	350	385	385	250	300	300	385	385	385	300	385	385
Low Medium	385	300	385	385	250	250	300	385	385	385	300	385	385
Low Medium	3100	4400	4400	4400	4290	2837	2664	4853	5575	6000	5604	5323	6000
Low Medium	500	550	385	385	385	250	385	385	770	770	542	300	770
Low Medium	2200	2200	2200	1900	1500	1500	1500	**1385**					
Low Medium	385	385	385	385	250	150	250	283	770	770	250	250	770
Low Medium	200	100	300	200	200	150	275	250	385	385	250	250	385
Low Medium	3500	3144	2623	1718	1000	1000	900	1000	2038				
Low Medium	960												
Low Medium	150	150	150	100	200	150	150	100	150	385	150	150	150
Low Medium	150	150	150	100	124	123	124	124	200	385	120	120	385
Low Medium	1930	1495	1100	1100	1000	1000	1000	1000	1200	1000	1000	1000	1600
Low Medium	1295	1117	883	800	700	725	754	800	900	800	800	598	1029
Low Medium	200	200	100										
Low Medium									250	385	250	250	385
Low Medium									500	385	300	300	770
Low Medium									250	385	250	250	385
Low Medium									250	349	250	250	504
Low Medium									300	300	250	250	250
Low Medium									263	150	150	150	150
Low Medium									250	300	122	122	122
Low Medium									170	150	150	150	150
Low Medium											100	100	100

FIG. 17. Portion of the spreadsheet showing the introduction of production centres as needed to fill middle demand case study RAR.

and resources associated with combined open pit and underground mining are depleted. Production capacity limitations are clearly a factor in the growth pattern of ISL output. In 2008, for example, when the first increment of new projects will have to be added to meet market based production requirements, ISL production centres will account for 56% of the total number of operations, but only 14% of production.

Table XXIII is a summary of the changing contributions of different geologic deposit types over time. The unconformity related deposits in Australia and Canada will clearly dominate production until 2015, with a significant contribution from the Olympic Dam breccia complex (note: uranium is recovered as a significant by-product of copper production at Olympic Dam). Beyond 2015 other deposit types will have to be developed to satisfy market based production requirements. The reduction in the contribution of breccia complex deposits is somewhat misleading. Olympic Dam is expected further to increase production capacity beginning in about 2016, but the addition of other deposit types needed to fill requirements reduces Olympic Dam's overall percentage contribution. The increasing role of sandstone deposits reflects both the increased need for

TABLE XXII. STUDY RAR MARKET BASED PRODUCTION BY EXTRACTION METHOD — FIVE-YEAR INCREMENTS

	2000	2005	2010	2015	2020	2025
Underground	53%	64%	61%	50%	43%	45%
ISL	7%	6%	11%	21%	20%	16%
Open pit	18%	8%	3%	5%	20%	31%
By-product	4%	5%	5%	4%	6%	6%
Open pit/underground	18%	17%	20%	20%	11%	2%

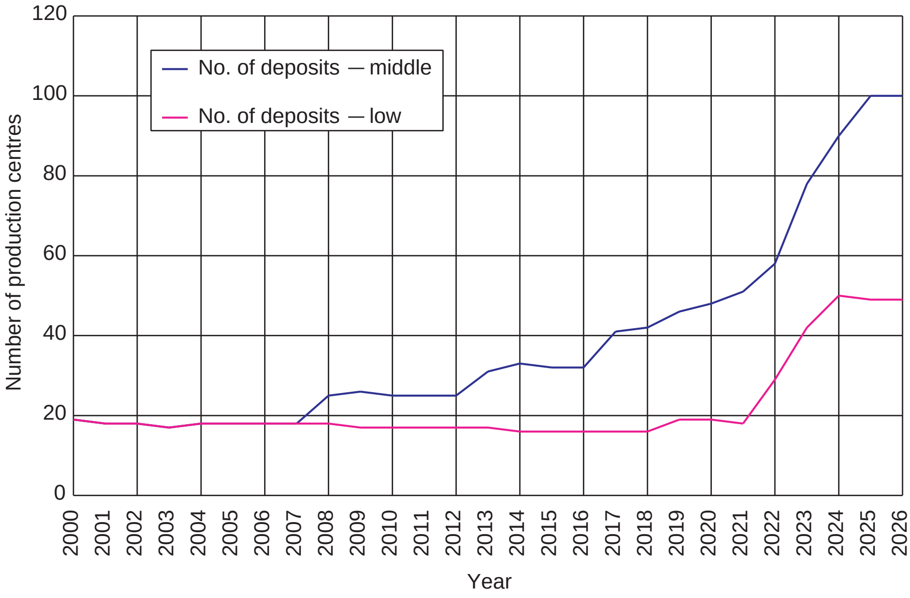


FIG. 18. Number of production centres in operation to 2026 — low and middle demand cases.

lower cost ISL projects as well as the availability of higher cost sandstone deposits that are not amenable to ISL extraction (e.g. the Westmoreland deposits in Australia and the Green Mountain deposits in the USA).

Figure 19 shows the changing contributions that different countries or regions will make in annual production between 2000 and 2026, when study RAR will no longer be adequate to fill market based production requirements. As noted in this figure, Canada and Australia will continue to be the dominant producers, although in about 2016 their positions are projected to reverse with Australia becoming the leading producing country. Two other trends are evident in Fig. 19. Production in the USA will begin to expand starting in 2008, at which point it will replace Niger as the third leading Western producing country behind Canada and Australia. This expansion reflects the large ISL amenable resource base in the USA and the increasing cost competitiveness of other US deposits as time progresses. In addition to the expansion in the USA, beginning in

TABLE XXIII. STUDY RAR MARKET BASED PRODUCTION BY DEPOSIT TYPE — FIVE-YEAR INCREMENTS

	2000	2005	2010	2015	2020	2025
Sandstone	19%	14%	17%	31%	27%	33%
Unconformity related	49%	59%	66%	54%	39%	17%
Quartz–pebble conglomerate	4%	5%	5%	4%	3%	5%
Breccia complex	26%	21%	12%	9%	12%	9%
Vein	1%				3%	4%
Intrusive					7%	9%
Volcanic						8%
Calcrete/surficial					4%	6%
Phosphate					2%	4%
Metasomatic						2%
Collapsed breccia pipe				2%	2%	2%
Metamorphic						1%
By-product	1%	1%	0.5%	0.5%	1%	0.5%

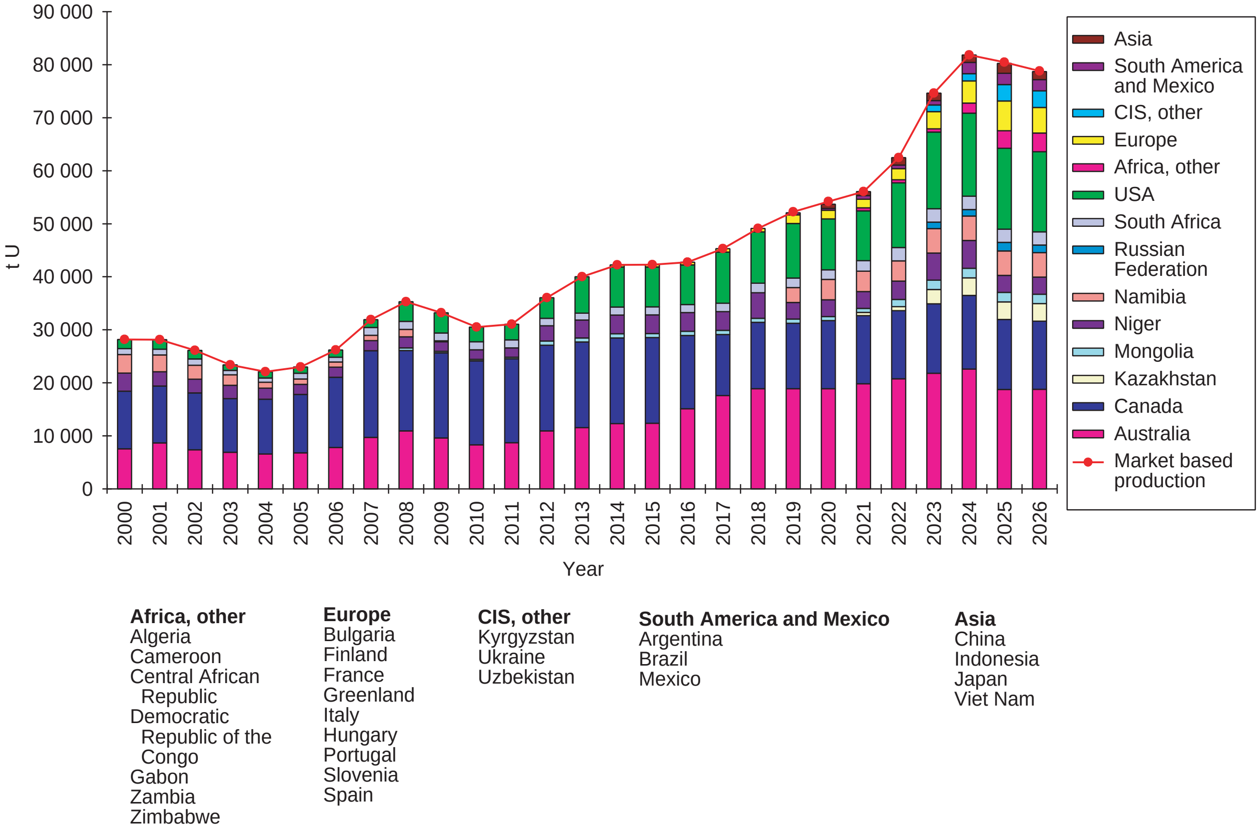


FIG. 19. Projection of study RAR market based production by country — middle demand case.

about 2021, production in the CIS that is not needed to satisfy the CIS production category is projected to start to enter the market on a cost justified basis.

4.1.2. Study RAR — data limitations

As previously noted, study RAR represent the highest confidence resources. In addition, since more specific information is publicly known about these deposits than for other resource categories, they are useful for projecting changing trends in the uranium production industry. Study RAR are, however, only the first building block in determining how market based production requirements will be filled. Therefore they provide only a partial perspective as to the total supply picture.

4.1.2.1. Unutilized resources

Table XVIII shows that there is a total of 3 276 100 t U of study RAR. However, only about 2 855 600 t U are available to satisfy market based production requirements, with the remainder being allocated to satisfy the CIS and Chinese production categories. In addition, it is not practical to expect that all of the remaining resources will be utilized within the time frame of this study. Under-utilization of resources typically comes about when deposits are not justified on a cost basis to come into production until later in the study period, in which case production capacity limitations can preclude total depletion of resources, particularly for deposits with large resource bases. Also, output from by-product operations is constrained by the demand for the primary product. Therefore uranium production capacity for by-product operations does not necessarily correspond to the uranium resource base as it does with conventional projects, which again can lead to under-utilization of resources. Table XXIV shows the potential impact of under-utilization of middle demand case study RAR.

This comparison indicates that owing to production timing and capacity constraints, 476 390 t U, or about 17%, of study RAR available to satisfy market based production requirements may not have been produced by

TABLE XXIV. PROJECTED UNUTILIZED STUDY RAR — MIDDLE DEMAND CASE

	t U
Total study RAR (Table XVIII)	3 276 100
Total required for CIS and Chinese production	480 500
Balance available for market based production	2 795 600
Total projected to be utilized for market based production	2 319 210
Potential unutilized resources	476 390

2050. Potential under-utilization highlights the fact that estimating resources is only part of the problem in assessing resource adequacy. Therefore production timing and capacity are also key components of this review. Table XXV shows the five production centres that account for approximately 93% of the unutilized resource total.

Nufcor produces uranium as a by-product of South Africa's gold mining operations. Therefore production capacity is constrained by gold output. The Nufcor resource base totals 239 000 t U, and even though the lower cost operation is projected to produce throughout the study period, and the higher cost operation from 2017 to 2050, there are simply practical limits to annual capacity, which explains the under-utilization of Nufcor resources. Total annual capacity of Kazakhstan's ISL operations is estimated at 4000 t U, of which 2600 t U is dedicated to the CIS production category. The remaining 1400 t U is not adequate to deplete the large ISL amenable resource base, which is estimated to total nearly 308 000 t U. The situation is the same for the Kokchetav complex in northern Kazakhstan, where a large resource base and production capacity constraints preclude depletion of resources prior to 2050. In the case of Kokchetav, the problem is exacerbated by the fact that this production is not cost justified until about 2023, which shortens the time frame in which to utilize its resources. Additional information regarding unutilized resources is provided in Section 5.1.6.

4.1.2.2. Implications of environmental and/or political opposition

The discussion in Section 4.1.1 assumes there are no constraints to implementing the resource utilization model, and resources are assumed to be brought into production as they are needed and cost justified. However, this is a very simplistic approach, and there are many potential obstacles to implementation of the model. Perhaps the most serious of these obstacles is that of the potential for environmental and/or political opposition. Western uranium mining and processing in recent times has an exemplary safety and environmental record, and programmes in the developing countries continue to adopt stronger environmental standards. Nevertheless, the world's environmental community continues to dwell on past mistakes, and to emphasize those mistakes in resisting uranium project development. A good example of the effect of environmental opposition on project development is the state of New Mexico in the USA. Up until 1983 New Mexico was the leading uranium producing state. Today, however, an informal coalition of environmental groups and Native American tribes has reversed what was once a pro-mining attitude, and New Mexico now has a strongly anti-uranium mining philosophy. An example of the effect that this philosophy has on project development is the permitting process for the Church Rock and Crown Point ISL projects, which has been underway for about nine years at a cost of US $10

TABLE XXV. PRODUCTION CENTRES THAT DOMINATE STUDY RAR UNUTILIZED RESOURCES

Centre	Country	t U
Itataia	Brazil	66 090
Nufcor	South Africa	113 340
Kazakhstan economic ISL	Kazakhstan	141 950
Kokchetav	Kazakhstan	59 030
Imouraren	Niger	62 570
Total		442 980

million — and there are still regulatory hurdles to overcome before either project can be put into production.

Australia is another case where anti-uranium policy has hindered project development. The Australian Labor Party's three mines policy effectively stalled expansion of the country's uranium production industry between 1983 and 1996. Although that policy was implemented by politicians, it had environmental underpinnings. The current government has made decisions regarding new uranium projects based on economics and lets economics and sound environmental planning rather than political policy control project development decisions. Nevertheless, the political risk remains high for the Australian industry because the Labor Party has indicated that if and when it is returned to power it will again restrict uranium output to then-producing mines. That policy would presumably allow two projects currently under development to proceed (Beverley and Honey-moon), but could prevent or deter future development of such projects as Kintyre, Koongarra and Manyingee.

Table XXVI serves to emphasize the potential that environmental opposition could have to disrupt implementation of the study RAR utilization model as currently projected in this analysis.

This table starts in 2013 when projects vulnerable to environmental opposition are projected to start coming on stream, and extends in two-year increments to 2025. It shows both total resources (t U) and the percentage of market based production requirements that could potentially be at risk because of environmental opposition. Table XXVI does not include projects (if any) in the CIS which could be affected by environmental constraints. It is important to emphasize that this discussion focuses on the possibility of opposition based on public perception of potential environmental risk; it in no way implies that these projects could not be developed and operated in compliance with modern environmental policy and practice. It is evident from Table XXVI that by midway through the study period, at least in the study RAR scenario, the risk of project deferrals or cancellations due to environmental opposition is no small consideration. Up to one quarter of the required resources that will be needed to meet market based production requirements in 2025 are potentially at risk. This is not meant to imply that the risks cannot be addressed and mitigated such that development can proceed, but only to identify and highlight the risk. Projects that were considered at risk of environmental opposition and are included in Table XXVI are shown in Table XXVII.

TABLE XXVI. SUMMARY OF STUDY RAR WITH POTENTIAL FOR ENVIRONMENTAL OPPOSITION

	2013	2015	2017	2019	2021	2023	2025
t U	1 100	3 393	7 027	8 390	9 108	15 675	20 532
Per cent of requirements	2.7	8	16	16	16	21	26

TABLE XXVII. PROJECTS CONSIDERED AT RISK OF ENVIRONMENTAL OPPOSITION

Australia	Canada	Czech Republic	France	Italy	USA (New Mexico)	USA (other)
Angela	Blizzard	Stráž	Coutras	Novazza	Borrego Pass	Arizona Strip breccia pipes — Arizona
Kintyre	Elliott Lake				Dalton Pass	Hansen — Colorado
Ben Lomond					Church Rock	Swanson — Virginia
Bigrlyi					Crown Point	
Koongarra					Grants mineral belt	
Manyingee					L Bar	
Mount Painter					Marquez	
Mulga Rock					Mount Taylor	
Valhalla/Mount Isa					Nose Rock	
Westmoreland					West Largo	
Yeelirree						
Yilgarn calcrete deposits						

A sensitivity analysis is included in Section 5.1.5.3 that evaluates the impact on the balance between supply and demand if the resources associated with projects potentially subject to environmental and/or political opposition are removed from the resource base.

4.1.3. Non-attributed RAR — data synthesis

For purposes of this report the highest confidence RAR are those that consultants working on the study could directly attribute to known deposits (i.e. study RAR). RAR not directly attributable to known deposits are termed non-attributed RAR. The total of the two categories comprises RAR as reported in the Red Book. Therefore, where study RAR are less than Red Book RAR in a given country (Table XVIII), they are subtracted from Red Book RAR to determine non-attributed RAR. The distinction between the two categories in no way calls into question the validity of the non-attributed RAR. Instead, it simply means that less is known about the non-attributed RAR in terms of their location, geology, extraction method and cost. However, designation as study RAR does not carry with it any assurance that a project will be developed, nor is it implied that non-attributed RAR will necessarily be developed after those in the higher confidence category.

Table XXVIII is a summary of non-attributed RAR. Without details as to geology or extraction method, production costs are assigned to these RAR based on Red Book cost estimates. Production cost is the only criterion that determines when non-attributed RAR are projected to begin operation. For example, in accordance with data from Table XXVIII, a project designated Australia high medium, with resources totalling 55 400 t U, is introduced into the production balancing model that is used to determine when additional production capacity is needed to meet market based production requirements. The exact placement of the non-attributed RAR in the cost ranking is subjective, and depends on the consensus judgement of the consultants.

Generally, however, non-attributed RAR in a given cost category are assumed to be similar to study RAR in the same cost category within a given country, and are placed in the cost ranking accordingly. Similarly, assigning a production capacity to non-attributed RAR is subjective, but is again guided by production facilities within the same country. Adjustments are made in production capacity to ensure maximum utilization of resources within practical limits. Non-attributed RAR in a lower cost category are assumed to start production before higher cost study RAR.

Since they typically have projected production costs in the high medium to very high range, introduction of non-attributed RAR will have little impact on the structure of the industry until about 2022, when the first non-attributed RAR production centre is cost justified. In fact, non-attributed RAR are only expected to extend for one year, from 2026 to 2027, the period when RAR will be adequate to satisfy market based production requirements. Figure 20 shows the contribution of study and non-attributed RAR between 2000 and 2050. Table XXIX shows a comparison of market based production with and without availability of non-attributed RAR.

TABLE XXVIII. SUMMARY OF NON-ATTRIBUTED RAR (1000 t U) BY COST CATEGORY

Country	High medium	High	Very high	Total
Australia	55.40	67.20		122.60
France	5.22	1.78		7.00
Greenland			16.00	16.00
Namibia	26.07	31.24		57.31
South Africa		48.90		48.90
USA		41.90		41.90
Subtotal of countries with study RAR	86.69	191.02	16.00	293.71
Germany		3.00		3.00
Peru	1.78			1.78
Somalia		6.60		6.60
Sweden		4.00		4.00
Turkey	9.13			9.13
Total	97.60	204.62	16.00	318.22

TABLE XXIX. MARKET BASED PRODUCTION WITH AND WITHOUT NON-ATTRIBUTED RAR

	Without non-Attributed RAR	With non-attributed RAR
First year of deficit compared with market based production requirement	2027	2028
Cumulative production (t U)	2 319 210	2 617 860
Cumulative deficit[a] (t U)	(1 839 070)	(1 540 410)
Potential unutilized resources (t U)	476 390	515 820

[a] Deficit between market based production requirements and cumulative production.

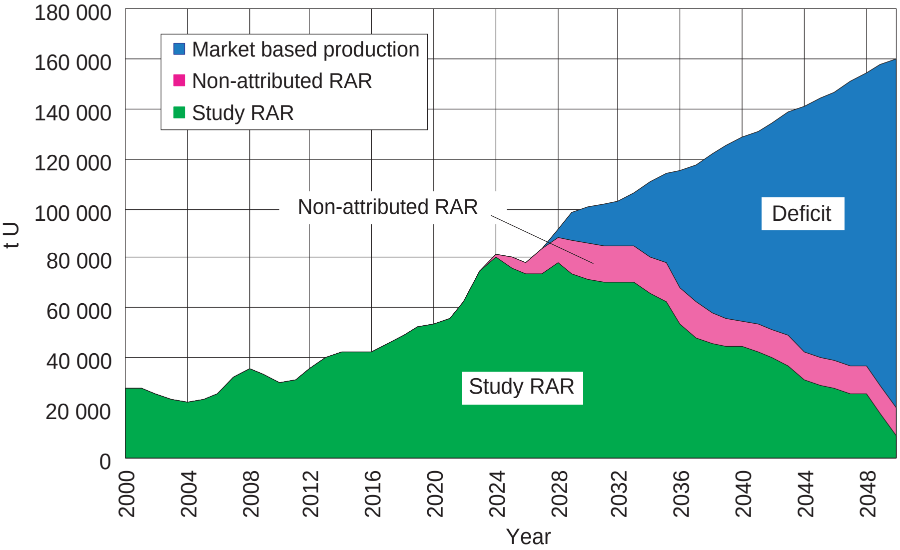


FIG. 20. Total RAR production compared with market based production requirements — middle demand case.

