XA0201911

IAEA-SM-362/2

Analysis of uranium supply to 2050

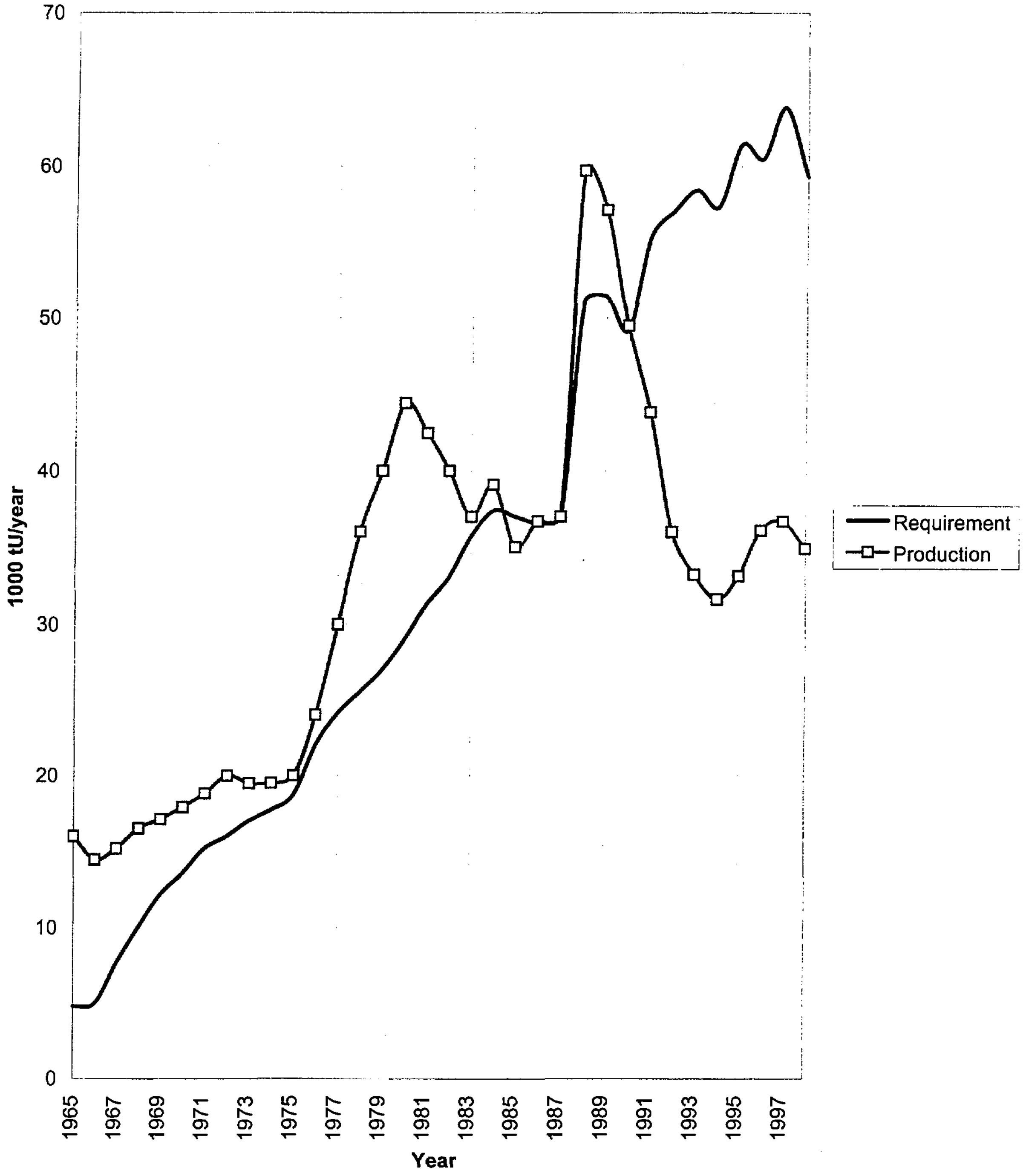
D.H. Underhill
International Atomic Energy Agency (IAEA), Division of Nuclear Fuel Cycle and Waste Technology, Vienna

Abstract. The 1999 uranium mine production was about 55% of the 61 500 tonnes uranium (t U) used by the nuclear industry, with the balance met by secondary supply. Based on a recent WEC-IIASA study which defines a wide range of possible future levels of nuclear electricity generation, it is estimated that by 2050 annual uranium requirements could increase to 177 000 and 283 000 t U respectively, in the mid and high cases, or fall to 52 000 t U in the low case. Cumulative requirements to 2050 for the low, mid and high cases are, respectively 3.39, 5.35 and 7.58 million t U. A new IAEA analysis describes how known uranium resources (RAR and EAR-1) plus undiscovered resources (EAR-II and SR), supplemented by secondary supplies, could be utilized to supply reactors to 2050. Secondary supplies include: existing inventories, blended down warhead material (LEU blended from HEU), MOX, Repu, and re-enrichment of tails. The methodology of this analysis estimates the amounts and annual deliveries of the secondary supply, plus non-market supply. The balance of demand is met from Market Based Production (MBP) or: "Uranium produced at or below market price to satisfy requirements not met by other supply sources". The analysis then evaluates the production role for 125 uranium deposits, which supply MBP considering individual deposit resources, production cost and capability, and timing. Production costs are classified from low (<$33.80/kgU), to very high (>$130/kgU). Annual supply and demand balancing is used to allocate the resources on an individual deposit basis, assuming use of the next lowest available cost production. Secondary supplies will continue to supplement mine production to about 2025, but their relative importance will decrease over the period. An analysis of the benefit of lowering the enrichment tails assay from 0.30% ^{235}U to 0.15% ^{235}U, when economically justified is also discussed. The report also discusses projected production cost trends to 2025 under the mid and high cases. The final conclusion is that significant exploration efforts will be required to discover new large, low-cost deposits, or it may be necessary to rely on resources with a very high production cost (i.e. >$130/kgU). Because of the long lead times for discovery, environmental assessment and project development, exploration will need to be started within the next few years if the discoveries are to have an impact on uranium supply prior to 2050. It will also be necessary to convince the world community that uranium can be produced with acceptable environmental impacts if projects are properly planned, operated and closed.

1. INTRODUCTION

Nuclear power is expected to be an important part of the worldwide energy mix at least through 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 many analysts. The importance that a reliable supply will have on the future of nuclear power led the IAEA to undertake a study of uranium supply-demand relationships through 2050. The ultimate goal of the study is to evaluate the adequacy of supply to meet demand, and to characterize the level of confidence that can be placed in the projected supply. This report describes key conclusions of the study. A detailed report describing the results of the study is available as an IAEA special publication.

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 the projections. Similar uncertainties also characterize the supply side of the equation including availability of secondary supply, impact of environmental opposition to uranium mining and the lack of incentive to explore for and develop new deposits in the face of the depressed market. To accommodate these uncertainties it has been necessary to consider a range of supply and demand projections.



Excludes the following countries because detailed information is not available: Bulgaria, China, Cuba, Czech Republic (and preceding states), GDR, Hungary, Kazakhstan, Mongolia, Romania, Russian Federation, Slovenia, Tajikistan, Ukraine, USSR, Uzbekistan, and Yugoslavia

FIG. 1. Relationship between newly mined uranium and reactor requirements in selected countries.