Because of the under-utilization of a portion of the non-attributed RAR, the difference in cumulative production does not equal total non-attributed RAR.

4.1.4. Non-attributed RAR — data limitations

The most obvious limitation to the non-attributed RAR is the lack of data on which to characterize them. As a rule, less is known about their geology, mining methods and production costs; therefore their placement within the cost ranking structure as well as their projected production capacity is subjective. Modelling these RAR after the study RAR counterparts in their respective countries at least provides a frame of reference, but the overall lack of specificity is definitely a limitation for the non-attributed RAR.

Without detailed information about the non-attributed RAR, assigning production capacity to these new resources is also subjective. Table XXX summarizes the capacities assigned to each cost category of non-attributed RAR. The capacities shown in this table represent the total for each category within a country. It is not meant to imply that the capacities shown represent a single production centre; several production centres could be involved in some countries and a single centre in others.

4.1.5. Total RAR — data limitations

There is one inconsistency in the RAR analysis that needs clarification. As noted in Section 3.2.5.1, the Russian Federation's and Uzbekistan's RAR are not adequate to satisfy their projected requirements in the CIS production category. Therefore 24 100 t U of EAR-I are required to satisfy the deficit between the Russian Federation's RAR and its CIS production category requirements. Uzbekistan's projected deficit will require all of its RAR, EAR-I and EAR-II plus 18 670 t U of SR.

TABLE XXX. PROJECTED PRODUCTION CAPACITIES FOR NON-ATTRIBUTED RAR

Country	Cost category	Capacity (t U)
Australia	High medium	2000
Australia	High	3000
France	High medium	770
France	High	250
Germany	Very high	385
Greenland	Very high	385
Namibia	Medium high	2000
Namibia	High	1250
Peru	High medium	250
Somalia	High	385
South Africa	High	2000
Sweden	High	385
Turkey	High medium	770
USA	High	2000

As has been previously discussed, the distinction between RAR and EAR-I, while clear in their definitions, is less distinct in practical use. One analyst may place resources in RAR, while another may feel that the data are insufficient for such a high confidence category and are insufficient for such a high confidence category and accordingly would place the same resources in EAR-I. Beginning in 1991, progress has been made in ensuring consistency between CIS resource categories and those utilized by the IAEA/NEA. Despite this progress, however, there remain inconsistencies in the distinction between the two resource categories. There may also be deposits included in RAR in this report that are not included in the Red Book RAR.

Therefore an analysis was completed to determine the effect that strictly confining this analysis to Red Book RAR for the CIS would have. Both the Russian Federation's and Uzbekistan's output in the CIS production category were reduced to equal their respective Red Book RAR. The Russian Federation's production based solely on Red Book RAR would terminate in 2038, while Uzbekistan's production would end in 2022. It is important to note that neither of these cases is considered likely to happen, as lower confidence resources are expected to be upgraded to RAR through further exploration and development. Table XXXI shows a comparison of the market based production category between two scenarios: (1) use of lower confidence resources to fill the Russian Federation's and Uzbekistan's requirements; and (2) limiting production in both countries strictly to Red Book RAR. This comparison is based only on study RAR.

As can be seen from this comparison, strict adherence to Red Book RAR for Russian and Uzbekistan production advances by three years the point at which RAR will no longer be adequate to satisfy market based production requirements. It also increases the market based production requirement in the years after 2024 to offset reduced production in the CIS production category due to resource limitations. Therefore the cumulative deficit increases from 1.54 million to nearly 2.0 million t U. These changes all take place after 2024, and do not, therefore, influence the dates at which higher cost projects are projected to come into production.

4.1.6. EAR-I — data synthesis

EAR-I constitute the next lower confidence level of resources below non-attributed RAR. As defined in the Red Book, RAR plus EAR-I comprise total known resources. The Red Book is used as the source of EAR-I for this study, but adjustments have been made in the Red Book totals to account for EAR-I that are projected to be required to support the Russian Federation's and Uzbekistan's requirements in the CIS production category. An additional adjustment was made to EAR-I in Canada. As shown in the following comparison, the study RAR total for Canada, including low, low medium and high

TABLE XXXI. COMPARISON BETWEEN MARKET BASED PRODUCTION LIMITED TO USE OF NON-RAR AND RED BOOK RAR TO SATISFY CIS PRODUCTION REQUIREMENTS

	Assuming use of non-RAR	Restricting use to Red Book RAR
First year of deficit	2027	2024
Cumulative production (t U)	2 617 860	2 303 420
Cumulative deficit[a] (t U)	(1 540 410)	(1 992 000)
First year high medium cost required	2019	2019
First year high cost required	2024	2023

[a] Deficit between market based production requirements and cumulative production.

medium cost resources, closely approximates RAR + EAR-I in the <US $80/kg U category in the Red Book. Additional information on Canada's known resources is provided in Appendix III.

Study RAR totals:	Low + low medium cost	416 000 t U
	High medium cost	8700 t U
	Total	424 700 t U
Red Book totals:	RAR <US $80/kg U	326 420 t U
	EAR-I <US $80/kg U	106 590 t U
	Total	433 010 t U

The close comparison between these two totals suggests that they include basically the same resources. However, they are classified differently, with this study according a larger percentage of the lower cost Athabasca Basin resources a higher confidence ranking than did the Canadian Red Book contributors. Neither is necessarily right or wrong, it is simply a matter of interpretation which points out the subjectivity of resource classification.

Table XXXII shows the distribution of EAR-I by geography and cost category. The five countries with the most EAR-I are identified separately; the remaining counties are grouped under a single category, other countries. Canada is not allocated any EAR-I because, as previously noted, the Red Book EAR-I are presumed already to be included in study RAR. Production capacities were assigned to each country or group of countries by cost category based on total resources (Table XXXIII). The size of each category's resource base and when they are projected to be cost justified to satisfy market based production requirements were the main criteria in determining production capacities. Resource utilization was also a factor in assigning production capacities, although knowledge of a country's geology and known uranium deposits was used to keep capacities within practical limits. As was the case with non-attributed RAR, the capacities shown in Table XXXI are not meant necessarily to represent a single production centre; several production centres could be involved in some countries and a single centre in others.

TABLE XXXII. DISTRIBUTION OF EAR-I BY GEOGRAPHY AND COST CATEGORY (1000 t U)

	Low medium	High medium	High	Very high	Total
Australia	88.20	58.20	47.00		194.00
Brazil		100.20			100.20
Canada					0[a]
Kazakhstan	79.24	57.68	57.33		194.25
Namibia	70.55	20.27	16.69		107.51
South Africa	48.10	18.70	6.90		73.70
Subtotal	286.09	255.65	127.92		669.66
Other countries	16.23	54.30	116.67	21.67	208.88
Total	302.32	309.95	244.59	21.67	878.54

[a] See discussion in text.

TABLE XXXIII. PRODUCTION CAPACITIES ASSIGNED TO EAR-I (t U/a)

	Low medium	High medium	High	Very high
Australia	2750	2250	2300	
Brazil		2000		
Kazakhstan	2000	2250	2000	
Namibia	2250	850	900	
South Africa	1000	770	385	
Other				
Four countries	770			
Eleven countries		2200		
Fourteen countries			3000	
Three countries				770

Since even less is known about the details of EAR-I regarding their deposit type and mining method, EAR-I are placed in the cost ranking at the bottom of their respective cost category. Therefore EAR-I are projected to start production before higher cost RAR, thus delaying development of higher confidence but higher cost resources. Since they are placed at the bottom of the cost ranking categories, EAR-I do not displace or delay RAR in the same category.

Figure 21 shows the contribution of study and non-attributed RAR and EAR-I between 2000 and 2050. Table XXXIV shows the impact of successively adding lower confidence levels of resources, starting with study RAR and progressing through non-attributed RAR and finally to EAR-I.

As shown in this comparison, with the addition of EAR-I, known resources (RAR + EAR-I) are adequate to satisfy market based production requirements to 2034, or eight years longer than the scenario restricted to study RAR. Cumulative production increases by about 42% with the addition of EAR-I, and the cumulative deficit decreases by 54%. Because EAR-I production is not projected to be cost justified until 2019, its introduction does not change the production cost structure significantly, adding only two years to when high medium cost production will be required. Cumulative production derived from known resources is adequate to satisfy 80% of total market based production requirements to 2050, despite the fact that 17% of known resources available to meet market based production requirements will not have been utilized by 2050.

4.1.7. EAR-I — data limitations

The most significant limitation to EAR-I is the limited specific information available as to deposit type, extraction method and production cost. Only Kazakhstan among the countries reporting significant EAR-I (Table XXXII) provides any information as to the location of its EAR-I. Kazakhstan estimates that 74% of its known resources (RAR + EAR-I) recoverable at <US $80/kg U are tributary to existing and committed production centres. It also estimates that 38.5% of the EAR-I are projected to be amenable to ISL; the remaining 61.5% are recoverable by conventional mining methods.

While EAR-I is reported by cost category, some countries provide a less specific cost breakdown than others. Australia, for example, groups all of its lower cost EAR-I in the <US $80/kg U category, so no information is available as to allocation in the <US $40 and US $40–80/kg U categories. As shown in Table XXXII, Australia reports a total of 194 000 t U of which 147 000 t U can be produced at <US $80/kg U.

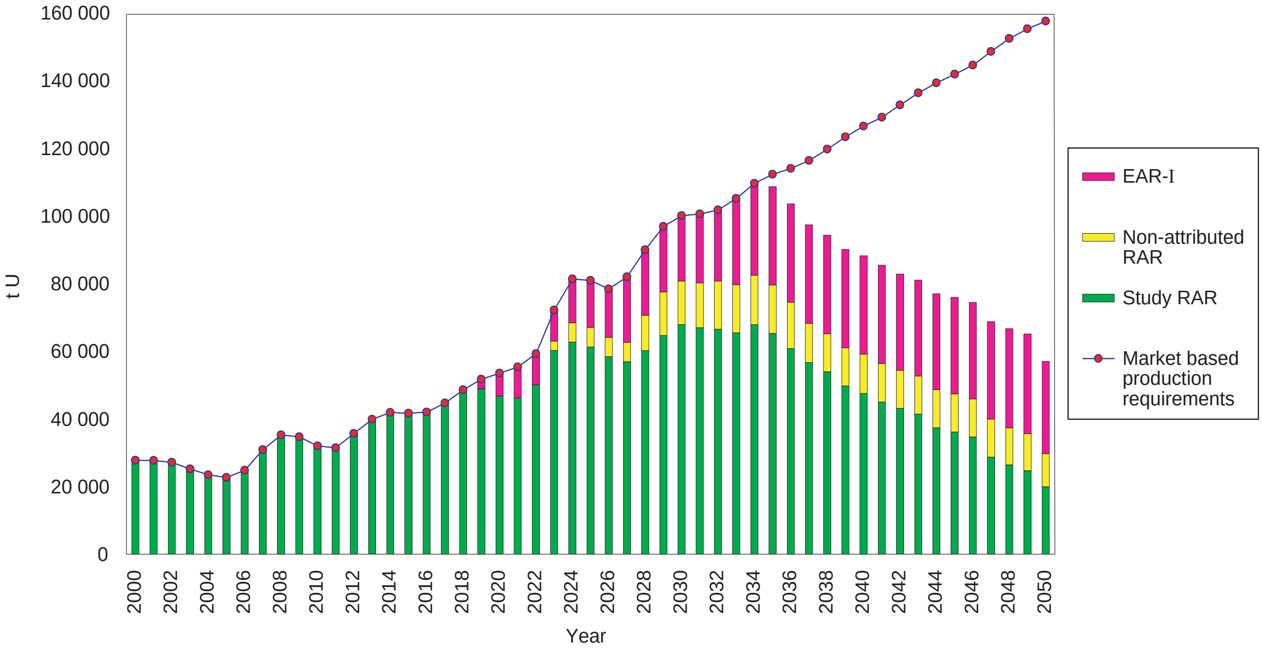


FIG. 21. Resource contribution by confidence level through to EAR-I — middle demand case.

TABLE XXXIV. COMPARISON OF THE EFFECT OF ADDING LOWER CONFIDENCE RESOURCES TO THE MARKET BASED PRODUCTION STREAM

	Study RAR	Total RAR	RAR + EAR-I
First year of deficit compared with market based production requirement	2027	2028	2035
Cumulative production (t U)	2 319 210	2 617 860	3 313 780
Cumulative deficit[a] (t U)	(1 839 070)	(1 540 410)	(844 500)
Potential unutilized resources (t U)	476 390	515 820	698 440
First year high medium cost required	2019	2019	2021
First year high cost required	2023	2024	2027
First year EAR-I cost justified	NA[b]	NA	2019

[a] Deficit between market based production requirements and cumulative production.

[b] NA: not applicable.

The cost distribution of Australia's study RAR was used as a guide to define further its EAR-I cost allocation. Distribution of Australia's study RAR in the low medium through to high cost categories is as follows:

Per cent of RAR in low medium to high cost categories	
Low medium	77
High medium	10
High	13

Since low medium cost resources dominate Australia's RAR, a similar pattern was used to estimate cost allocation for its EAR-I. However, a more conservative estimate of the percentage contribution of low medium cost EAR-I was used (45% for EAR-I compared to 77% for RAR), with the remainder distributed between the two higher cost categories. Australia's EAR-I cost categories are allocated as follows:

Per cent of EAR-I allocated to low medium and high medium cost categories	
Low medium	45
High medium	30
High	25

Some countries do not report EAR-I, which is obviously another significant limitation to this resource category. The USA, for example, does not report EAR-I and EAR-II separately; instead, it reports only EAR-II. It is important to note that US EAR-II accounts for 57% of EAR-II in the <US $80/kg U category and 55% of total EAR-II. Therefore it is likely that at least a portion of US EAR-II belongs in EAR-I, but without information to base it on there is no way to allocate resources between the two categories. Consequently, none are included in EAR-I, which could result in significantly understating known resources.

4.1.8. EAR-II — data synthesis

With the inclusion of EAR-II we move from known resources to undiscovered resources. Significant exploration will be required to move EAR-II into the known resources category. As noted in Appendix V, EAR-II are based on indirect evidence, which puts them in a lower confidence, higher risk category than EAR-I. They are, however, believed to occur within well defined geologic trends containing known deposits.

The same basic approach has been used for EAR-II as was used for EAR-I. Red Book data were the only source for EAR-II. Table XXXV shows the distribution of EAR-II by geography and cost category. The six countries reporting the most EAR-II are listed separately. All remaining countries are grouped under 'other countries'. As noted in Table XXXV, Uzbekistan's reported EAR-II have been adjusted to account for EAR-II needed to satisfy its requirements under the CIS production category.

Production capacities were assigned to each country or group of countries by cost category. The total resource base in each category was the main criterion for determining production capacities. Resource utilization within practical limits was also a factor in assigning capacities. The production capacities shown in Table XXXVI for each country and cost category could represent a single production centre or several centres.

EAR-II are placed in the cost ranking at the bottom of their respective cost categories (i.e. below EAR-I in the same cost category). Therefore EAR-II in a lower cost category are projected to start cost justified production before all higher cost resources, even those with a higher confidence ranking. Figure 22 shows the projected contribution of RAR through to EAR-II between 2000 and 2050, and how the gap between market based production requirements and production narrows with the addition of lower confidence

TABLE XXXV. DISTRIBUTION OF EAR-II BY GEOGRAPHY AND COST CATEGORY (1000 t U)

	High medium	High	Total
Brazil	120		120
Canada	50	100	150
Kazakhstan	290	20	310
Russian Federation	56	49	105
South Africa	35	113	148
USA	839	434	1273
Subtotal	1390	716	2106
Other countries	22	97	119
Total[a]	1412	813	2225

[a] Uzbekistan reports 48 000 and 20 000 t U in the <US $80 kg U and US $80–130 kg U categories, respectively; however, all but 11 000 t U is needed to satisfy its CIS production requirements.

TABLE XXXVI. PRODUCTION CAPACITIES ASSIGNED TO EAR-II (t U/a)

	High medium	High
Brazil	3000	
Canada	4000	4000
Kazakhstan	4000	770
Russian Federation	4000	4000
South Africa	2000	4 000
USA	5000	5000
Other		
Five countries	1000	
Twelve countries		4000

resources. As shown in Fig. 22 and in Table XXXVII, the total of RAR through to EAR-II is projected to be sufficient to satisfy market based production requirements to 2041.

As shown in this comparison, total resources including EAR-II are adequate to cover market based production requirements until 2042, or only eight years from the end of the study period, compared with 2028 and 2035 for total RAR and RAR + EAR-I, respectively. Introduction of EAR-II reduces the deficit between based production requirements and production to 306 750 t U. Also of significance is the fact that potentially unutilized resources are projected to total 2 385 680 t U, or eight times the projected deficit. High medium and high cost EAR-II are not projected to be cost justified until 2027 and 2038, respectively, which limits their production life, hence the significant underutilization total. However, there are clearly available resources to cover market based production requirements. If market prices increase at a higher than projected rate, or if production capacity can be increased for even 20% of the projected unutilized resources, market based production requirements could be readily covered by RAR + EAR-I + EAR-II. Lowering of production costs is certainly possible. Reporting of EAR-II is limited to only two cost categories: <US $80 and US $80–130/kg U. However, an unspecified amount of the <US $80/kg U EAR-II are likely to be recoverable in the low medium cost range, which would accelerate their entry into the production stream. This acceleration in production would reduce EAR-II under-utilization, perhaps even to a level that resources through to EAR-II would entirely cover market based production requirements in the middle demand case.

4.1.9. EAR-II — data limitations

The same limitations that apply to EAR-I also apply to EAR-II, namely the limited amount of information available regarding deposit type, extraction method and production cost. Kazakhstan estimates that 84% of its EAR-II are amenable to ISL and 16% to conventional extraction, but that is the only detail available among the countries reporting significant EAR-II. Although countries do not provide specific information regarding their reported EAR-II, there are, nevertheless, prospective areas that are probably included in EAR-II totals about which at least some information is available. For example, the P2 geophysical conductor along which the McArthur River deposit in Canada is located extends for 8 km beyond the currently defined limits of the ore body. There is insufficient information to make detailed resource calculations along this trend, but it clearly has significant potential, either to extend the McArthur River deposit or to host another, similar ore body. Therefore it is probable that the McArthur River trend is included in Canada’s reported EAR-II. Although Canada only

TABLE XXXVII. COMPARISON OF PRODUCTION AND COST PARAMETERS — RAR THROUGH TO EAR-II, MIDDLE DEMAND CASE

	Total RAR	RAR + EAR-I	RAR + EAR-I + EAR-II
First year of deficit compared with market based production requirement	2028	2035	2042
Cumulative production (t U)	2 617 860	3 313 780	3 851 530
Cumulative deficit[a] (t U)	(1 540 420)	(844 500)	(306 740)
Potential unutilized resources (t U)	515 820	698 440	2 385 680
First year high medium cost required	2019	2021	2021
First year high cost required	2024	2027	2029
First year EAR-I cost justified	NA[b]	2019	2019
First year EAR-II cost justified	NA	NA	2027

[a] Deficit between market based production requirements and cumulative production.

[b] NA: not applicable.

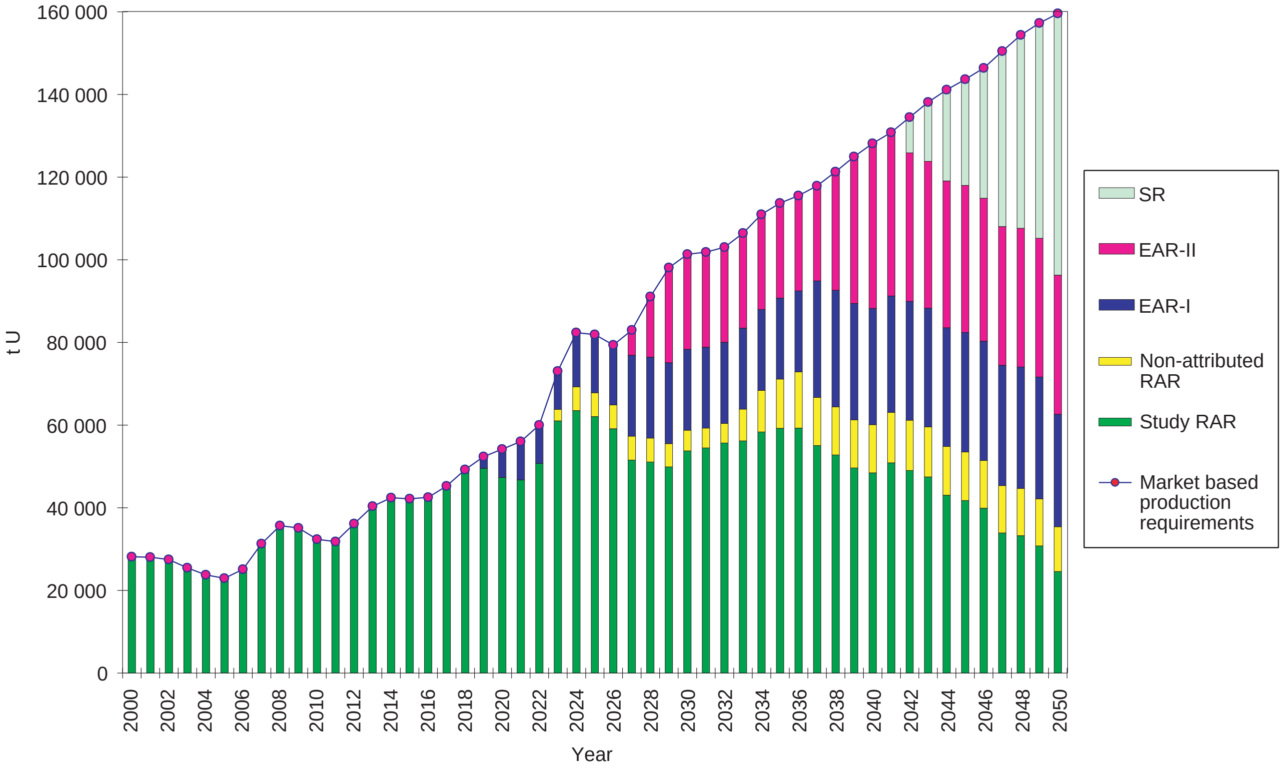


FIG. 22. Resource contribution by confidence level through to EAR-II and SR — middle demand case.

reports EAR-II as <US $80/kg U, resources along the P2 conductor certainly have the potential to be in the low medium cost category.

The potential for other discoveries in the Athabasca Basin was underscored by Cameo's 1999 announcement of drill results on the LaRocque Lake claims, which are part of the Dawn Lake joint venture (Cameco, Cogéma and PNC Exploration (Canada)). High grade mineralization has been encountered in three drill holes at depths of approximately 285 m below the surface. Included among the intercepts in the three drill holes are: 8.6 m, 7.0% U, 7.0 m, 25.4% U and 2.5 m, 16.1% U. Cameco's announcement was cautiously worded, stating that the results are encouraging, but are "not sufficient to draw conclusions as to the economic significance of the mineralization or the likelihood of the occurrence of a uranium deposit". Nevertheless, the LaRocque claims mineralization is separate from the known Dawn Lake deposit, and apparently constitutes a new, yet to be evaluated, discovery. Although much more drilling and evaluation is required, the LaRocque mineralization clearly indicates that the eastern margin of the Athabasca

Basin still has the potential for discoveries at a reasonable depth, which lends credence to Canada's EAR-II estimates.

These examples are included to emphasize that, while EAR-II have limitations because they are not accompanied by specific supporting information, they have a sound geologic basis. According to the 1999 Red Book [3], historical worldwide exploration expenditures to 1998 totalled nearly US $7800 million dollars, and this total does not include pre-1990 expenditures in the USSR or Eastern Bloc countries. These expenditures led to the discovery of the resources that are either currently being mined or have been mined in the past. They also provide the data on which RAR through to EAR-II are based. In addition, past exploration expenditures provided a much better geologic framework that in turn has led to a better understanding of exploration models on which to base resource projections.

4.2. URANIUM RESOURCES AVAILABILITY AND UTILIZATION — LOW DEMAND CASE

Market based production requirements based on the low demand case total 1 917 990 t U. Study RAR are projected to be adequate to meet these requirements with sufficient unutilized resources to accommodate eventualities such as reduced HEU deliveries. Once it was established that study RAR will be adequate to satisfy market based production requirements under the low demand case, no other analysis was deemed necessary for this case. Table XXXVIII compares the low and middle demand cases based solely on the study RAR scenario.

As shown by this comparison, the low demand case would extend by five years the time before which high medium cost production will be required. Based on this projection, uranium spot market prices could remain at or below US $52/kg U (US $20/lb U_3O_8, US $44/kg U_3O_8) until 2024. As shown in Fig. 18, the industry is expected to grow at a much slower rate under the low demand case. Only 19 production centres are projected to be required in 2020 under the low demand case compared to 48 for the middle demand case.

4.3. URANIUM RESOURCES AVAILABILITY AND UTILIZATION — HIGH DEMAND CASE

As noted in Section 3.1, the high demand case assumes high economic growth and provides for significant development of nuclear power compared to the more modest expectations of the middle demand case. As a consequence, cumulative reactor uranium requirements from 2000 to 2050 for the middle and high demand cases total 5.4 million and 7.6 million t U, respectively. As shown in Fig. 6, the middle and high demand cases begin to diverge in 2005. This divergence continues to grow throughout the study period, and as a consequence cumulative market based production requirements are approximately 2.25 million t U higher in the high demand case compared to the middle demand case. Since we are dealing with the same resource base in both demand cases, satisfying the accelerated demand schedule requires accelerated utilization of resources. Figure 23 and Tables XXXIX–XLI compare the net effect of this accelerated pace of resource utilization at different confidence levels.

As shown in Tables XXXIX–XLI, the accelerated production schedule required under the high demand case results in:

TABLE XXXVIII. COMPARISON OF PRODUCTION AND COST PARAMETERS BETWEEN MIDDLE AND LOW DEMAND CASES — STUDY RAR

	Study RAR — middle demand case	Study RAR — low demand case
First year of deficit compared with market based production requirement	2027	NA[a]
Cumulative production (t U)	2 319 210	1 917 990
Cumulative deficit (t U)	(1 839 070)	NA
Potential unutilized resources (t U)	476 390	914 000
First year high medium cost required	2019	2024
First year high cost required	2023	2023

[a] NA: not applicable. No deficits are projected to occur in any of these years.

TABLE XXXIX. COMPARISON OF RESOURCE UTILIZATION PARAMETERS — MIDDLE AND HIGH DEMAND CASES, BASED ON PRODUCTION DERIVED FROM TOTAL RAR

	Middle demand case	High demand case
First year of deficit compared with market based production requirement	2028	2023
Cumulative production (t U)	2 617 860	2 672 390
Cumulative deficit[a] (t U)	(1 540 420)	(3 733 800)
Potential unutilized resources (t U)	515 830	461 190
First year high medium cost required	2019	2013
First year high cost required	2024	2019

[a] Deficit between market based production requirements and cumulative production.

TABLE XL. COMPARISON OF RESOURCE UTILIZATION PARAMETERS — MIDDLE AND HIGH DEMAND CASES, BASED ON PRODUCTION DERIVED FROM RAR + EAR-I

	Middle demand case	High demand case
First year of deficit compared with market based production requirement	2035	2026
Cumulative production (t U)	3 313 780	3 455 840
Cumulative deficit[a] (t U)	(844 500)	(2 950 350)
Potential unutilized resources (t U)	698 440	556 380
First year high medium cost required	2021	2015
First year high cost required	2027	2022
First year EAR-I cost justified	2019	2013

[a] Deficit between market based production requirements and cumulative production.

TABLE XLI. COMPARISON OF RESOURCE UTILIZATION PARAMETERS — MIDDLE AND HIGH DEMAND CASES, BASED ON PRODUCTION DERIVED FROM RAR + EAR-I + EAR-II

	Middle demand case	High demand case
First year of deficit compared with market based production requirement	2042	2031
Cumulative production (t U)	3 851 530	4 346 270
Cumulative deficit[a] (t U)	(306 740)	(2 059 920)
Potential unutilized resources (t U)	2 385 690	1 890 950
First year high medium cost required	2021	2015
First year high cost required	2029	2023
First year EAR-I cost justified	2019	2013
First year EAR-II cost justified	2027	2022

[a] Deficit between market based production requirements and cumulative production.

— The potential that high medium cost projects (>US $52/kg U) could be needed as early as 2013 (RAR scenario), which means that the uranium market price would have to at least double compared to 1999 levels.

— Under practical resource utilization scenarios the deficit between production derived from known resources (RAR + EAR-I) and market based production requirements is projected to total nearly 3 million t U. With the addition of EAR-II, the deficit is reduced to 1.9 million t U.

— Under the constraints of practical production capacities, production derived from known resources and from RAR through to EAR-II will cover only 54 and 68% of high demand case market based production requirements, respectively.

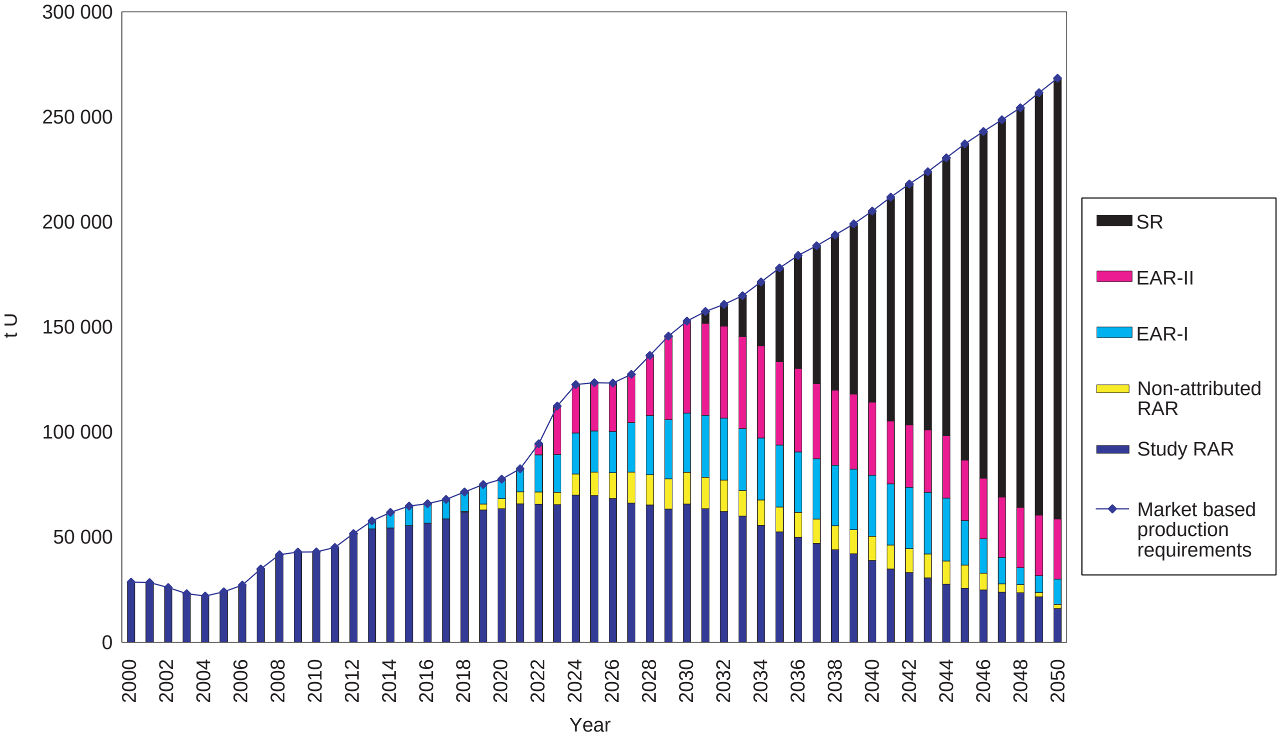


FIG. 23. Resource contribution by confidence level through to EAR-II and SR — high demand case.

- — Potentially unutilized resources (RAR + EAR-I + EAR-II) are nearly equal to the deficit between cumulative production and market based production requirements (Table XLI). In other words, resources are adequate to satisfy requirements if production capacity could be increased to utilize the resources fully.
- — EAR-II (i.e. relatively low confidence, undiscovered resources) could be needed and cost justified as early as 2022. These are resources that must be confirmed by additional exploration and evaluation and subjected to rigorous environmental licensing procedures before they can be developed.

It is important to emphasize that these conclusions are based on the high demand case. In addition, the discussion up to this point has been limited to conventional resources up to and including EAR-II. We have yet to address the discovery potential of speculative or potential resources in known geologic environments that are the target of uranium exploration programmes in various parts of the world. Furthermore, as we will see in Section 5.1.4, there are huge untapped unconventional resources such as phosphorite deposits, and even the potential to extract uranium from sea water, which, given proper economic incentive, could supplement conventional uranium resources. Also, we have yet to address the potential reduction in uranium requirements associated with decreasing enrichment tails assays, which is addressed in Section 5.1.2. Therefore at this point we have not covered the full range of potential resources. At the same time it is important to emphasize that EAR-II are not adequate to satisfy the high demand case, unless production capacity constraints can be overcome to utilize these resources more effectively.

5. CONCLUSIONS

The ultimate goal of this study has been to determine the adequacy of supply to meet reactor uranium requirements (demand), and to characterize the level of confidence that can be placed in the projected supply. Three demand cases are considered — the low, middle and high demand cases — that cover a range of expectations regarding the future of nuclear power, including phasing out the nuclear option by 2100 (low demand case) to the high demand case which envisions significant, albeit gradual, expansion of nuclear power. Supply is broadly subdivided into two categories: secondary supply (the so-called above ground supply) and primary supply (newly mined and processed uranium). These two categories are in turn divided into subcategories, each of which is discussed and analysed separately. More than one projection is provided for the secondary supply categories to cover a range of possible supply scenarios. Section 5.1.5 addresses the impact of choosing one projection compared to the other for each category or combination of categories (sensitivity studies). Secondary supply is combined with primary production in the CIS, in national programmes and in China, and that total is subtracted from reactor uranium demand to determine market based production requirements. The balance of the report to this point has centred on projecting how market based production requirements will be met. It should once again be emphasized that these projections and the analyses on which they are based are neither predictions nor forecasts of precisely how the uranium production industry will develop during the next 50 years. Instead, they present a number of scenarios based on current technology, each of which shows alternatives as to how the industry could unfold given changing sets of conditions. The analyses do not take into account new technology, innovations or changing circumstances that could result in unforeseen major changes in project resources, capacity, licensing or production costs.

This section will serve to bring together the ideas expressed in the preceding sections by addressing such issues as:

- Adequacy of resources,
- Production capacity limitations and potential,
- Sensitivity to variations in supply,
- Effect of lowering enrichment tails assays,
- Speculative and unconventional resources,
- Future exploration requirements,
- Lead times between discovery and production,
- Market price implications.

5.1. ADEQUACY OF RESOURCES

5.1.1. Adequacy of RAR through to EAR-II

Table XLII compares resources at different confidence levels with market based production requirements for the middle and high demand cases. Study RAR are projected to be more than adequate to satisfy requirements in the low demand case, so it is not included in this discussion.

As shown in Table XLII, known resources (RAR + EAR-I) nearly cover the middle demand case market based production requirements, with a deficit of only 146 060 t U. With the addition of EAR-II there is actually a 2 million t U surplus of available resources compared to requirements. The problem lies in utilizing these resources within the time frame of the study. As a result of nearly 700 000 t U not being produced by the end of the study period, the deficit between production derived from known resources and market based production requirements is projected to be 844 500 t U, or nearly six times the deficit between resources and requirements. Similarly, with the addition of EAR-II, a 2 million t U surplus of resources compared to requirements becomes a 306 750 t U deficit compared to production, with nearly 2.4 million t U of projected unutilized resources. As would be expected, with the accelerated production schedules required to meet the high demand case, the deficits between production and requirements are larger. However, the accelerated schedules provide for more efficient utilization of resources, so the problem of under-utilization of resources actually diminishes in the high demand case. Otherwise, the deficits in the high demand case would be even larger than those projected in Table XLII.

The issue of the potential for large quantities of unutilized resources is obviously very important, and will be discussed in Section 5.1.6. Before addressing that issue in detail, however, there are three other aspects of resource adequacy that should be addressed — speculative and unconventional resources and the impact of lowering enrichment tails assays.

5.1.2. Effect of lowering enrichment tails assay

The reactor uranium demand scenarios on which this report is based assume an enrichment tails assay of 0.30% uranium. However, as will be shown in the following analysis, changing the tails assay to 0.15%

TABLE XLII. COMPARISON BETWEEN REQUIREMENTS, RESOURCE AVAILABILITY AND PRODUCTION AT DIFFERENT CONFIDENCE LEVELS FOR THE MIDDLE AND HIGH DEMAND CASES

	Middle demand case (t U)	High demand case (t U)
RAR		
Market based production requirements	4 158 280	6 406 190
Available resources	3 133 690	3 133 690
Deficit between resources and requirements	(1 024 590)	(3 272 500)
Cumulative production	2 617 860	2 672 390
Deficit between production and requirements	(1 540 420)	(3 733 800)
Potential unutilized resources	515 830	461 190
RAR + EAR-I		
Market based production requirements	4 158 280	6 406 190
Available resources	4 012 220	4 012 220
Deficit between resources and requirements	(146 060)	(2 393 970)
Cumulative production	3 313 780	3 455 840
Deficit between production and requirements	(844 500)	(2 950 350)
Potential unutilized resources	698 440	556 380
RAR + EAR-I + EAR-II		
Market based production requirements	4 158 280	6 406 190
Available resources	6 237 220	6 237 220
Deficit between resources and requirements	+2 078 940	(168 970)
Cumulative production	3 851 530	4 346 270
Deficit between production and requirements	(306 750)	(2 059 920)
Potential unutilized resources	2 385 690	1 890 950

uranium could result in a significant reduction in market based production requirements. The following assumptions were used in this analysis:

1. Eighty per cent of the world's reactors use LEU, and thus will burn ≈80% of the natural uranium requirements;
2. The average enrichment level for LEU is 4%;
3. One kilogram of 4% LEU at 0.30% tails assay requires 9 kg U and 5.28 SWU;
4. One kilogram of 4% LEU at 0.15% tails assay requires 6.86 kg U and 7.51 SWU.

Based on these assumptions, for every 1000 t U of requirements, 800 t U (80%) comes from LEU. At 9 kg U required per 1 kg LEU (0.30% tails assay), 800 t U would yield approximately 90 t LEU. At a tails assay of 0.15%, only 610 t U would be required to produce 90 t LEU, resulting in a saving or reduction in requirements of 190 t U. This saving equals 24% of the 800 t U requirement or 19% of the total 1000 t U requirement.

Table XLIII compares the cost of 1 kg of 4% LEU at a range of uranium costs, assuming 0.30 and 0.15% tails assays.

It is evident from this table that based on current SWU and conversion prices, at a cost of uranium of US \$78/kg U (US \$30/lb U_3O_8, US \$66/kg U_3O_8), the cost of 1 kg of 4% LEU is approximately equal for tails assays of 0.30 and 0.15%. Consequently, if the cost of uranium exceeds US \$78/kg U, there is an incentive to

TABLE XLIII. COST OF 1 kg OF 4% LEU ASSUMING TAILS ASSAYS OF 0.30 AND 0.15% AND URANIUM COSTS RANGING BETWEEN US \$26 AND US \$104/kg U (US \$10 AND US \$40/lb U_3O_8, US \$22/kg AND US \$88/kg U_3O_8)

	Natural uranium cost (US $/kg U)				
Tails assay (%)	26	39	52	78	104
0.30	692	809	926	1160	1394
0.15	806	896	965	1163	1342

lower the tails assay, and as the price increases above US $78/kg U so too does the incentive.

In the high demand case (RAR scenario), high cost projects (US $78–130/kg U) are projected to be cost justified beginning in 2019, which, everything else being equal, would justify a uranium market price of >US $78/kg U. Between 2020, the year after high cost projects are cost justified, and 2050, cumulative total demand and requirements for market based production are projected to total 6 million and 5.4 million t U, respectively. As previously shown, lowering the tails assay from 0.30% (the demand assumption) to 0.15% results in a saving of 190 t U per 1000 t U of demand. Therefore the savings applied against cumulative demand between 2020 and 2050 could result in a potential reduction in reactor uranium requirements totalling 1.14 million t U. Similarly, if applied only to market based production, the savings would total 1.1 million t U.

These savings represent just over one half of the total deficit between production based on RAR + EAR-I + EAR-II and cumulative market based production requirements projected for the high demand case. They would, therefore, reduce the requirement for speculative or potential resources that would otherwise be required to offset the deficit by about half. If the same assumptions were applied to the middle case demand scenario, the savings applied to cumulative demand between 2030, when high cost projects will be cost justified, and 2050 would total 0.58 million t U. Similarly the savings relative to market based production would total 0.51 million t U, if tails assays were lowered beginning in 2030, which would virtually eliminate the deficit between market based production requirements and production derived from known resources (RAR + EAR-I) for the middle demand case.