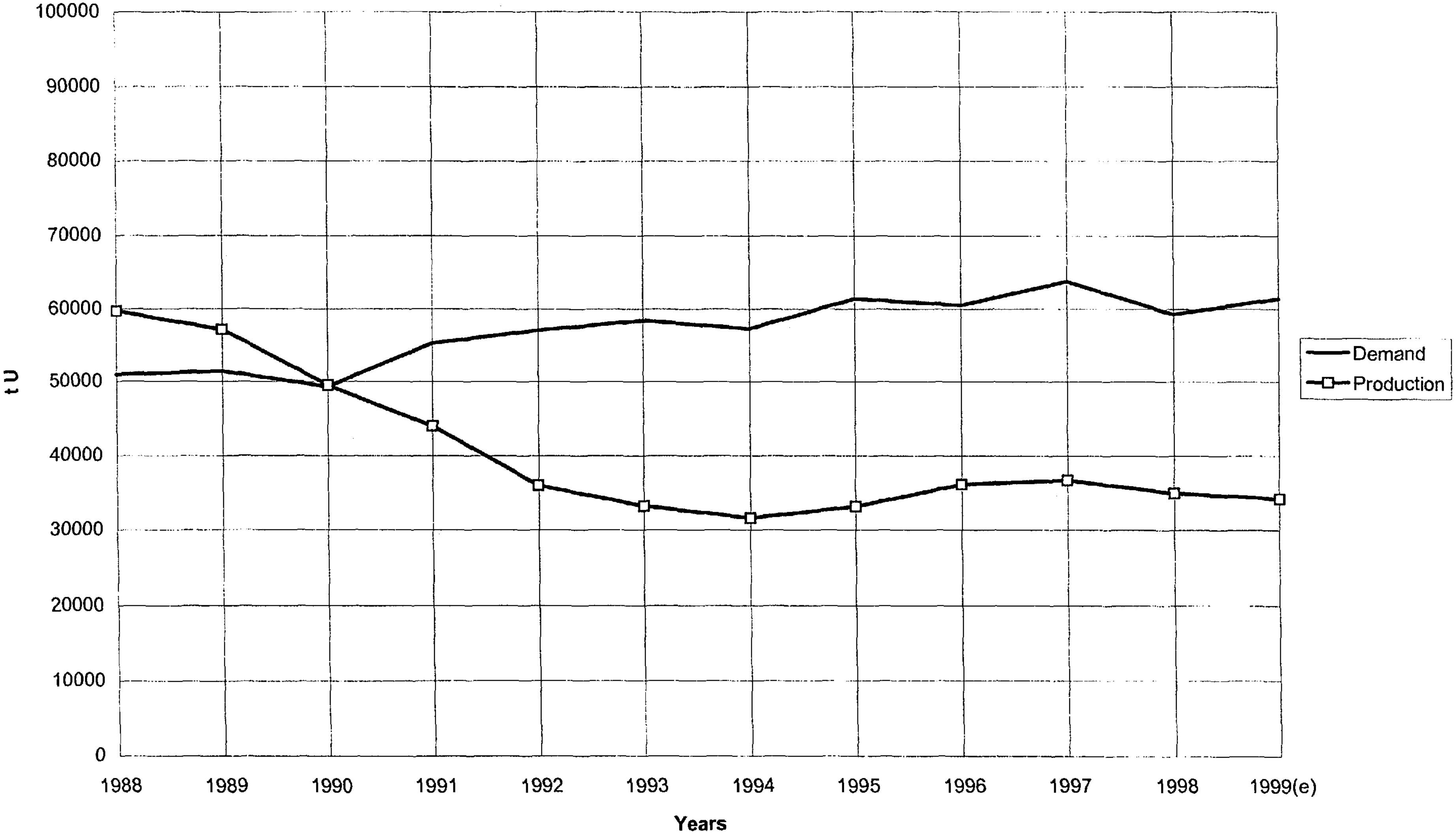


FIG. 2. Relationship between newly mined uranium and worldwide reactor requirements 1988–1998.