5.1.3. SR

Production derived from RAR through to EAR-II, after discounting for unutilized resources, is not adequate to cover market based production requirements in either the middle or high demand cases. As shown in Table XLII, the deficit between production and requirements is projected to be 306 750 and 2 059 920 t U in the middle and high demand cases, respectively. Although reducing enrichment tails assays will lower requirements, sustainable nuclear power to 2050 will nevertheless require the discovery of additional resources. The potential for discovery of additional resources is addressed in the SR category. As noted in the definition in Appendix V, SR are based mostly on indirect evidence and geological extrapolations. Exploration models have been developed for the basic uranium deposit types, and recognition criteria have been established from these models that can be used as guides for assessing the discovery potential of each geologic environment. In addition, as previously noted in the discussion on EAR-II, historical exploration expenditures totalling approximately US $7800 million are the basis for a broad understanding of geologic environments throughout the world that have the potential to host significant new uranium discoveries. The discussion of SR is divided into two subsections. The first subsection describes uranium deposit types, their geologic characteristics and geologic environments. The second section discusses reported SR and evaluates their potential.

5.1.3.1. Uranium deposit types and examples

Uranium deposits have been broadly grouped into 14 categories, which, along with deposits typical of each category, are listed in Table XLIV.

Of the deposit types listed in Table XLIV, two types — unconformity related and sandstone — are considered to have the best potential to host significant SR.

Unconformity related deposits. Unconformity related deposits account for 18% of study RAR, but only 8% of the deposits or deposit groups included in study RAR, which is an indication of their high ore grade and resource potential. The largest known high-grade deposits in the world are located in the Athabasca Basin in northern Saskatchewan, Canada, including McArthur River (184 200 t U, average grade 12.6% uranium) and Cigar Lake (138 800 t U, average grade 11.5% uranium); both are unconformity related deposits. The Northern Territory in Australia also hosts significant unconformity related resources, including the Ranger, Jabiluka and Koongarra deposits. Recognition criteria and/or geologic characteristics for unconformity related deposits include:

- Basement rocks with higher than average uranium content.
- Intracratonic basins active during the middle to upper Lower Proterozoic time (≈2×10^9 years before present).
- Relative tectonic stability since basin filling by sediments.
- Metasedimentary basin fill including graphitic zones.
- Cover of Middle Proterozoic continental red bed facies.
- Ancient techtonic structures in the basement; reactivated structural zones in the basement extending into overlying red bed units.

The Athabasca Basin in Canada and the Northern Territory, Australia, host significant unconformity related resources, and they are both considered to have good potential for additional discoveries, even of the magni-

TABLE XLIV. URANIUM DEPOSIT TYPES AND EXAMPLES

Deposit type	Deposit example	Location
Unconformity related	McArthur River	Athabasca Basin, Canada
	Ranger	Northern Territory, Australia
Sandstone	Smith Ranch	Powder River Basin, USA
	Uvanus	Kazakhstan
Quartz–pebble conglomerates	Witwatersrand	South Africa
	Blind River	Canada
Vein	Schwartzwalder	USA
Breccia complex	Olympic Dam	South Australia
Intrusive	Rossing	Namibia
Phosphorite (by-product)	New Wales	USA
Collapsed breccia	Arizona Strip	USA
Volcanic	Streltsovsk	Russian Federation
Surficial	Yeelirree	Western Australia
Metasomatic	Michurinskoye	Ukraine
Metamorphic	Forstau	Austria
Lignite	Yili Basin	China
Black shale	Ranstad	Sweden

tude of McArthur River, Cigar Lake or Jabiluka. As noted in the discussion on EAR-II (Section 4.1.9), recent drilling by the Dawn Lake joint venture has intersected high grade mineralization, and although the significance of these drilling results is yet to be proven, they do indicate that discoveries are still possible at reasonable depths in the Athabasca Basin. The same holds true for northern Australia, although deep lateritic weathering presents a difficult environment for geophysical prospecting. Although geologic conditions in the Thelon Basin in the Northern Territories, Canada, are not exactly the same as those in the Athabasca Basin, this area is still thought to be prospective for additional unconformity related deposits similar to Kiggavik and Sissons South.

In the Russian Federation, both the Baltic and Aldan shields are considered to be prospective for unconformity related deposits, and preliminary drilling results are the basis for attributing SR to this deposit type. The Guyana shield in northern South America, the Ukrainian shield and the west African shield all have at least the basic framework to be considered as potentially prospective areas for unconformity related deposits. However, these areas either have geological shortcomings or present extraordinary exploration challenges. For example, the Guyana shield is characterized by deep lateritic weathering, which makes it a difficult environment for geophysical prospecting, and the west African shield lacks a fertile basement, one of the key characteristics of the Athabasca Basin. The potential remains for discovering new unconformity related deposits outside of Canada and Australia. At the same time, it should be remembered that the first unconformity related deposits were discovered in the late 1960s, and they have been the target of extensive exploration efforts since with no measurable success outside of Canada, Australia and perhaps the Russian Federation.

Sandstone deposits. Uranium deposits hosted in sandstones account for nearly 30% of the study RAR listed in Table XVIII. Production from sandstone deposits is the cornerstone of the uranium industries of Kazakhstan, Niger, the USA and Uzbekistan. Recognition criteria and geologic characteristics for sandstone deposits include:

- Continental sandstones, generally fluvial or deltaic in origin;
- Abundant uranium precipitants/reductants, including carbonaceous material, hydrocarbons or sulphides;
- Sources of uranium in uplifts surrounding sedimentary basins or in sedimentary units overlying the host sandstones.

There are no age constraints on the geologic systems that host sandstone deposits. The ages for sandstone host rocks range from Precambrian in Gabon to Tertiary in Kazakhstan, Uzbekistan and the USA.

Areas considered to have the best potential for the discovery of significant new sandstone resources include:

- The Trans-Baikal region (valley type deposits) in the Russian Federation and northern Kazakhstan;
- The Gobi Basins in Mongolia;
- The Lake Frome Basin in Australia;
- The Yili, Junger and Erlian Basins in China;
- The Karoo Basins in southern Africa and Madagascar;
- The Franceville Basin in Gabon.

Potential for other deposit types. Although unconformity related and sandstone deposits are considered to have the best potential for the discovery of significant new resources, the potential of the other deposit types should not be discounted. For example, Olympic Dam, a breccia complex deposit, accounts for nearly 10% of the study RAR (Table XVIII). In addition, Olympic Dam contains 660 000 t U classified as indicated and inferred resources that are not included in the Table XVIII totals. The resource potential of breccia complexes is obviously significant. At the same time, exploration programmes throughout the world, including those for base and precious metals as well as for uranium, have not discovered another breccia complex deposit, at least not one with commercial uranium resources. Olympic Dam may not be geologically unique, but the probability of discovering another comparable uranium bearing breccia complex deposit comparable to Olympic Dam seems to be limited. Vein deposits also hold potential for significant new discoveries. The potential of orogenic belts such as the Congo–Zambia copper belt which hosts the Shinkolobwe deposit (production plus resources ≈30 000 t U), although in many cases already extensively explored, cannot be discounted.

5.1.3.2. Reported SR

The 1999 Red Book [3] reports SR totalling 10.6 million t U, compared to 6.7 million t U for RAR through to EAR-II. Of the SR total, 4.4 million t U are projected to be recoverable at a cost of <US $130/kg U; the cost range of the remaining 6.1 million t U is unspecified. Table XLV lists the five leading countries in SR in both the <US $130/kg U category and total SR. Australia, which is the world leader in known resources, does not report SR.

TABLE XLV. LEADING COUNTRIES IN REPORTED SR

	<US $130/kg U (1000 t U)	Total (1000 t U)
Canada	700	700
China	[a]	1770
Kazakhstan	500	500
Mongolia	1390	1390
Russian Federation	544	1000
South Africa	[a]	1113
USA	858	2198
Total	3992	8671

[a] Not reported.

There are very few details available on SR, so it is difficult to put them in any sort of geologic framework or comment on their true potential. Furthermore, the cost categories are either too broad (<US $130/kg U) or projected costs are not assigned, so SR cannot be placed in the cost ranking with any degree of accuracy.

By the very nature of their name, SR should be considered with caution. However, although they lack specificity as to deposit type and cost information, one can still make observations about SR reported in the Red Book. For example, SR in countries that are sparsely explored but are known to host favourable geologic environments would intuitively have more credibility than SR in countries that have been extensively explored. Historical exploration expenditures in the USA to 1998 totalled US $2730 million, more than twice that of Canada, which ranks second in expenditures at US $1180 million. While it can be argued that a disproportionate percentage of the US exploration dollars were spent in the western half of the country, the fact remains that the USA has been extensively explored. Despite the extent of past exploration, the USA still reports nearly 2.2 million t U SR, three times that reported by Canada. By contrast, though, the Russian Federation conducted exploration in Mongolia prior to 1992 (expenditure total not available), and expenditures between 1991 and 1997 totalled about US $8.2 million; by most accounts Mongolia is sparsely explored. Exploration up to this point has, however, indicated extensive favourable areas with potential for sandstone deposits in the Gobi Basins and volcanic deposits in the northern part of the country. Therefore, given the extent of favourable exploration areas, Mongolia's projected 1.34 million t U SR seems plausible, and is probably more credible than the SR total reported by the USA.

As indicated by the magnitude of projected SR, uranium experts throughout the world remain optimistic as to the potential for future discoveries. Translating that optimism into viable resources will, however, require extensive exploration and development expenditures, which in turn will require the incentive of sustainably higher market prices. Estimated SR are clearly adequate to cover the projected shortfall between production and market based production requirements in both the middle and high demand cases. SR are projected to be needed in

2041 (middle demand case) and 2029 (high demand case), when RAR through to EAR-II will no longer be adequate to satisfy market based production requirements (Table XLII). However, whether market conditions will support the level of exploration needed to convert SR into viable resources in a timely manner to meet demand remains to be seen. These issues are addressed in more detail in Sections 5.1.6, 5.2 and 5.3.

Although projecting entry of SR into the market is highly subjective, it is instructive at least to consider a scenario in which SR are available to offset the production deficit. For example, assume that 15% of SR are recoverable at <US $130/kg U (Table XLV), and that 5% falls into each of the low medium, high medium and high cost categories. Three variations are considered for introducing production derived from SR into the middle demand case production stream. Case A assumes that the three units of SR have the highest cost within their respective cost category, and each has a production capacity of 3000 t U/a. Case B assumes that the three units of SR have costs in the middle of their respective cost category, and each has a production capacity of 3000 t U/a. Case C is similar to case B except that the low medium cost unit has a production capacity of 6000 t U/a (comparable to McArthur River) compared to 3000 t U for case B. Table XLVI compares the effect of introducing SR into the production stream based on these assumptions.

As noted in Table XLVI, introduction of production from only 15% of projected SR reduces the deficit between requirements and production by between 30% (case A) and 52% (case C). By adding only a small percentage of SR to the equation, production is projected to be adequate to satisfy 95% (case A) of market based production requirements in the middle demand case.

5.1.4. Unconventional resources

An analysis of uranium resources would not be complete without discussing unconventional resources; that is, deposits with low uranium concentrations, which, by virtue of their shear size, constitute large, but very high cost, uranium resources. At least some of the unconventional resources are included in other resource categories. This is particularly true for the phosphorite deposits (e.g. in Table XVIII New Wales and Uncle Sam in the USA and Pricaspian in Kazakhstan), but only a fraction of the worldwide potential of phosphorite deposits is included in other resource categories. The same holds true for the other unconventional resources. The following sections describe deposit types included in the unconventional resources category.

5.1.4.1. Phosphorite deposits

As recently as 1999 uranium was recovered as a by-product of processing marine phosphorite. However, the last two plants in the USA closed their uranium recovery circuits in 1999, marking at least temporarily the end of uranium recovery as a by-product of the manufacture of phosphate fertilizer products. By-product uranium recovery from phosphate processing was terminated in Belgium in 1997, and uranium was recovered as the primary product from processing organic phosphate deposits (fish bone detritus) in the Pricaspian district in western Kazakhstan until 1994.

Although uranium is not currently being recovered from phosphate fertilizer operations, phosphorite deposits nevertheless host large uranium resources that could theoretically provide significant production in the

TABLE XLVI. EFFECT OF ADDING SR TO THE PRODUCTION STREAM — MIDDLE DEMAND CASE

	RAR through to EAR-II	Case A RAR through to EAR-II + SR	Case B RAR through to EAR-II + SR	Case C RAR through to EAR-II + SR
Market based production requirement (t U)	4 158 280	4 158 280	4 158 280	4 158 280
Available resources (t U)	6 237 220	6 836 020	6 836 020	6 836 020
Deficit between resources and requirements (t U)	+2 078 940	+2 677 740	+2 677 740	+2 677 740
Cumulative production (t U)	3 851 530	3 948 540	3 958 430	4 010 660
Deficit between production and requirements (t U)	(306 750)	(209 740)	(199 850)	(147 620)
Potential unutilized resources (t U)	2 385 690	2 887 480	2 887 590	2 825 360
SR low medium cost production begins	NA[a]	2021	2013	2013
SR high medium cost production begins	NA	2030	2024	2024
SR high cost production	NA	2042	2036	2036

[a] NA: not applicable.

future. Worldwide uranium resources associated with marine phosphorite deposits are estimated at approximately 9 million t U. However, there are no rigorous estimates of phosphorite deposit resources, so this total should be considered a mineral inventory rather than conforming to standard resource categories. Four countries, Jordan (0.1 million t U), Morocco (6.9 million t U), Mexico (0.15 million t U) and the USA (1.2 million t U), account for more than 90% of the estimated resources associated with marine phosphorite deposits. Organic phosphorite deposits in Kazakhstan and the Russian Federation contain resources totalling about 0.12 million t U.

Two factors will control eventual large scale recovery of uranium from phosphate fertilizer operations — the uranium market price and the phosphate fertilizer market. The uranium content of the marine phosphorite deposits typically averages from between 0.0006 to 0.012% uranium, while the grade of organic phosphorite deposits can average up to 0.06% uranium. The low ore grade of the phosphorite deposits precludes their being economically viable for recovery of only uranium. Instead uranium will only be recoverable as a by-product of fertilizer operations, in which case eventual development will depend on the fertilizer market.

Theoretically, uranium recovery from worldwide phosphate operations could total up to 3700 t U/a. This total assumes annual production of phosphate rock of 142 million tonnes per year yielding 66 million tonnes of concentrate. Marine phosphorite deposits account for 80% of the world output of phosphate based fertilizer products, and 70% of this total is converted into wet-process phosphoric acid, the base for the current uranium extraction process. Assuming an average recoverable content of 100 ppm of uranium, this scenario would result in an annual output of 3700 t U/a.

Since the middle demand scenario assumes ecologically driven policies, and since we are looking 50 years into the future, it is appropriate at least to consider a potential scenario that would guarantee recovery of uranium from phosphate fertilizer operations. Uranium is retained in the phosphate fertilizer products unless it is separately extracted. Future environmental awareness and regulations could require that phosphate producers remove the uranium from the fertilizer, which, as unlikely as this scenario may sound in today’s world, would guarantee another supply source.

5.1.4.2. Black shale deposits

Uraniferous black shales are marine, organic rich, commonly pyritic shale in which uranium (and other metals) is adsorbed on to organic material and clay minerals. Average grades for the black shale deposits range between 50 and 400 ppm of uranium, but because of their large areal extent they contain very large resources. Alum shale deposits in the Ranstad area in Sweden cover about 500 km^2 and contain approximately 254 000 t U at an average grade of between 170 and 250 ppm of uranium [15]. In the Ronneburg area in Germany, graptolitic black shale covers an area of about 164 km^2 and contains resources of 169 230 t U with grades ranging between 0.085 and 0.17% uranium. The higher grades are attributable to supergene enrichment and the presence of pitchblende veinlets of hydrothermal origin. The Chattanooga Shale in the southeastern USA is estimated to cover 80 000 km^2, and at an average grade of 57 ppm of uranium contains resources of between 4 million and 5 million t U.

As is the case with the phosphorite deposits, the resources mentioned above are more of a mineral inventory than a rigorous resource estimate. Because of their limited economic potential, there is no reliable estimate of worldwide resources hosted in black shale deposits. While the black shale deposits represent a large resource, they will require very high production costs, and their development would require huge mines, processing plants and mill tailings dams, which would certainly elicit strong environmental opposition. In addition, the Ronneburg area is currently the subject of the multibillion dollar Wismut reclamation project. Therefore the black shale deposits represent a long term resource that will require market prices in excess of US $130/kg U to be economically attractive, assuming environmental opposition could be overcome, which is by no means certain for any of the three deposits mentioned above.

5.1.4.3. Lignite and coal deposits

Lignite and sub-bituminous coal deposits often contain uranium adsorbed on to carbonaceous material or as urano-organic complexes. The average uranium content is typically only a few tens of ppm of uranium. Uraniferous lignite deposits are typically small, but deposits in the Ily Basin in eastern Kazakhstan and northwestern China reportedly range between 20 000 and 50 000 t U.

In order to achieve acceptable uranium recovery from lignite deposits, to concentrate the uranium the lignite must first be burned; the uranium is then leached from the resulting ash. However, the high temperature associated with burning the lignite converts the uranium adsorbed on the organic material into a refractory uranium silicate from which uranium extraction is complex and expensive.

There are no systematic resource calculations for uranium hosted in lignites. SR are probably in the millions of tonnes of uranium in lignites worldwide, but because of their high production costs these resources are of limited practical interest.

5.1.4.4. Sea water

Just as an assessment of uranium resources would not be complete without including unconventional resources, a summary of unconventional resources would be incomplete without at least mentioning sea water as a potential source of uranium. The uranium content of sea water averages about 3 parts per thousand million of uranium. Estimates of the uranium resources in sea water range up to 4×10^9 t U. As is the case with other unconventional resources, extracting uranium from sea water, while technically feasible, is very costly compared to conventional resources. Research in Japan indicates that uranium could potentially be extracted from sea water at a cost of approximately US $300/kg U, more than 10 times the spot market price at year end 1999. Research on extracting uranium from sea water will undoubtedly continue, but at the current costs sea water as a potential commercial source of uranium is little more than a curiosity.

5.1.5. Sensitivity studies

When projecting supply–demand relationships for 50 years there are inherent uncertainties in most if not all of the supply categories. While these uncertainties cannot be precisely quantified, a range of eventualities can be projected, and the impact of supply additions and/or reductions within that range can be evaluated. In the following sections sensitivity to supply additions or limitations is reviewed for several of the secondary supply sources.

5.1.5.1. HEU

The base case for both the middle and high demand cases include 250 t of Russian HEU and 55 t of US HEU that are not included in the current Russian Federation–USA HEU agreement (Section 3.2.1.5). This additional material extends the availability of uranium derived from HEU to 2023, or 10 years beyond the existing agreement. There is currently every reason to believe that the base case represents the most likely scenario. At the same time, there is no assurance that additional Russian material will be available beyond that provided in the current agreement. Table XLVII shows the effect that restricting availability of Russian HEU to the current agreement would have on supply–demand relationships to 2050. The comparisons in Table XLVII assume market based production derived from known resources (RAR + EAR-I).

As noted in this comparison, limiting Russian HEU to the current agreement will not have a significant impact on long term supply–demand relationships. The resulting loss of 97 900 t U accelerates by only one year the first year in which known resources are not adequate to satisfy market based production requirements. The deficit between market based production requirements and cumulative production increases by only 71 340 t U, because accelerating production reduces unutilized resources. Reducing the availability of Russian HEU will also have limited impact on the uranium market, advancing

TABLE XLVII. COMPARISON OF PRODUCTION AND COST PARAMETERS — LOW AND HIGH HEU CASES: ASSUMES PRODUCTION BASED ON MIDDLE DEMAND CASE, KNOWN RESOURCES

	Base HEU case	Low HEU case	High HEU case
First year of deficit compared with market based production requirement	2035	2034	2036
Market based production requirement (t U)	4 158 280	4 256 210	4 048 230
Cumulative production (t U)	3 313 780	3 340 370	3 246 230
Cumulative deficit[a] (t U)	(844 500)	(915 840)	(801 990)
Potential unutilized resources (t U)	698 440	672 870	764 410
First year high medium cost required	2021	2019	2021
First year high cost required	2027	2026	2028
First year EAR-I cost justified	2019	2015	2019

[a] Deficit between market based production requirements and cumulative production.

by only two years, from 2021 in the base case to 2019 in the limited HEU case, the year in which high medium cost production will be cost justified.

As suggested in Section 3.2.1.5, bilateral reductions in nuclear weapons could make additional HEU available for commercialization. The high HEU case assumes that increased availability of HEU will result in an additional 109 900 t U and will extend HEU contribution to 2040 compared to 2023 for the base case. As shown in Table XLVII, the additional uranium derived from the incremental HEU will have a limited effect on supply–demand relationships to 2050. The material is assumed to be available beginning in 2023, so it will not affect the cost/price structure. It only reduces the deficit between market based production requirements and production by 42 510 t U, because the uranium derived from the incremental HEU delays higher cost projects and consequently increases under-utilized resources compared to the base case for HEU.

5.1.5.2. MOX, RepU and re-enrichment of depleted uranium

Sections 3.2.3 and 3.2.4 project the availability of a secondary supply from MOX, RepU and re-enrichment of depleted uranium (tails). These projections include a base case and a low case for each of these supply sources. The low MOX case assumes that the ‘stop MOX’ movement will prevail, and that MOX use will end in 2005. The current trend towards higher burnup could decrease the availability of economically attractive spent fuel by 2010, which is the basis for the low RepU case. Uncertainty as to the availability of US tails for re-enrichment is accounted for by reducing tails output, as shown in Table XLVIII.

The net effect of combining the low cases for MOX, RepU and tails is shown in Table XLIX.

The combined low cases for MOX, RepU and tails result in a reduction of 270 200 t U compared to their combined base cases. Nevertheless, the comparison between the base and low cases shows that the potential reductions in these supply sources have a limited impact on supply–demand relationships to 2050. Cost justified high medium cost projects will be needed only two years earlier under the low case than under the base case. The deficit between market based production requirements and cumulative production increases with the low case by 223 650 t U. However, accelerated market based production also allows for better resource utilization, which partially offsets the deficit increase.

5.1.5.3. Impact of removing resources with potential environmental and/or political opposition from the resource base

Section 4.1.1.2 discusses the potential that certain projects could be either delayed or abandoned because of environmental or political opposition. Within the study

TABLE XLVIII. UNCERTAINTY OF THE AVAILABILITY OF US TAILS (t U)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Base case	4500	4500	5200	4850	4250	3650	3300	3000	2800	2650	2350	2350
Low case	2500	2500	3000	3000	3500	3500	3500	3500	3500	3500	3500	3500

TABLE XLIX. COMPARISON OF PRODUCTION AND COST PARAMETERS — COMBINED LOW CASES FOR MOX, RepU AND TAILS: ASSUMES PRODUCTION BASED ON THE MIDDLE DEMAND CASE, KNOWN RESOURCES

	Base case	Low case
First year of deficit compared with market based production requirement	2035	2033
Market based production requirement (t U)	4 158 280	4 432 550
Cumulative production (t U)	3 313 780	3 364 400
Cumulative deficit [a] (t U)	(844 500)	(1 068 150)
Potential unutilized resources (t U)	698 440	647 820
First year high medium cost required	2021	2019
First year high cost required	2027	2024
First year EAR-I cost justified	2019	2017

[a] Deficit between production and requirements.

RAR resource base, a total of approximately 414 670 t U associated with 31 projects in six countries have been identified as being potentially subject to such opposition. This total represents nearly 15% of study RAR and 10% of RAR + EAR-I available to satisfy market based production requirements. Since we are looking ahead 50 years there is no way to forecast accurately whether public and governmental attitudes toward uranium mining will change, either positively or negatively. We can, however, evaluate the impact on supply–demand relationships if projects that currently have the potential for environmental and/or political opposition are removed from the resource base. Table L compares production and cost parameters for known resources both with and without resources that could be subject to opposition.

As shown in Table L, without the resources subject to environmental or political opposition known resources are only adequate to cover market based production requirements to 2029, compared to 2035 if the resources are assumed to be available. Cumulative production is reduced by 10%, and the deficit between production and requirements is increased by nearly 40%. The projected change in the cost structure is relatively minor, as is the timing when EAR-I will first be cost justified.

This sensitivity analysis is included as a cautionary note to highlight the potential impact of environmental or political opposition on the overall resource base. It is, however, not intended to prejudge whether such opposition will have any permanent impact on the resource base.

5.1.6. Production capacity and unutilized resources

A recurring theme throughout the preceding analyses has been the potential that significant resources will not be utilized prior to the end of the study period, resulting in a shortfall in production compared to production requirements. As noted in Table XLII, known resources come within 146 060 t U of satisfying market based production requirements for the middle demand case. However, because nearly 700 000 t U of available resources will not be utilized by 2050, the deficit between cumulative production and market based production requirements is projected to total 844 500 t U, or nearly six times the projected shortfall between available resources and requirements. The potential value of the resources beyond 2050 is not being questioned. However, if significant resources are not produced during the study period, it follows that resource estimates alone do not provide a complete supply–demand picture. The combination of production timing and annual capacity control resource utilization; production timing is in turn controlled by production cost. In a market based production scenario, resources associated with high cost deposits will be brought into production later in the study period. Therefore they are less likely to have their resources depleted by the end of the study period than are lower cost projects. The larger the resources for a given project, the less likely that they will be fully utilized within the study period.

Of the three controlling parameters — resources, cost and capacity — production capacity is potentially the most subjective. Production capacities of current operations are reasonably well documented, and capacities that have been announced for planned projects are assumed to be reliable. Therefore subjectivity begins really to come into play for projects in the study RAR category which have no announced development plans and no published capacities, and it increases significantly with the lower confidence resources. Resource size,

TABLE L. COMPARISON OF PRODUCTION AND COST PARAMETERS WITH AND WITHOUT RESOURCES POTENTIALLY SUBJECT TO ENVIRONMENTAL AND POLITICAL OPPOSITION — RAR THROUGH TO EAR-I, MIDDLE DEMAND CASE

	With projects subject to opposition	Without projects subject to opposition
Market based production requirement (t U)	4 158 280	4 158 280
Available resources (t U)	4 012 220	3 597 550
First year of deficit compared with market based production requirement	2035	2029
Cumulative production (t U)	3 313 780	2 981 160
Cumulative deficit[a] (t U)	(844 500)	(1 177 120)
Potential unutilized resources (t U)	698 440	616 390
First year high medium cost required	2021	2019
First year high cost required	2027	2024
First year EAR-I cost justified	2019	2017

[a] Deficit between market based production requirements and cumulative production.

deposit type and geology, and extraction methods were all considered in projecting production capacity. Relatively small deposits will not support large production centres and are assigned smaller capacities. For example, ISL projects, even those with large resource bases, were assigned capacities of between 385 and 1345 t U/a. Wellfield development is typically the bottleneck in an ISL operation. Central processing plants could potentially process higher fluid volumes from wellfields or increased resin shipments from satellite facilities, that would result in higher uranium production. However, because of the relatively low grade mineralization and complexity of roll front geology, the orderly development of wellfields to deliver the required volumes of fluids to support higher capacities is impractical.

Tables XXXIII and XXXVI show the production capacities assigned to EAR-I and EAR-II. As noted with each table, the projected capacities are subjective, and could represent a single production centre in some countries and several centres in others. The subjectivity associated with assigning production capacities leaves open the possibility that achieving higher capacities for projects with significant unutilized resources could reduce or even eliminate the deficit between production and requirements. Minor capacity increases could ensure full resource utilization for projects with limited unutilized resources. However, capacity increases within the realm of reason would not entirely eliminate unutilized resources for the projects that dominate unutilized resources. As shown in Table LI, six projects account for 70% of unutilized resources in the middle demand case, assuming production derived from known resources.

There is little flexibility to increase significantly the production capacities of the projects in Table LI. Table LII helps put the issue of production capacity and unutilized resources into perspective by showing projected output at ten-year intervals from the ten leading producing countries based on known resources.

Kazakhstan is a good example of why there is limited flexibility to increase production capacities beyond those shown in Table LII. Kazakhstan's economic ISL production is market based production (i.e. cost justified production) that is incremental to the ISL output projected in the CIS production category. Combining the two categories means that annual ISL output from Kazakhstan could reach 4100 t U by 2030 (assuming 1100 t U from conventional operations), a fourfold increase over projected 2000 output. Production at Kokchetav, another market based production project, is limited as much by mining capacity as by the capacity of the Stepnogorsk mill. Mill feed will come from labour intensive underground mines, each with limited capacity. Because of its large resource base, total production in Kazakhstan is projected to increase to about 5200 t U in 2030 and to 11.2 in 2050, or between 5 and 10 times its projected output in 2000. There is no certainty that Kazakhstan will be able to support this magnitude of increase, and further production capacity increases will only add to the uncertainty.

Imouraren, another project with significant unutilized resources, is currently being tested for ISL amenability. As an ISL project, Imouraren would have a smaller production capacity than if it were developed as a conventional project. There is, however, no assurance that Imouraren will be amenable to ISL. If not, under the study methodology, its resources would be assumed to be recoverable by conventional mining methods, but with a much higher cost, in which case Imouraren will be delayed in the production schedule. Therefore increasing its capacity as a conventional project will probably not offset the delay in starting production, and unutilized resources will remain about the same. The other two projects, Nufcor and Itataia, are by-product operations and their output will be constrained by the markets for their primary product. Similar constraints on increasing production capacity characterize other projects with

TABLE LI. PRODUCTION CENTRES ACCOUNTING FOR THE MAJORITY OF UNUTILIZED RESOURCES: BASED ON PRODUCTION DERIVED FROM KNOWN RESOURCES, MIDDLE DEMAND CASE

Project/production centre	Country	Total resources (t U)	Unutilized resources (t U)	Production capacity (t U)
Brazil EAR-I	Brazil	100 200	46 450	2 000
Imouraren	Niger	100 500	62 570	1 150
Itataia	Brazil	80 000	67 450	600
Kazakh economic ISL	Kazakhstan	179 100	143 320	1 500
Kokchetav	Kazakhstan	99 000	59 800	2 500
Nufcor	South Africa	239 000	113 640	2 000

TABLE LII. PROJECTED ANNUAL PRODUCTION IN TEN-YEAR INCREMENTS FOR THE TEN LEADING PRODUCING COUNTRIES IN 1998: BASED ON PRODUCTION FROM KNOWN RESOURCES, MIDDLE DEMAND CASE (1000 t U)

	2000	2010	2020	2030	2040	2050
Total market based production plus CIS production	34.4	43.6	65.4	112.6	139.3	113.0
Australia	7.6	9.9	21.6	26.0	19.6	9.9
Canada	10.6	15.8	11.3	8.8	7.9	4.2
Kazakhstan	1.0	2.6	2.6	5.2	9.4	11.1
Namibia	3.5			8.7	5.6	4.1
Niger	3.4	1.8	3.3	3.2	1.3	1.2
Russian Federation	2.5	3.8	3.8	4.1	3.8	3.8
South Africa	1.1	1.5	1.8	5.2	7.7	7.7
Ukraine	1.0	1.0	1.0	2.4	2.5	1.2
USA	1.7	3.0	9.4	15.5	7.2	2.2
Uzbekistan	2.0	3.8	3.8	3.8	3.8	3.8
Total	34.4	43.2	58.6	82.9	68.8	49.2
Per cent of total	100	99	90	74	49	44

significant unutilized resources, and while assigning production capacity to projects or groups of projects is subjective, it is unlikely under a reasonable capacity scenario that all resources could be utilized during the report period.

5.2. EXPLORATION REQUIREMENTS

Past exploration expenditures and success rates provide an interesting historical perspective on the uranium industry's accomplishments. However, variable reporting procedures among the different uranium producing countries preclude broadly applying these statistics to the future. We can, however, examine individual countries as a measure of expenditure trends and results, and to illustrate some of the problems with applying these figures to the future. Both Canada and Australia have a history of consistent Red Book reporting, so they can be used to compare long term and more recent expenditures and results. Table LIII compares the discovery costs in Australia and Canada based on historical exploration expenditures and production plus known resources (RAR + EAR-I).

Canada's discovery cost would have been lower if its know resources were increased to include the quartz–pebble conglomerate deposits at Blind River and Elliot Lake (100 000 t U included in study RAR; the total could be as high as 154 000 t U). As shown in Table LIV, discovery costs have risen dramatically in Australia and Canada during the 10 year period from 1989 to 1998. Table LIV clearly indicates that exploration is becoming more expensive in relatively mature exploration areas. At the same time, all it would take would be the discovery of another deposit similar to McArthur River in Canada or

TABLE LIII. COMPARISON OF HISTORICAL RESOURCE DISCOVERY COSTS IN AUSTRALIA AND CANADA

	Historical exploration expenditure (million US $)[a]	Historical production plus known resources (1000 t U)	Discovery cost (US $/kg U)
Australia	492.28	987.60[b]	0.50
Canada	1184.76	754.60[c]	1.57

[a] Expenditures to 1998.

[b] Australia's historical production (77 600 t U) and known resources (910 000 t U) reported in the Red Book to 1998.

[c] Canada's historical production (321 600 t U) and known resources (433 000 t U) reported in the Red Book to 1998.

TABLE LIV. COMPARISON OF DISCOVERY COSTS IN AUSTRALIA AND CANADA BETWEEN 1989 AND 1998

	1989–1998 exploration expenditure (million US $)	Resources beginning 1989 minus production 1989–1998 (1000 t U)	Known resources added 1989–1998 (1000 t U)	Discovery cost (US $/kg U)
Australia	108.92	894.2	15.8	6.89
Canada	369.03	337.6	95.4	3.87

Jabiluka in Australia to reduce the discovery costs to historical levels.

It is not practical to apply broadly historical discovery costs to future exploration requirements. The historical discovery costs benefited from low cost discoveries associated with surface exposures of uranium minerals or anomalous radioactivity. The recent discovery costs in Australia and Canada in part reflect the high cost of exploration in hostile environments, ranging from arctic conditions in Canada to high rainfall conditions in northern Australia. Future exploration will be more difficult as the remaining targets are either deeper, located in difficult terrain or inhospitable climates, or in geologic terrain where geophysical prospecting is very difficult (e.g. the deep lateritic weathering that characterizes the Alligator Rivers area in northern Australia). Geography and geologic conditions control exploration costs, and there is simply too much variability throughout the world to project the exploration costs required to satisfy future demand. It is, however, safe to say that future discovery costs will probably be closer to the average during the past 10 years in Australia and Canada than to the longer term historical costs.

As shown in Table XLII, there is a projected shortfall of 2.39 million t U between market based production requirements and available known resources in the high demand case. Table LV shows projected exploration expenditures at a range of discovery costs that could be required to ensure discovery of sufficient resources to satisfy the high demand case deficit. The totals shown in Table LV are only order of magnitude figures, but they show the potential range of exploration expenditures that could be required to sustain the high demand case, assuming that production is derived only from known resources. The projected deficit between known resources and market based production requirements in the middle demand case is only 146 060 t U, so exploration expenditure requirements will be considerably less. However, because of unutilized resources, there is a projected deficit between requirements and production derived from known resources of 844 500 t U, which will only be reduced by early discoveries that are large enough to support high production capacities at low cost.

TABLE LV. EXPLORATION EXPENDITURES REQUIRED TO FILL THE PROJECTED DEFICIT IN THE HIGH DEMAND CASE: ASSUMES PRODUCTION FROM KNOWN RESOURCES

Discovery cost (US $/kg U)	Required exploration expenditure (US $ × 10^9)
0.50	1.20
1.00	2.39
2.00	4.78
3.00	7.18
4.00	9.57

The real challenge for the future will be to find large, relatively high grade deposits that can be brought into production by at least 2025, so that their resources can be utilized within the remaining 25 years of the study period, thus avoiding the problem of unutilized resources. To meet this challenge exploration expenditures will have to begin to increase within the next five years to ensure that discoveries are made early enough to accommodate the long lead time between discovery and production. The McArthur River project in Canada is a good example of the time requirements to bring a deposit into production. Exploration in the McArthur River area, which dates back to the 1970s, was intensified in the early 1980s when a new generation of geophysical surveys could detect conductive zones at depth. Encouraging but subeconomic mineralization was discovered in 1985, and discovery of ore grade mineralization occurred in 1988, nearly eight years after the start of systematic exploration. Eleven years lapsed between the discovery of ore grade mineralization and the start of production in late 1999. During this time, surface and underground explorations were completed, and several levels of feasibility studies were completed. The feasibility studies were the basis for an environmental impact statement which was subjected to an exhaustive round of environmental hearings and reviews. Approval to begin development was given by government regulatory agencies in 1997, and production was underway in 1999.

Future discoveries can be expected to undergo the same kind of environmental scrutiny that McArthur River was subjected to. Therefore, based on McArthur River's history, if the recently discovered high grade mineralization in the Dawn Lake area turns out to be a viable discovery, it would likely not be ready for production until 2009 at the earliest. The message is clear: long lead times will be the rule rather than the exception, and exploration will have to accelerate to ensure a stable supply of relatively low cost uranium. In other words, the exploration expenditure requirements shown in Table LV cannot be evenly spread throughout the 50 year study period. They need to come early enough that the resulting discoveries can contribute to production requirements in a timely manner.

5.3. PRODUCTION COSTS AND URANIUM MARKET PRICE IMPLICATIONS

Table XVII defines the cost categories that are used in this study. For each combination of supply and demand, the dates when high medium and high cost production will be required have been noted throughout this report as an indication of market price trends. As secondary supply becomes less important, market prices will more accurately reflect production costs than is currently the case. Table LVI combines these cases to show when, under varying supply–demand combinations, market prices are projected to break into the next higher cost category to cover production costs. For example, in the middle demand case, with production limited to known resources (RAR + EAR-I), high medium cost production is projected to be needed to fill market based production requirements in 2021. It follows, therefore, that the spot market price will have to increase to >US \$52/kg U (US \$20/lb U_3O_8, US \$44 U_3O_8) in 2021, and to >US \$78/kg U (US \$30/lb U_3O_8, US \$66 U_3O_8) in 2027.

Projected increases in market price are based on the year in which projects in the next highest cost category will be needed to satisfy market based production requirements. These projections may not, however, accommodate the fact that because of unutilized resources, deficits between production from RAR through to EAR-II and production requirements are forecast in both the middle and high demand cases. As noted in Section 5.2, SR must be converted to discoveries early enough in the study period to ensure that their resources will be fully utilized by 2050. Therefore exploration must begin sufficiently early to ensure that discoveries can be made, environmental review and licensing procedures completed and projects developed in a timely manner. For this to happen, producers must have assurances that market prices will be sustainable at high enough levels to support exploration and development risks and expenses. For example, it is estimated that the owners of the McArthur River project in Canada spent more that US \$300 million in exploration and development costs before the project began production. If secondary supply continues to keep market prices at artificially low levels there will be little incentive for producers to undertake the major exploration programmes needed to make significant discoveries, which in turn could exacerbate future production shortfalls.

5.4. ENVIRONMENTAL IMPLICATIONS OF THE THREE DEMAND CASES

The middle and low demand cases both assume that future energy policy will be ecologically driven (scenarios C1 and C2, Appendix I) and will be characterized by international co-operation focused on environmental protection. The extent to which the interests of individual countries can be moderated in favour of a comprehensive global energy policy centred on the reduction of greenhouse gases remains to be seen. However, as the debate on global warming continues, the advantage that nuclear power has in not directly producing greenhouse gases could become more widely recognized. If nothing else, it may help stabilize nuclear power's role in the energy mix, and to offset the paradox in which those that purport to be the most concerned about the potential for human induced global warming are the same as those most opposed to nuclear energy.

TABLE LVI. PROJECTIONS OF WHEN NEXT HIGHER COST CATEGORIES WILL BE REQUIRED TO FILL PRODUCTION REQUIREMENTS

	Middle demand case		High demand case	
	High medium cost	High cost	High medium cost	High cost
RAR	2019	2024	2013	2019
RAR + EAR-I	2021	2027	2015	2022
RAR + EAR-I + EAR-II	2021	2029	2015	2023

All three demand cases envision a role for nuclear power and, therefore, ensure a demand for uranium at least until 2050. It is estimated that every tonne of uranium used in lieu of burning coal avoids the emission of approximately 40 000 tonnes of carbon dioxide, the gas which accounts for about 55% of the greenhouse gases from human activity. Table LVII shows the projected cumulative reactor uranium demand for the three demand cases and the amount of carbon dioxide generation that would be saved relative to burning coal if any one of these cases is implemented.

In Ref. [4, p. 103] the World Energy Council reports that "Nuclear power is of fundamental importance for most WEC members because it is the only energy supply which already has very large and well-diversified resources (and potentially unlimited resources if breeders are used), is quasi-indigenous, does not emit greenhouse gases, and has either favourable or at most slightly unfavourable economics. In fact should the climate change threat become a reality, nuclear is the only existing power technology which could replace coal in baseload. While it faces a public acceptance problem, the present evolution of safety, waste disposal and regulatory independence, should lower the existing concerns".

TABLE LVII. CARBON DIOXIDE SAVINGS FROM THE USE OF URANIUM IN LIEU OF COAL: LOW, MIDDLE AND HIGH DEMAND CASES

	Reactor demand (1000 t U)	Carbon dioxide saved (tonnes × 10^9)
Low demand case	3390	135
Middle demand case	5394	216
High demand case	7577	303

Appendix I

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS (IIASA) AND WORLD ENERGY COUNCIL (WEC) STUDY

As noted in Section 3.1, reactor uranium requirements based on the nuclear energy projections in the IIASA/WEC study [6] serve as the basis for the projected uranium demand between 2020 and 2050. This study was conducted in two phases, the first phase of which was published in 1995 [2]. Data gathering for the first phase took place between 1993 and 1995. Since we have five additional years of history on nuclear power use not available to IIASA/WEC analysts, more up to date uranium demand projections were used in this study for the period from 2000 to 2020. However, the IIASA/WEC study still stands as the most definitive work on long term energy use and the projected role of nuclear energy; it has hence been the basis for projecting demand throughout the last 30 years of this study.

The cornerstone of the IIASA/WEC study is the premise that the world's population is expected to grow to 10 100 million by the middle of the twentyfirst century (compared to 6000 million in 1999), which in turn will result in a three- to fivefold increase in world economic output by 2050. The expanding world economy will be accompanied by a 1.5- to threefold increase in energy demand, with technological developments leading to improved energy efficiency accounting for the slower increase in energy demand compared to economic output. In addition to being more efficient, energy output will become increasingly compatible with growing global environmental concerns. Based on these underlying themes, the IIASA/WEC study presents three cases, with a total of six separate scenarios.

Case A: characterized by high economic growth of nearly 2% per year in OECD countries and nearly twice that rate in developing countries. Case A assumes limited constraints on fossil fuel resources, relatively low energy prices and limited emphasis on environmental measures.

- Scenario A1: emphasizes development of oil and gas resources, with the assumption that there will be sufficient availability of these resources. Limited growth of nuclear power is envisioned.
- Scenario A2: assumes the greenhouse warming debate is resolved in favour of continued use of coal as the fossil fuel of choice. Nuclear power is accorded only limited growth.
- Scenario A3: labelled the 'bio-nuc' scenario, this scenario envisions a large scale use of renewable energy and a new generation of nuclear reactors combining to lead a transition away from the dominance of fossil fuels. By 2100 this scenario envisions nearly equal reliance on nuclear energy, natural gas, biomass and a fourth category that combines solar energy, wind and 'new' renewables.

Case B: case B steers a middle course. Characterized by moderate economic growth, case B reflects near term setbacks in economic growth in the former Soviet Union and painfully slow growth in much of Africa. It is termed the 'muddling through' scenario, with the greatest reliance on fossil fuels of all scenarios except the coal intensive scenario A2. Significant growth for nuclear power is assumed.

Case C: case C is ecologically driven and includes policies to reduce carbon emissions. It is characterized by progressive international co-operation focused on environmental protection and international equity. Nuclear energy takes widely divergent paths in two different scenarios projected for this case.

- Scenario C1: nuclear energy is assumed to be phased out entirely by the end of the twentyfirst century.
- Scenario C2: assumes a new generation of nuclear reactors will be developed that are small, inherently safe and finds wide social acceptability, leading to a sustained growth of nuclear energy.

The IIASA/WEC study covers a wide range of potential energy developments, ranging from:

- A huge increase in the use of coal, to strict limits.
- Phase-out of nuclear power, to a substantial increase.
- Carbon emissions which are one third of today's levels, to increases by a factor of three.

Table LVIII compares economic and energy demand assumptions and projections based on the three cases for 1990 and 2050.

The six scenarios developed in the IIASA/WEC study project a wide range of energy mixes by 2050, but in all cases fossil fuels, including coal, oil and natural gas, continue to dominate energy supply to 2050. Fossil fuel usage in 2050 is projected to range between 52 and 78% of the energy supply in scenarios C1 and A1, respectively. The share that nuclear power will contribute to the total energy mix in 2050 is projected to range

TABLE LVIII. IIASA/WEC ECONOMIC AND ENERGY DEMAND ASSUMPTIONS (ADAPTED FROM TABLE 2 OF REF. [6])

	Case A	Case A	Case C
Gross world product (US [1990] $ × 10^{12})			
1990	20	20	20
2050	100	75	75
Primary energy demand (gigatonnes oil equivalent)			
1990	9	9	9
2050	25	20	14
Net carbon emissions (gigatonnes carbon)			
1990	6	6	6
2050	9–15	10	5

between 4% in scenarios A2 and C1 to approximately 12% in scenarios A1, A3, B and C2.

The IAEA selected scenarios A3, C1 and C2 for further analysis because they effectively defined the upper, middle and lower range of projected nuclear power usage between 2020 and 2050. In support of the IAEA analysis a program that converts projected nuclear generating capacity to reactor uranium requirements was developed to model the nuclear fuel cycle associated with the IIASA/WEC study. The model is discussed by Shani [16] and its application is discussed in Ref. [1].

Appendix II

ECONOMIC MODEL FOR TAILS RE-ENRICHMENT

Table LIX provides a means of determining the feed requirements to produce 1 kg U equivalent, given a range of depleted uranium feed content (per cent ^{235}U) and secondary tails assays of 0.10 and 0.15%.

Figure 24 can be used in conjunction with Table LVIII to project the economics of tails re-enrichment under a varied set of SWU and feed costs. For example, re-enrichment of 2.805 kg of depleted feed with 0.35% residual ^{235}U content:

- —Assuming 0.15% secondary tails assay,
- —Tails availability in the form of UF_6 at no cost,
- —US $40/SWU re-enrichment cost,

yields 1 kg of ‘reconstituted’ natural uranium at a cost of US $33.04 (0.826 × 40), which is comparable to the current market price. Using the same set of conditions, but increasing the re-enrichment cost to US $80/SWU, pushes the price to about US $65/kg U.

TABLE LIX. DATA FOR DEPLETED URANIUM RE-ENRICHMENT TO PRODUCE NATURAL URANIUM EQUIVALENT: FOR 1 kg OF ‘NATURALIZED’ URANIUM PRODUCED

Secondary tails assay (% U^{235})	Depleted feed ^{235}U content (% ^{235}U)	Depleted feed required (kg DU)	SWU consumption (SWU)
0.10	0.20	6.110	2.285
0.10	0.25	4.073	1.780
0.10	0.30	3.055	1.403
0.10	0.35	2.444	1.107
0.15	0.20	11.220	1.681
0.15	0.25	5.610	1.318
0.15	0.30	3.740	1.043
0.15	0.35	2.805	0.826

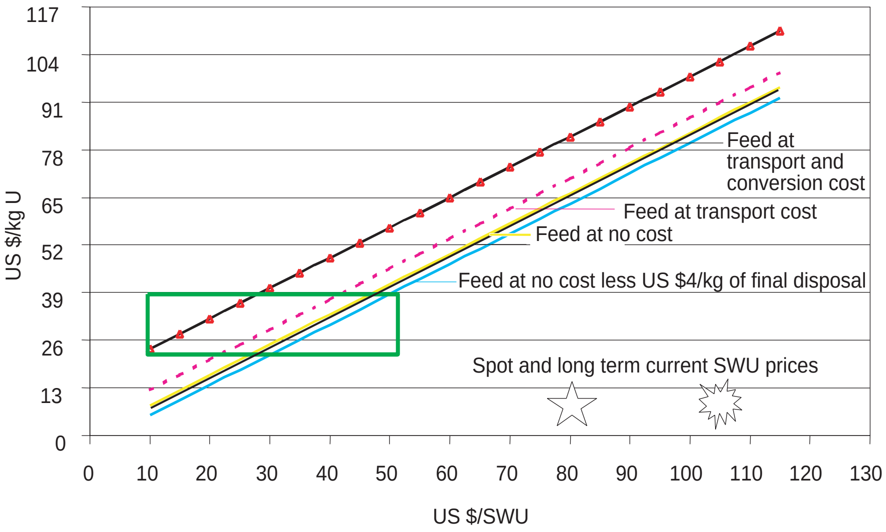


FIG. 24. Economics of tails re-enrichment.

Appendix III

REVIEW OF THE WORLDWIDE URANIUM PRODUCTION INDUSTRY

This appendix provides an overview of the uranium production industries of the major producing countries. Figures 25–29 show the location of major deposits and/or important production centres; space limitations preclude showing the locations of all production centres and deposits on the figures. Typically only one deposit is included in major districts; inclusion or exclusion of deposits on these maps is not meant to imply their overall importance. Figures 30–36 show views of various uranium production facilities and equipment in various countries.

III.1. AUSTRALIA

The history of Australia's uranium production industry is divided into two separate periods. Production began in the Rum Jungle (Northern Territory) in 1954, followed by startup of the Mary Kathleen mine in Queensland in 1958. By 1971, however, production had virtually stopped. Australia's modern era of uranium production began in 1980 with the opening of the Ranger open pit mine in the Northern Territory. Ranger, along with Olympic Dam, which began operations in 1988, have been the mainstays of Australia's uranium production industry.

Australia's three mines policy limited development of new uranium mines until the policy was rescinded in 1996. With the lifting of that policy, three new uranium projects, Beverley, Honeymoon and Jabiluka, are under development. Table LX is a summary of Australia's current uranium production industry.

Australia's geologic diversity is reflected in the variety of deposit types included in its resource base. Table LXI is a listing of the deposit type for Australia's five largest known deposits.

Table LXII is a summary of Australia's historical production.

Resources reported by Australia (1999 Red Book [3]) are as in Table LXIII.

III.2. CANADA

Uranium production began in Canada in 1942 with the reopening of the Port Radium radium mine. From that beginning, the industry expanded to the Elliot Lake district in Ontario and finally to the eastern margin of the Athabasca Basin, the centre of Canada's current uranium production industry.

Uranium production in Canada currently comes exclusively from unconformity related deposits in the Athabasaca Basin district. Table LXIV is a summary of Canada's uranium production industry.

Table LXV is a summary of Canada's historical production (t U).

Like most of the rest of the Western producing countries, Canada's production history has been cyclical, with

TABLE LX. AUSTRALIA'S CURRENT URANIUM PRODUCTION INDUSTRY

Production centre	Production capacity (t U)	Ownership	Mining method	Resources (t U)	Status
Ranger	5 000	Energy Resources of Australia	Open pit	47 140	Operating
Jabiluka	1 000[a]	Energy Resources of Australia	Underground	76 680	In development
Olympic Dam	3 880[b]	WMC Ltd	Underground	336 000[c]	Operating
Beverley	770	Heathgate Resources	ISL	17 690	In development
Honeymoon	385[d]	Southern Cross Resources	ISL	6 800[e]	In development

[a] A final decision as to whether to process Jabiluka ore on-site or at the Ranger mill is pending.

[b] Olympic Dam has received government approval to increase capacity to 6540 t U.

[c] Includes 63 000 t U of probable reserves. WMC also reports 488 000 t U of indicated resources and 172 000 t U of proven reserves and 273 000 t U of inferred resources.

[d] Potential to increase capacity to 770 t U/a.

[e] Southern Cross Resources estimates that 'available resources' along the Honeymoon, Gould's Dam/Bileroo and Yarramba trends could total as much as 21 440 t U (measured, indicated and inferred reserves/resources).

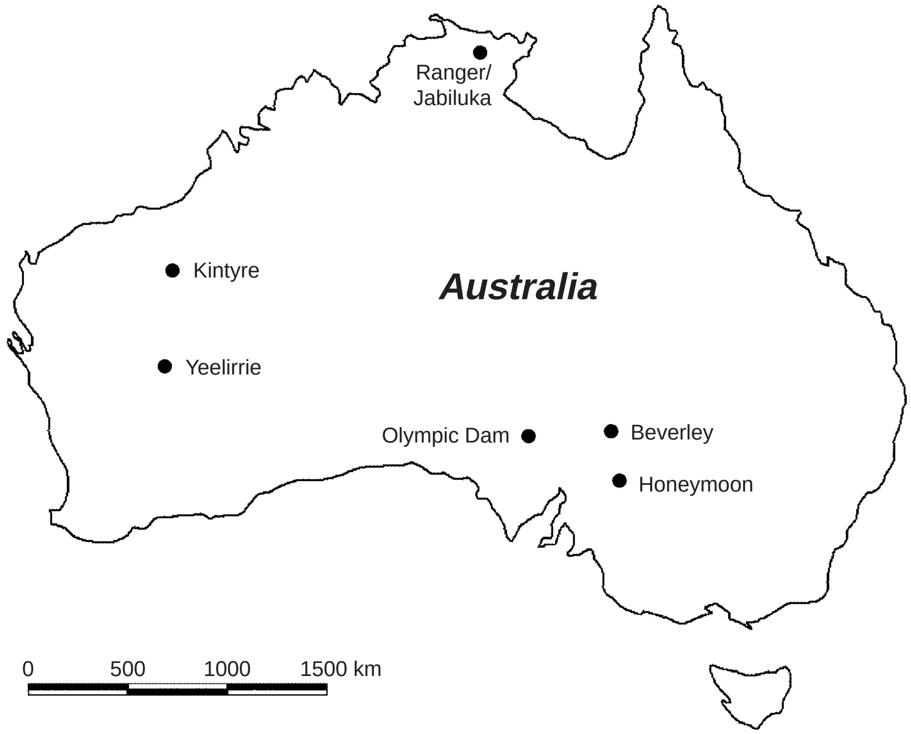


FIG. 25. Project location map — Australia.

TABLE LXI. AUSTRALIA'S FIVE LARGEST KNOWN URANIUM DEPOSITS

Deposit	Resources (t U)	Deposit type
Olympic Dam	336 000	Breccia complex
Ranger/Jabiluka	123 800	Unconformity
Yeelirrie	40 800	Surficial/calcrete
Kintyre	24 400	Unconformity
Beverley	17 690	Sandstone

TABLE LXIII. AUSTRALIA'S REPORTED RESOURCES

	1000 t U
RAR	716
EAR-I	194
EAR-II	None reported

production increases and decreases in response to civilian reactor requirements and market price cycles. The level of production reached in 1997 (12 031 t U) was approximately the same as peaks reached in 1959 (12 200 t U) and 1988 (12 393 t U), when the operations in the quartz–pebble conglomerate deposits in Ontario were still active. Production in 1997 came from only three operations in the Athabasca Basin, while that in the other two peak years also included output from the deposits in Ontario, the last one of which shut down in June 1996.

Resources reported by Canada (1999 Red Book [3]) are as in Table LXVI.

As noted in Section 4.1.6, known resources (RAR + EAR-I) are allocated differently in the Red Book than they have been in this study. Table LXVII shows that total study RAR for Canada, including low, low medium and high medium cost resources, closely approximates RAR + EAR-I in the <US $80/kg U category in the Red Book.

TABLE LXII. AUSTRALIA'S HISTORICAL URANIUM PRODUCTION (t U)

Pre-1990	1990	1991	1992	1993	1994	1995	1996	1997	1998
44 503	3 530	3 776	2 334	2 256	2 208	3 712	4 975	5 488	4 910

FIG. 26. Project location map — Africa.

TABLE LXIV. CANADA'S CURRENT URANIUM PRODUCTION INDUSTRY

Production centre	Production capacity (t U)	Ownership	Mining method	Resources (t U)
McArthur River	6 920[a]	69.8% Cameco, 30.2% Cogéma	Underground	184 230[b]
McClean Lake/ Midwest Lake	2 310	70.0% Cogéma,[c] 22.5% Denison, 7.5% OURDC	Open pit/underground	34 460
Rabbit Lake	4 620	100% Cameco	Underground	14 400
Cluff Lake	1 500	100% Cogéma	Underground	8 700
Cigar Lake[d]	6 920	50.0% Cameco, 37.1% Cogéma, 7.9% Idemitsu, 5.0% Tokyo Elec.	Underground	135 800

[a] McArthur River ore is processed at the Key Lake mill, which is owned 83.33% by Cameco and 16.67% by Cogéma.

[b] Includes 96 590 t U of reserves and 87 640 t U of resources as reported by Cameco and adjusted for projected 1999 production.

[c] Reflects ownership of the McClean Lake project. Ownership of Midwest Lake slightly different.

[d] Currently under development. Production expected to start in 2001 to 2003.

FIG. 27. Project location map — Brazil.

TABLE LXV. CANADA'S HISTORICAL URANIUM PRODUCTION (t U)

Pre-1990	1990	1991	1992	1993	1994	1995	1996	1997	1998
231 506	8 729	8 160	9 297	9 155	9 647	10 473	11 706	12 031	10 922

TABLE LXVI. CANADA'S REPORTED RESOURCES

	1000 t U
RAR	326.4
EAR-I	106.6
EAR-II	150.0
SR	700.0

The close comparison between the two totals suggests that they include basically the same resources. The main difference in the two interpretations probably results from the distinction between 'reserves' and 'resources' reported by project operators. This distinction follows strict reporting requirements under Canadian securities laws. Typically in the unconformity related deposits, reserves are based on underground exploration and development drilling while resources are based on surface drill holes. Therefore Cameco reports 266 846 t U of reserves and 100 889 t U of resources. The Canadian Red Book contributors apparently classify the resources as EAR-I. The consultants preparing this study classified the resources as RAR, because, in their opinion, the quality of the data on which they are based warrant the higher confidence ranking.

III.3. KAZAKHSTAN

Uranium production began in Kazakhstan in 1953 with the opening of mines in the Pribalkhash district. Today Kazakhstan's uranium production industry is based exclusively on ISL operations at three production centres, as shown in Table LXVIII.

Kazakhstan's ISL amenable resources are located in two districts or provinces separated by the intervening Karatau uplift. The host rocks for the Chu-Sarysu province are Cretaceous and Paleocene sandstones; in the Syr-Darya province the ore is hosted in Cretaceous sandstones. The ore is controlled along oxidation/reduction roll fronts, similar to the roll front deposits in the Wyoming Basins of the USA.

FIG. 28. Project location map — eastern Europe and Asia.

TABLE LXVII. COMPARISON OF TOTAL STUDY RAR AND RED BOOK TOTALS FOR CANADA

Study RAR totals	Low plus low medium cost	416 000 t U
	High medium cost	8 700 t U
	Total	424 700 t U
Red Book totals	RAR <US $80/kg U	326 420 t U
	EAR-I <US $80/kg U	106 590 t U
	Total	433 010 t U

In the past Kazakhstan also conducted open pit and underground mining operations in the Kokchetav, Pribalkhash and Pricaspian districts, all three of which still host significant uranium resources. The last of the conventional operations was shut down in 1994 due to their high production costs. Kazakhstan has one conventional uranium mill at Stepnogorsk located in the northern part of the country, which has a nominal capacity of 2500 t U. The conventional processing circuit is currently on standby status, but the Stepnogorsk (Tselinny) mill continues to dry yellowcake slurry from the ISL operations, none of which has an on-site dryer. Slurry from the ISL operations is also dried at the Kara Balta mill in Kyrgyzstan and the Vostok Redmet mill in Tajikistan.

In 1995 the Government of Kazakhstan entered into joint ventures with the Cameco Corporation and Cogéma to develop the ISL potential of the Inkai and Moynkum

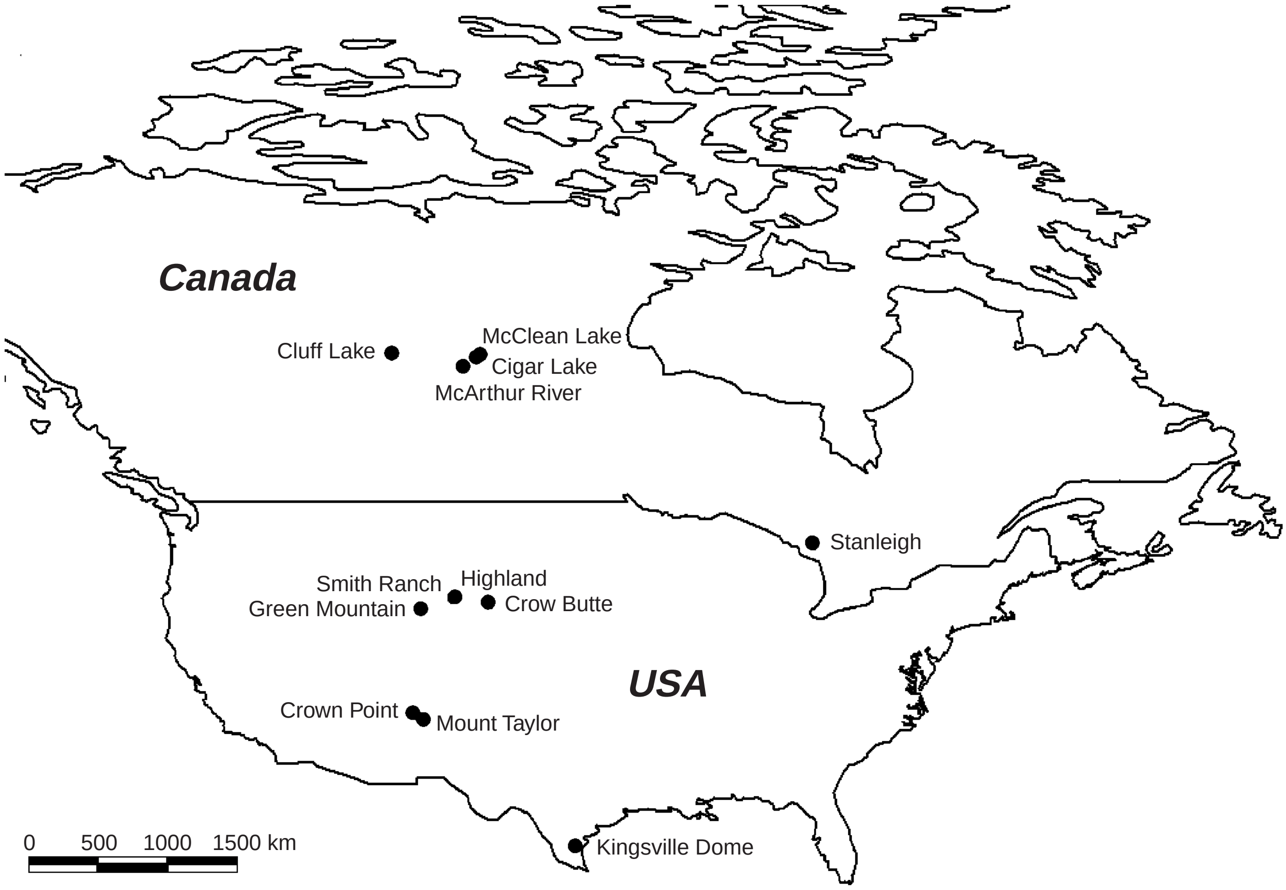


FIG. 29. Project location map — Canada and the USA.

TABLE LXVIII. KAZAKHSTAN'S URANIUM PRODUCTION INDUSTRY

	Production capacity (t U)	Deposits	Resources (t U)
Stepnoye Ore Company	1 000	Uvanus	20 000
Central Ore Company	1 000	Kandjugan	50 000
Ore Company No. 6	600	Karamurun	28 000

TABLE LXIX. KAZAKHSTAN'S HISTORICAL URANIUM PRODUCTION (t U)

Pre-1992	1992	1993	1994	1995	1996	1997	1998
72 000	2 802	2 700	2 240	1 630	1 210	1 090	1 270

deposits, respectively. These operations could be in production as early as 2001, but no definite production schedule has been released. Both projects could eventually have production capacities of between 700 and 800 t U/a. Resources of the Inkai and Moynkum projects total 127 000 and 82 000 t U, respectively.

Table LXIX is a summary of Kazakhstan's historical production.

Resources reported by Kazakhstan (1999 Red Book [3]) are as in Table LXX.

TABLE LXX. KAZAKHSTAN'S REPORTED RESOURCES

	1000 t U in situ	1000 t U recoverable[a]
RAR	598.7	450.9
EAR-I	259.3	
EAR-II	310.0	
SR	500.0	

[a] Kazakhstan reports in situ resources in the Red Book. RAR were converted to recoverable resources as follows. The 1997 Red Book estimated that approximately 73% of Kazakhstan's RAR were ISL amenable. This percentage was applied to RAR reported in the 1999 Red Book [3], resulting in an estimated RAR allocation of 439 420 t U ISL amenable and 159 240 t U amenable to conventional and by-product extraction. A 70% recovery factor was applied to the ISL amenable resource base and a 90% recovery factor to the conventional resource base.

III.4. NIGER

Uranium production began in Niger in 1971 at Arlit. Table LXXI summarizes Niger's current production centres.

Table LXXII is a summary of Niger's historical production.

Niger's known uranium deposits are located in the Tim Mersoi Basin on the western flank of the Air Massif. Host rocks for Niger's deposits are Carboniferous to Jurassic sandstones. The uranium occurs in tabular sandstone deposits, with local modification to stacked ore bodies along fractures. Resources of the better known ore bodies are summarized in Table LXXIII.

Resources reported by Niger (1999 Red Book [3]) are as in Table LXXIV.

There is a significant difference between RAR reported in the Red Book and study RAR. Niger reported

TABLE LXXI. NIGER'S CURRENT URANIUM PRODUCTION CENTRES

	Production capacity (t U)	Mining method	Ownership
Akouta	2000	Underground	34.0% Cogéma, 31.0% ONAREM (Niger), 25.0% Overseas Uranium Resources Development Co. (Japan)
Arlit	1540	Open pit	10.0% ENUSA (Spain), 63.4% Cogéma, 36.6% ONAREM

TABLE LXXII. NIGER'S HISTORICAL URANIUM PRODUCTION (t U)

Pre-1990	1990	1991	1992	1993	1994	1995	1996	1997	1998
47 809	2 839	2 963	2 965	2 914	2 975	2 974	3 321	3 487	3 714

TABLE LXXIII. NIGER'S RESOURCES

Production centre	Resources (1000 t U)	Average ore grade (% U)	Current or proposed mining method
Afasto	25.2	0.25	Underground
Akouta	40.5	0.42	Underground
Arlit	22.2	0.25	Open pit
Imouraren	100.5	0.18	Currently testing for ISL
Madaouela	5.1	NA[a]	Open pit

[a] NA: not available.

FIG. 30. Freeze chamber on the 530 m level of McArthur River underground mine, Saskatchewan, Canada.

FIG. 31. Deilmann tailings management facility, Key Lake, Saskatchewan, Canada.

FIG. 32(a). ISL wellfield, Zarafshan, Uzbekistan. Alternating rows of injection and production wells.

FIG. 32(b). ISL wellfield, Zarafshan, Uzbekistan. Close-up of row of production wells.

FIG. 33(a). ISL production equipment, Wyoming, USA. Newly constructed production well.

TABLE LXXIV. NIGER'S REPORTED RESOURCES

	1000 t U
RAR	71.12
EAR-I	18.58
EAR-II	None reported

only resources on which recent feasibility studies have been completed. Therefore this report was limited to current operations at Akouta and Arlit. However, Niger has significant, well defined resources associated with other known deposits, including Afasto, Imouraren and Madaouela. In the 1993 Red Book, using less restrictive reporting criteria, Niger reported RAR and EAR-I totalling 165 820 and 305 770 t U, respectively. While these resource totals may be somewhat out of date, they clearly indicate that Niger's resources far exceed those reported in the 1999 Red Book [3].

III. 5. THE RUSSIAN FEDERATION

The Russian Federation currently has only one operating uranium production centre, the Priargunsky mine–mill complex near the southeastern Siberian city of Krasnokamensk. Development of the Priargunsky complex began in 1968, and the facility has produced without interruption since. Past production also took place in the Stavropol district in the northern foothills of the Caucasus Mountains and the Trans-Ural district on the eastern flank of the Ural Mountains. Lermontov Mining and Industrial Association, 'Almaz', in the Stavropol area processed ore from the Beshtau deposit, which has been mined out. The operator in the Trans-Ural district was Malyshevsks Mining Complex, which processed ore from the Sanarskoe deposit.

The ore bodies that are being mined at Priargunsky are located within the Streltsovsk uranium district. The ore is associated with a system of hydrothermal veins and stockworks in interbedded late Jurassic volcanic and volcaniclastic rocks within a caldera that measures nearly 20 km in diameter, and in the granites and dolomites in the basement. The Streltsovsk district is not a single deposit, but is instead several deposits hosted in different environments within the caldera. Table LXXV lists of some of the larger deposits that together comprise the Streltsovsk district.

Mining at Priargunsky is now limited to underground operations, with the deepest shaft extending to a depth of about 1470 m; open pit mining was stopped in 1994. Priargunsky utilizes conventional milling of higher grade ore, supplemented by underground stope leaching and surface heap leaching. The Priargunsky mill has a capacity of 3500 t U/a. Molybdenum has in the past been recovered as a by-product of uranium processing. In response to low uranium prices, mining at Priargunsky is currently limited to ore zones with average grades of 0.28% uranium or higher. Priargunsky estimates that RAR in the Streltsovsk district are sufficient to satisfy operations planned for the next 20 years.

The Russian Federation has also completed extensive evaluation of the ISL potential of valley type (sandstone) uranium deposits in three areas: Trans-Ural, western Siberia and Vitim. Extensive ISL pilot testing has been conducted at the Dalmatovsk deposit in the Trans-Ural area and full scale operations are scheduled to begin in 2001 to 2003. The Dalmatovsk mineralization,

TABLE LXXV. THE LARGER URANIUM DEPOSITS IN THE STRELTSOVSK DISTRICT

Streltsovsk
Argunskoe
Shirondukuevskoye
Yubileinoye
Novogodneye
Martovskoye
Lutchistoye
Vesenneye
Antei
Malo-Tulukuevskoye
Oktyabrskoye

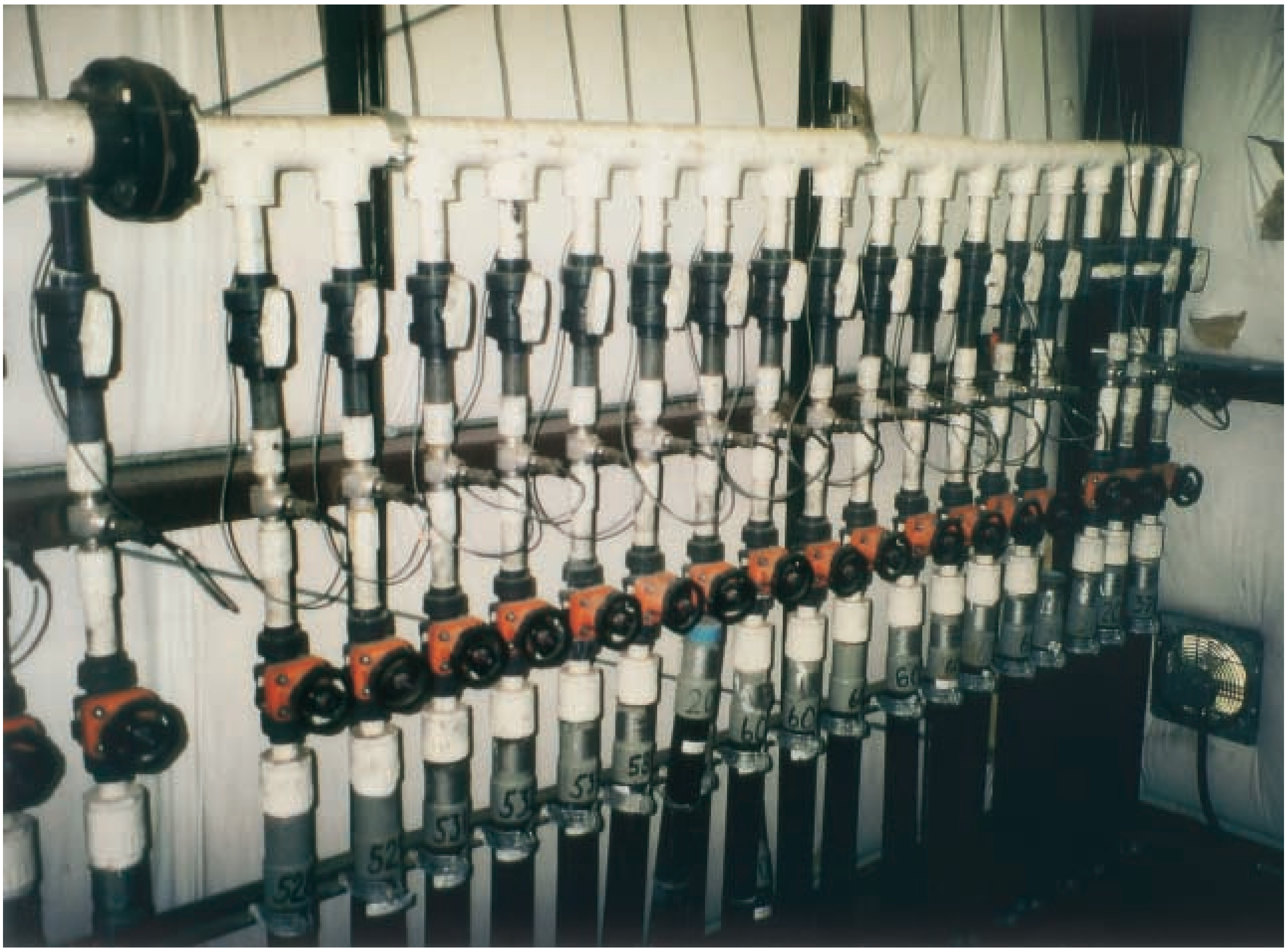


FIG. 33(b). ISL production equipment, Wyoming, USA. Wellfield plumbing and monitoring equipment.

which occurs in late Jurassic–early Cretaceous sandstones and gravels, ranges in depth between 420 and 560 m. Ore grades range between 0.038 and 0.043% uranium. An acid leach system will be utilized at Dalmatovsk. The Russian Federation plans to begin development of the ISL potential of the Vitim area after production at Dalmatovsk is underway.

Table LXXVI is a summary of the Russian Federation's historical production.

Resources reported by the Russian Federation (1999 Red Book [3]) are given in Table LXXVII.

The Russian Federation reported only RAR and EAR-I recoverable at costs below US $80/kg U in the Streltsovsk and Trans-Ural areas. These totals do not include up to 75 000 t U in the EAR-I category in the Vitim area that are currently under review but have not been approved for publication. Total resources in both RAR and EAR-I are projected to be higher if all cost categories are included.

III. 6. UKRAINE

Ukraine's uranium production industry includes underground mines in the Kirovograd district and a

TABLE LXXVI. THE RUSSIAN FEDERATION'S HISTORICAL URANIUM PRODUCTION (t U)

Pre-1992	1992	1993	1994	1995	1996	1997	1998
93 980	2 640	2 697	2 541	2 160	2 605	2 580	2 530

FIG. 33(c). ISL production equipment, Smith Ranch, Wyoming, USA. Columns hold ion exchange resin to recover uranium from leach solution pumped from the wellfield.

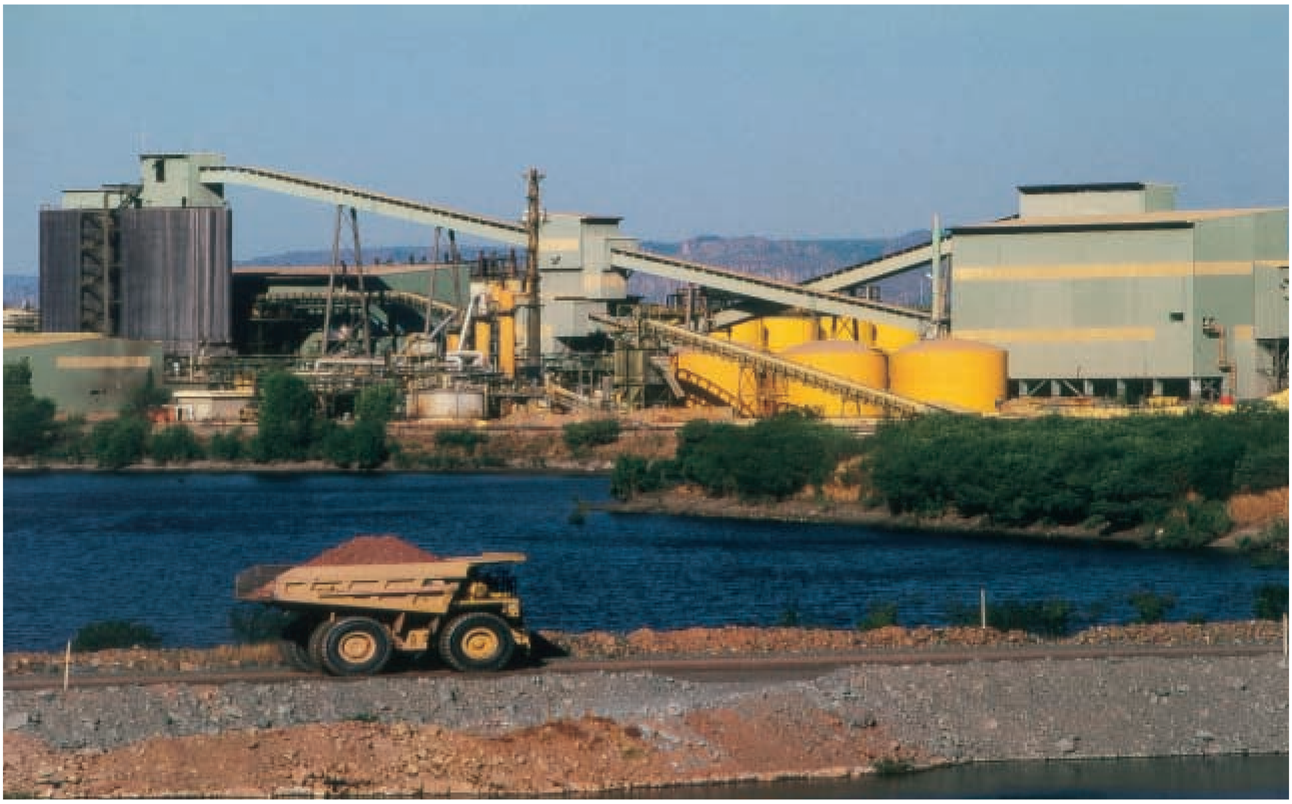


FIG. 34. Truck hauling ore to the Ranger uranium ore processing facility, Northern Territory, Australia.

FIG. 35. Olympic Dam copper–uranium–gold mine–mill–smelter complex, South Australia. The headframes for the underground mine are near the left-hand side of the picture.

FIG. 36. Uranium recovery crushing circuit, Olympic Dam, South Australia. The solvent extraction circuit is located near the centre, uranium recovery columns to the left and yellowcake calciner to the right. The headframes for the underground mine are on the horizon to the centre and right of the picture.

TABLE LXXVII. THE RUSSIAN FEDERATION'S REPORTED RESOURCES

	1000 t U
RAR	140.9
EAR-I	36.5
EAR-II	105.0
SR	1000.0

conventional mill at Zheltiye Vody. Production at the Zheltiye Vody mill began in 1959. The Dnieprodzerzhinsk mill, which operated between 1947 and 1990, has been converted to the production of other metals. Ukraine also conducted ISL operations at the Devladovskoe, Bratskoe and Sanfonovskoye deposits in paleovalley sandstone deposits south of the Kirovograd district.

The host rocks in the Kirovograd district are a complex mixture of Precambrian gneiss and granite altered by metasomatic albitization. The ore occurs in veins and stockworks associated with a 10 km wide tectonic zone.

There are currently two active mines in the Kirovograd district — Ingul'skii mine (Michurinskoye ore body) and Vatutinskii mine (Vatutinskoye ore body). The Ingul'skii mine, which has been in operation since 1971, accounts for about 90% of Ukraine's uranium production. Ore from both mines is hauled by rail to the Zheltiye Vody mill, which has a nominal capacity of 1000 t U/a.

Table LXXVIII is a summary of Ukraine's historical production.

Resources reported by Ukraine (1999 Red Book [3]) are as given in Table LXXIX.

Approximately 75% of Ukraine's resources are in albitite type deposits such as those currently being exploited in the Vatutinskii and Ingul'skii mines.

III.7. THE USA

Uranium exploration and production in the USA date back to the mid 1940s, when the main focus was ensuring that military requirements were satisfied. Between 1946 and 1958, the US Government created exploration incentives to stimulate development of a domestic uranium production industry. In 1954 private ownership of nuclear reactors was approved and in 1958 domestic producers were first allowed to sell uranium to domestic and foreign buyers. US uranium production reached a peak of 16 800 t U in 1980 and steadily declined to a low of 1180 t U in 1993, before rebounding modestly in subsequent years.

The rebound in production was, however, short lived, and production is once again declining. ISL operations are now the backbone of the US production industry. ISL production is now limited to the Wyoming Basins, as operations in south Texas were placed on standby in 1999. The uranium deposits in the Wyoming Basins occur as oxidation/reduction roll fronts in Tertiary sandstones. Two conventional mills were in operation in 1999, one processing stockpiled uranium–anadium ore from Colorado Plateau mines which suspended operations in 1999, and the other processing ore from the Schwartzwalder vein deposit in Colorado. Recovery of uranium as a by-product of phosphate operations in Louisiana was suspended in 1999. Table LXXX is a summary of the US's uranium production industry.

In addition to the operations listed above, the uranium mills shown in Table LXXXI are on standby status.

Table LXXXII is a summary of the USA's historical production.

Resources reported by the USA (1999 Red Book [3]) are as given in Table LXXXIII.

TABLE LXXIX. UKRAINE'S REPORTED RESOURCES

	1000 t U
RAR	81
EAR-I	50
EAR-II	4
SR	231

TABLE LXXVIII. UKRAINE'S HISTORICAL URANIUM PRODUCTION (t U)

Pre-1992	1992	1993	1994	1995	1996	1997	1998
NA[a]	1000	1000	1000	1000	1000	1000	1000

[a] NA: not available.

TABLE LXXX. THE US URANIUM PRODUCTION INDUSTRY

Production centre	Production capacity (t U)	Ownership	Mining method	Resouces (t U)
Higland	770	100% Power Resouces	ISL	7 300
Crow Butte	385	100% Cameco	ISL	14 700
Smith Ranch	770	100% Rio Algom	ISL	21 500
Christensen Ranch	385	100% Cogéma	ISL	6 000
Uravan/White Mesa[a]	385	100% International Uranium Corp.	Underground	4 700
Canon City	385	100% General Atomics	Underground	2 600

[a] The White Mesa mill also processes and recovers uranium from non-ore 'alternative feed' (ores or residues from other processing facilities that contain uranium in quantities or forms that are either uneconomic to recover or cannot be recovered at these other facilities).

TABLE LXXXI. URANIUM MILLS ON STANDBY STATUS IN THE USA

Mill	Operator	Capacity (t U)	Deposits served by mill
Sweetwater	US Energy	1540	Green Mountain
Shootering Canyon	US Energy	385	Tony M, regional mill for small deposits
Ambrosia Lake	Rio Algom	[a]	
Ford (Washington)	Dawn Mining	[b]	

[a] Decommissioning plan in place.
[b] Unlikely ever to restart.

TABLE LXXXII. THE USA'S HISTORICAL URANIUM PRODUCTION (t U)

Pre-1990	1990	1991	1992	1993	1994	1995	1996	1997	1998
330 640	3 420	3 060	2 170	1 180	1 289	2 324	2 432	2 170	1 810

TABLE LXXXIII. THE USA'S REPORTED RESOURCES

	1000 t U
RAR	355
EAR-I	[a]
EAR-II	1273
SR	2198

[a] The USA does not report EAR-I and EAR-II separately.

III.8. UZBEKISTAN

Uranium production began in Uzbekistan in 1952 in the Fergana Valley in the eastern part of the country. Production now comes exclusively from ISL operations in the Kyzylkum district in central Uzbekistan. Uranium mining began at the Uchkuduk open pit mine in the Kyzylkum district in 1961. Although emphasis has now shifted to ISL operations, uranium production has continued uninterrupted since 1961 in the Kyzylkum district.

Two types of uranium deposits have been identified in the Kyzylkum district — oxidation/reduction roll front deposits in the basins and black schist related uranium–vanadium deposits in the uplifted basement complexes. Although heap leach pilot tests have been conducted on ore from the black schist deposits, production currently comes exclusively from the roll front deposits in the basins. The roll fronts occur in several stratigraphic horizons ranging in age from Cretaceous to Tertiary.

There are currently three ISL production centres in the Kyzylkum district — Uchkuduk, Zafarabad and

Nurabad. Table LXXXIV is a summary of their production capacities and the deposits currently being exploited.

Slurry from the three ISL operations is processed in the solvent extraction circuit at the conventional mill in Navoi.

Table LXXXV is a summary of Uzbekistan's historical production.

TABLE LXXXIV. UZBEKISTAN'S PRODUCTION CAPACITIES AND DEPOSITS CURRENTLY BEING EXPLOITED

	Production capacity (t U)	Deposits
Uchkuduk	1000	Uchkuduk, Kendyktube
Zafarabad	1000	Bukinai, Lyavlyakan
Nurabad	700	Sabyrsai, Ketmenchi

Resources reported by Uzbekistan (1999 Red Book [3]) are as given in Table LXXXVI.

TABLE LXXXV. UZBEKISTAN'S HISTORICAL URANIUM PRODUCTION (t U)

Pre-1994	1994	1995	1996	1997	1998
82 763	2 015	1 644	1 459	1 764	1 926

TABLE LXXXVI. UZBEKISTAN'S REPORTED RESOURCES

	1000 t U
RAR	83.1
EAR-I	47.0
EAR-II	68.0
SR	102.0

Appendix IV

INTERNATIONAL URANIUM RESOURCES EVALUATION PROJECT (IUREP)

In 1976 the Joint IAEA/NEA Steering Committee on Uranium Resources was formed, with the mandate to 'review and evaluate the potential for discovery of additional uranium resources, to identify areas favourable for such resources, and to suggest new exploration efforts which might be carried out in promising areas in collaboration with the countries concerned'. This effort was undertaken in response to the projected shortfall between reasonably assured resources plus estimated additional resources and projected reactor uranium requirements. The steering committee focused on areas of the world for which information on uranium resources was limited, with its ultimate goal to quantify the world's uranium discovery potential. The concept of speculative resources was established to accommodate the lack of data in many parts of the world.

The International Uranium Resources Evaluation Project (IUREP) was initiated in 1977. The initial phase of IUREP was based on published reports and literature. A team of full-time staff members and consultants compiled the following data on 185 countries:

(a) General geography — including the area, population, climate, terrain, communications, means of access to different areas and, when available, a brief summary of laws which would be pertinent to an exploration programme;
(b) Geology in relation to potentially favourable uranium bearing areas;
(c) Past exploration;
(d) Uranium occurrences, resources and past production;
(e) Status of exploration;
(f) Potential for new discoveries.

Areas were identified which were believed to be favourable for the discovery of uranium resources in addition to those reported in the 1977 Red Book. A consensus ranking system was established to facilitate the process of judging the relative favourability of each country. For purposes of determining a broadly based estimate of worldwide resources, the IUREP team estimated a wide range of speculative resources potentially recoverable at a cost of less than US $130/kg U. Speculative resources in 185 countries were estimated to total between 9.9 million and 22.1 million t U. These totals were not meant to indicate ultimate resources, since the perspective of the team was restricted by then current knowledge.

The speculative resources were assigned to one of six descriptive deposit types as follows:

(a) Quartz–pebble conglomerate deposits,
(b) Proterozoic unconformity related deposits,
(c) Disseminated magmatic, pegmatitic and contact deposits in igneous and metamorphic rocks,
(d) Vein deposits,
(e) Sandstone deposits,
(f) Other types of deposits.

All of the information was compiled into the IUREP phase I report and was ultimately published under the title World Uranium Geology and Resource Potential [17].

From the data collected during phase I, the IUREP team identified 65 countries that it considered to have a good potential for the discovery of additional uranium resources. From this total approximately 40 counties were selected to participate in a second or orientation phase designed to gather more detailed information on uranium resource potential. During the orientation phase teams of explorers spent time in the field compiling first hand information on geology and uranium resource potential. Twenty countries were visited during the orientation phase. Following is a comparison of the ranges of resource potential estimated for these 20 countries in phase I and the orientation phase.

— IUREP phase I resources: 221 000–960 000 t U.
— Orientation phase resources: 230 000–1 350 000 t U.

The IUREP programme made a significant contribution to the understanding of the uranium geology of the world. At the same time, the range of resources estimated in the IUREP reports is considered too broad to have a direct application in the current study, other than the contribution, either direct or indirect, that IUREP data may have made to current Red Book estimates of speculative resources.

Appendix V

RESOURCE DEFINITIONS AND TERMINOLOGY

Resource estimates are divided into separate categories reflecting different levels of confidence in the quantities reported. The resources are further separated into categories based on the cost of production. All resource estimates are expressed in terms of metric tonnes (t) of recoverable uranium (U) rather than uranium oxide (U_3O_8). Estimates refer to quantities of uranium recoverable from minable ore, unless otherwise noted. Below are definitions of the resource categories used in this report. These definitions are the same as those used in the Red Book.

Reasonably assured resources (RAR) refers to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits, and on knowledge of deposit characteristics. RAR have a high assurance of existence.

In this study RAR are divided into two categories: study RAR and non-attributed RAR. Study RAR have been identified with specific deposits by the consultants involved in compiling this report. The total of study RAR is subtracted from total RAR listed in the Red Book to determine non-attributed RAR. Even though they are all classified as RAR, the reliability of the information on which study RAR are based varies considerably. Three broad sources of information served as the basis for this separate category of RAR: (1) the personal knowledge of the consultants who contributed to the study; (2) the IUREP study; and (3) the Red Book. The consultants in turn relied on various sources of information to estimate resources for specific deposits. In many cases the consultants were directly involved in the projects through completing feasibility studies and/or resource calculations.

As has been noted in the text, assessing the adequacy of resources to meet demand is one of the key objectives of this report. The level of confidence that can be placed in the resource estimates is essential to fulfilling this objective. Therefore Table LXXXVIII includes the sources of data on which study RAR are based. This table provides a subjective ranking of the data on which the information is based, using the following data source ranking categories. It is important to remember that even a low ranking for study RAR places these resources in a higher confidence category than resources in any other confidence category.

Low: typically the IUREP information without any other corroborative information is given the lowest ranking of study RAR. Also, study consultant contributions can be included in this category if they themselves are based on limited data.

Medium: this category includes Red Book information and information in Battey et al. [18] and from the Uranium Information Centre without any corroborative information. (The Uranium Information Centre is funded by companies involved in uranium exploration, mining and export in Australia.)

High: Uranium Information Centre data with corroborative and/or supplemental information; published papers or reports by people known to be knowledgeable about a deposit are included in this category.

Excellent: company annual reports and stock exchange prospectuses are included in this category.

The Table LXXXVII summary shows the resources that fall into each of the four data source ranking categories. It is important to note that only about 2% of the resources are based on poor data, while 34% are based on excellent data. There are 119 production centres/districts listed in Table LXXXVIII, of which 13 fall in the poor data quality category, 50 in the medium category, 33 in the good category and 23 in the excellent category. Both on the basis of percentage of total resources and number of projects, data in the combined good and excellent categories dominate study RAR, lending credibility to the analyses based on these resources.

Estimated additional resources category I (EAR-I) refers to uranium in addition to RAR that is inferred to

TABLE LXXXVII. THE FOUR DATA SOURCE RANKING CATEGORIES

Low (t U × 1000)	Per cent of total resources	Medium (t U × 1000)	Per cent of total resources	Good (t U × 1000)	Per cent of total resources	Excellent (t U × 1000)	Per cent of total resources
72	2	1135	36	895	28	1091	34

occur, mostly on the basis of direct geological evidence, in extensions of well explored deposits or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposits' characteristics are considered to be inadequate to classify the resource as RAR. Estimates of tonnage, grade and cost of further delineation and recovery are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best known parts of the deposit or in similar deposits. Less reliance can be placed on the estimates in this category than on those for RAR.

Estimated additional resources category II (EAR-II) refers to uranium in addition to EAR-I that is expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well defined geological trends or areas of mineralization with known deposits. Estimates of tonnage, grade and cost of discovery, delineation and recovery are based primarily on knowledge of deposit characteristics in known deposits within the respective trends or areas and on such sampling, geological, geophysical or geochemical evidence as may be available. Less reliance can be placed on the estimates in this category than on those for EAR-I.

Speculative resources (SR) refers to uranium, in addition to EAR-II, that is thought to exist, mostly on the basis of indirect evidence and geological extrapolations, in deposits discoverable with existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are speculative.

TABLE LXXXVIII. LISTING OF INFORMATION SOURCES FOR STUDY RAR

Country/uranium district production centre	Resources (1000 t U)	Confidence in information	Source of data
Algeria			
Hoggar	26.0	Medium	IUREP, study consultant
Argentina			
Cerro Solo	3.5	Excellent	CNEA feasibility study
Sierra Pintada	4.0	Medium	Red Book total minus Cerro Solo
Australia			
Angela	6.8	Medium	Battey et al. [18]
Ben Lomond/Maureen	6.6	Medium to high	Company publication — Anaconda Uranium Corp.
Beverley	17.7	Excellent	Company publication; environmental impact statement
Bigrlyi	2.0	Medium	Battey et al. [18]
Crocker Well	3.8	Medium	Battey et al. [18]
Honeymoon	6.8	Excellent	Company publication; environmental impact statement
Kintyre	24.4	Excellent	Company publication
Koongarra	10.3	Excellent	Company publication
Manyingee	7.9	Medium	Uranium Information Centre[a]
Mount Painter district	5.6	Medium	Battey et al. [18]
Mulga Rock	8.4	Medium	Battey et al. [18]
Olympic Dam	281.3	Excellent	Company publication
Ranger/Jabiluka	123.8	Excellent	Company publication
Valhalla/Mount Isa	14.0	Medium	Battey et al. [18]
Westmoreland	17.8	High	Company publication
Yeelirree	40.8	Excellent	Company publication
Yilgarn calcrete deposits	12.4	Medium	Battey et al. [18]
Brazil			
Itataia	80.0	Medium	Red Book
Lagoa Real	52.0	Medium	Red Book
Poços de Caldas	22.8	Medium	Red Book
Bulgaria	16.3	Medium	Published report — Nuexco market report
Canada			
Blizzard	3.8	Medium	Study consultant

TABLE LXXXVIII. (cont.)

Country/uranium district production centre	Resources (1000 t U)	Confidence in information	Source of data
Cigar Lake	135.8	Excellent	Company publication
Cluff Lake	8.7	Excellent	Company publication, study consultant
Dawn Lake	8.6	Excellent	Company publication
Elliot Lake/Blind River	100.0	Medium	IAEA–TECDOC–500 [19]
Kiggavik/Sisson Schultz	38.5	Medium	Published report
Kitts–Michelin	7.2	Low	Study consultant
McArthur River	184.2	Excellent	Company publication
McClean Lake	34.5	Excellent	Company publication
Rabbit Lake	14.4	Excellent	Company publication
Cameroon			
Kitongo	5.0	Low to medium	IUREP
Central African Republic			
Bakouma	16.0	Medium	Published report
Czech Republic			
Stráž ISL	22.0	High	Study consultant
Rozhna	7.0	High	Study consultant
Finland	3.4	Low to medium	IUREP, study consultant
France			
Coutras	6.0	High	Study consultant
Democratic Republic of the Congo	3.5	Low	Red Book
Gabon	4.3	Medium	Published report
Greenland (Denmark)			
Illimaussaq	11.0	Medium	Study consultant
Hungary			
Mecsek area	15.8	High	Study consultant
Indonesia			
West Kalimantan	6.3	Low	IUREP
Italy	4.8	Medium	Study consultant
Japan			
Tono/Ningyo Toge	6.6	Medium	Red Book
Kazakhstan			
Economic ISL	179.1	High	Published report, study consultant, Red Book
ISL CIS production	128.5	High	Published report, study consultant, Red Book
Kokchetav district	99.0	Medium	Published report, Red Book
Pribalkhash district	10.0	Medium	Published report, Red Book, study consultant
Pricaspian district	15.0	High	Published report, Red Book, study consultant
Mexico			
Las Margaritas	7.6	Low	Study consultant
Mongolia			
Dornod	51.0	Medium	Company publication, study consultant
ISL	22.0	Medium	Company publication, study consultant
Namibia			
Langer Heinrich	11.3	Medium	Study consultant report
Rossing	112.0	Excellent	Company publication
Niger			
Afasto	25.2	Medium to high	Published report — Nuexco market study
Akouta	40.5	High	Published report, study consultant

TABLE LXXXVIII. (cont.)

Country/uranium districts production centre	Resources (1000 t U)	Confidence in information	Source of data
Arlit	22.2	High	Study consultant
Imouraren	100.5	High	Study consultant
Madaouela	5.1	Medium to high	Study consultant
Portugal			
Nisa	1.9	Medium	Company published report — Anaconda Uranium Corp.
Urgeiriça	5.6	Medium	Red Book less Nisa deposit resources
Russian Federation			
Far east	4.0	Medium	Study consultant, Red Book
Onezhsky	2.0	Medium	Study consultant, Red Book
Streltsovsk/Priargunsky	130.7	High	Study consultant, Red Book
Trans-Baikal (incl. Vitim)	6.0	Medium	Study consultant, Red Book
Trans-Ural	10.2	High	Study consultant, Red Book
Slovenia			
Zirovsk	2.2	Low	Study consultant
South Africa			
Nufcor	239.0	Medium	Study consultant
Palabora	4.7	Medium	Study consultant
Spain			
Ciudad Rodrigo area	6.7	Medium	Red Book
Ukraine			
Dnepr-Donets	15.9	Medium	Study consultant, Red Book
Kirovograd	62.6	Medium	Study consultant, Red Book
Krivorzh	2.2	Medium	Study consultant, Red Book
Pobuzhy	15.0	Medium	Study consultant, Red Book
USA			
Alta Mesa	1.6	High	Company published report
Ambrosia Lake	2.2	High	Study consultant
Arizona Strip breccia pipes	25.4	High	Company published reports, study consultant
Big Red	2.3	Excellent	Company published report
Borrego Pass	5.8	Low	Study consultant
Bull Frog	5.0	High	Study consultant
Canon City	2.6	High	Published report
Charlie	1.3	High	Company published report
Christensen Ranch	6.0	High	Study consultant
Church Rock	4.8	High	Company published report
Crow Butte	14.7	Excellent	Company published report
Crown Point	9.7	High	Company published report
Dalton Pass	4.9	Low	Study consultant
Dewey Burdock	2.4	High	Company published report
Gas Hills	28.8	Excellent	Company published report
Grants mineral belt	12.7	Medium	Study consultant
Green Mountain	19.2	High	Company published report, study consultant
Hansen	8.0	High	Study consultant
Highland/Ruby Ranch	7.3	Excellent	Company published report
Kingsville Dome/Vasquez	6.0	High	Company published report
L Bar	3.0	Medium	Study consultant
Marquez	5.8	Medium	Study consultant
McDermitt Caldera	5.5	Low	Study consultant
Moore Ranch	1.8	Low	Study consultant
Mount Taylor	16.2	High	Company published report

TABLE LXXXVIII. (cont.)

Country/uranium districts production centre	Resources (1000 t U)	Confidence in information	Source of data
New Wales	19.7	Medium	Study consultant
North Butte	4.0	Medium to high	Study consultant
Nose Rock	10.0	Low	Study consultant
Red Desert	11.3	High	Company published report
Reno Creek	2.3	Excellent	Company published report
Reynolds Ranch	3.1	Excellent	Company published report
Shootering Canyon	2.6	High	Study consultant
Smith Ranch	21.5	Excellent	Company published report
Sundance	1.4	Low	Study consultant
Swanson	7.3	Medium	Published report, study consultant
Taylor Ranch	3.9	Excellent	Company published report
Uncle Sam/Faustina	18.0	Medium	Study consultant
Uravan	4.7	High	Company published report
West Largo	3.8	High	Company published report
Uzbekistan			
Conventional	17.5	Medium	Published reports
ISL	63.0	High	Study consultant, Red Book
Viet Nam	7.5	Low	IUREP
Zambia	6.0	Medium	Study consultant
Zimbabwe			
Kanyemba	1.8	Medium to high	Study consultant, IUREP, Red Book

[a] Companies involved in uranium exploration, mining and export in Australia fund the Uranium Information Centre.

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GLOSSARY

burnup. Measure of total energy released by a nuclear fuel compared to its mass, typically measured in gigawatt days per tonne.

by- and co-products. Uranium is frequently associated with other minerals in nature, particularly occurring with copper, gold, phosphates and vanadium. Uranium may be recovered as a by- or co-product of the minerals with which it occurs.

conventional resources. Resources that have a history of production where uranium is either a primary product, co-product or an important by-product (e.g. gold and copper).

depleted uranium. Uranium where the ^{235}U isotope concentration is less than 0.711% (by weight), the concentration for naturally occurring uranium. Depleted uranium is a residual product from the enrichment process.

enrichment. Process by which the ^{235}U isotope concentration in uranium is increased from the naturally occurring 0.711%.

enrichment tails. The relatively depleted fissile uranium (^{235}U) remaining from the uranium enrichment process. The natural uranium ‘feed’ that enters the enrichment process generally contains 0.711% by weight ^{235}U. The ‘product stream’ contains enriched uranium (greater than 0.711% ^{235}U) and the ‘waste’ or ‘tails’ contains depleted uranium (less than 0.711% ^{235}U). At an enrichment tails assay of 0.3%, the tails would contain 0.3% ^{235}U. A higher enrichment tails assay requires more uranium feed (thus permitting natural uranium stockpiles to be decreased), while increasing the output of enriched material for the same energy expenditure.

high enriched uranium. Any form of uranium having a ^{235}U concentration of 20% or higher. HEU is used principally for producing nuclear weapons and fuel for reactors to propel submarines and other vessels. Weapons grade HEU contains at least 90% ^{235}U.

in situ leach (ISL) mining. The recovery by chemical leaching of valuable components of an ore body without the physical extraction of the ore above ground. Also sometimes known as solution mining.

known resources. Total of reasonably assured resources and estimated additional resources category I.

low enriched uranium. Any form of uranium having a ^{235}U concentration greater than 0.711% but below 20%. Typical concentrations used in light water reactors range from 3 to 5%.

mixed oxide fuel (MOX). A fuel fabricated from plutonium and depleted or natural uranium oxide which can be used in standard light water reactors. MOX fuel assemblies are typically loaded in light water reactors with uranium fuel assemblies in the ratio of one to two.

natural uranium. Uranium whose natural isotopic composition (approximately 0.711% ^{235}U by weight) has not been altered.

plutonium. A heavy, fissionable, radioactive metallic element with atomic number 94. Plutonium is not naturally occurring, but is produced as a by-product of the fission reaction in a uranium fuelled nuclear reactor and is recovered from irradiated fuel. It is used in preparing commercial nuclear fuel and in manufacturing nuclear weapons.

reprocessed uranium. Uranium extracted from spent fuel which may return to the fuel cycle to be fabricated as new fuel.

reprocessing. The chemical separation of uranium and plutonium from spent fuel. It allows the recycling of valuable fuel material and minimizes the volume of high level waste material.

separative work unit (SWU). The standard measure of enrichment services, measuring the effort expended in increasing the ^{235}U content of uranium above the naturally occurring 0.711%. It typically measures the amount of enrichment capacity required to produce a given amount of enriched uranium from a particular feed material.

unconventional resources. Very low grade resources which are not now economic or from which uranium is only recoverable as a minor by-product (e.g. phosphates, monazite, coal, lignite and black shale).

uranium. A heavy, naturally occurring radioactive element, with atomic number 92.

uranium hexafluoride (UF_6). A white solid obtained by chemical treatment of uranium oxide, which forms a vapour at temperatures above 56°C. UF_6 is the form of uranium required for the enrichment process.

uranium spot market. The buying and selling of uranium for immediate or very near term delivery.

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17–19 November 1999,
20–22 March 2000