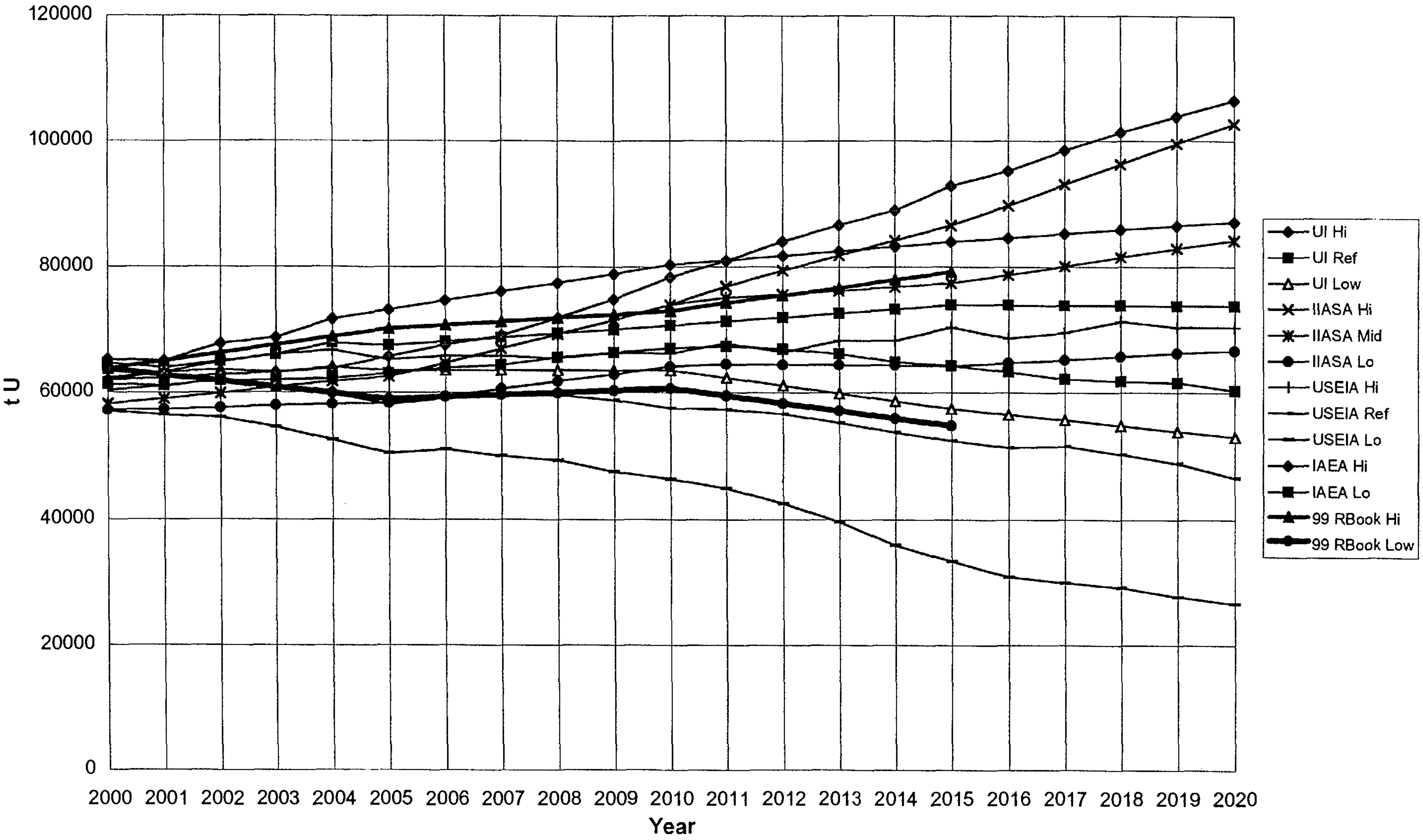
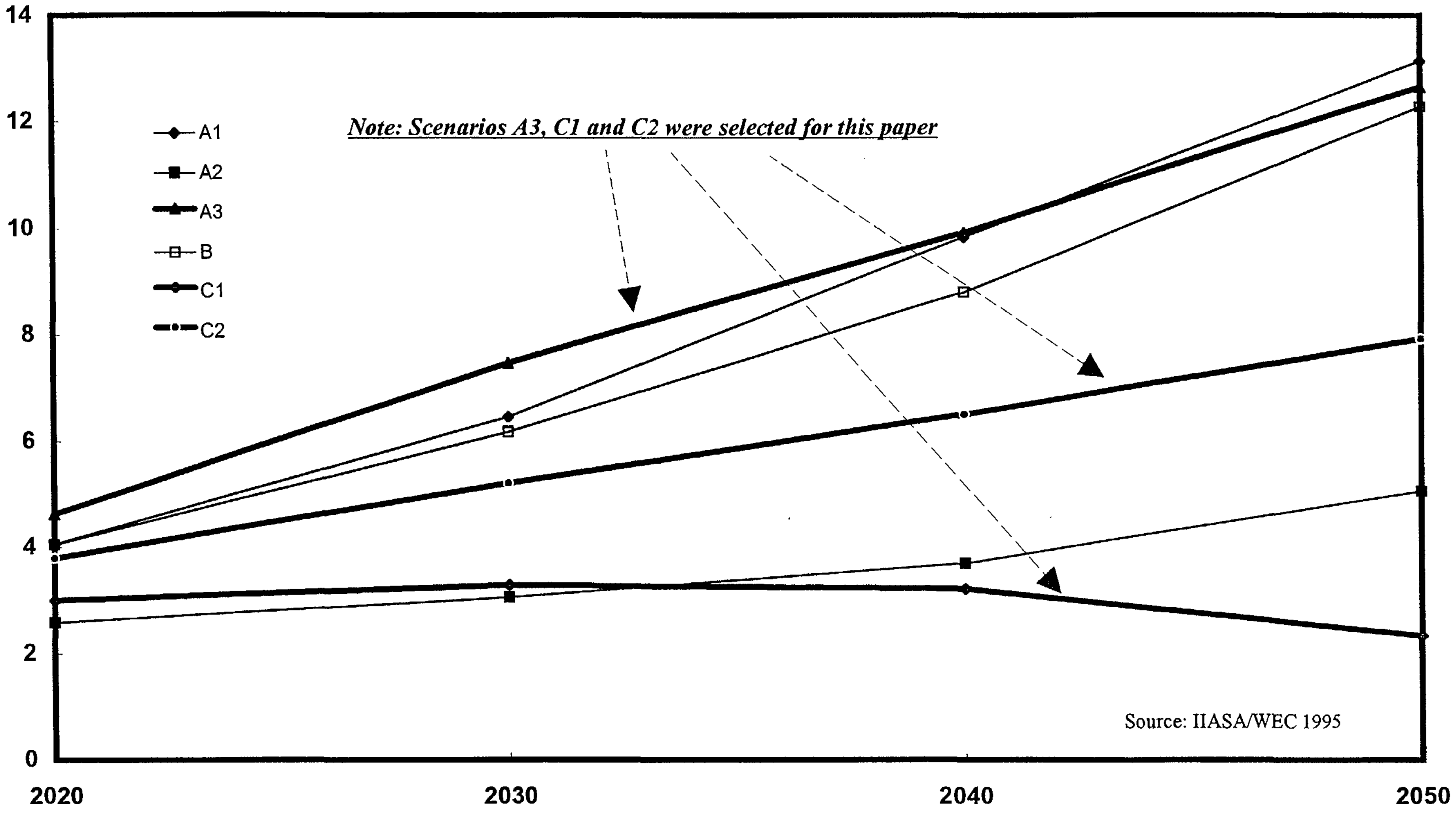


FIG. 3. Previously published projections of annual uranium requirements to 2020.



Note: Scenarios A3, C1 and C2 were selected for this paper

Source: IIASA/WEC 1995

FIG. 4. IIASA/WEC scenarios to 2050 —nuclear generation (10^3 TW(h)).

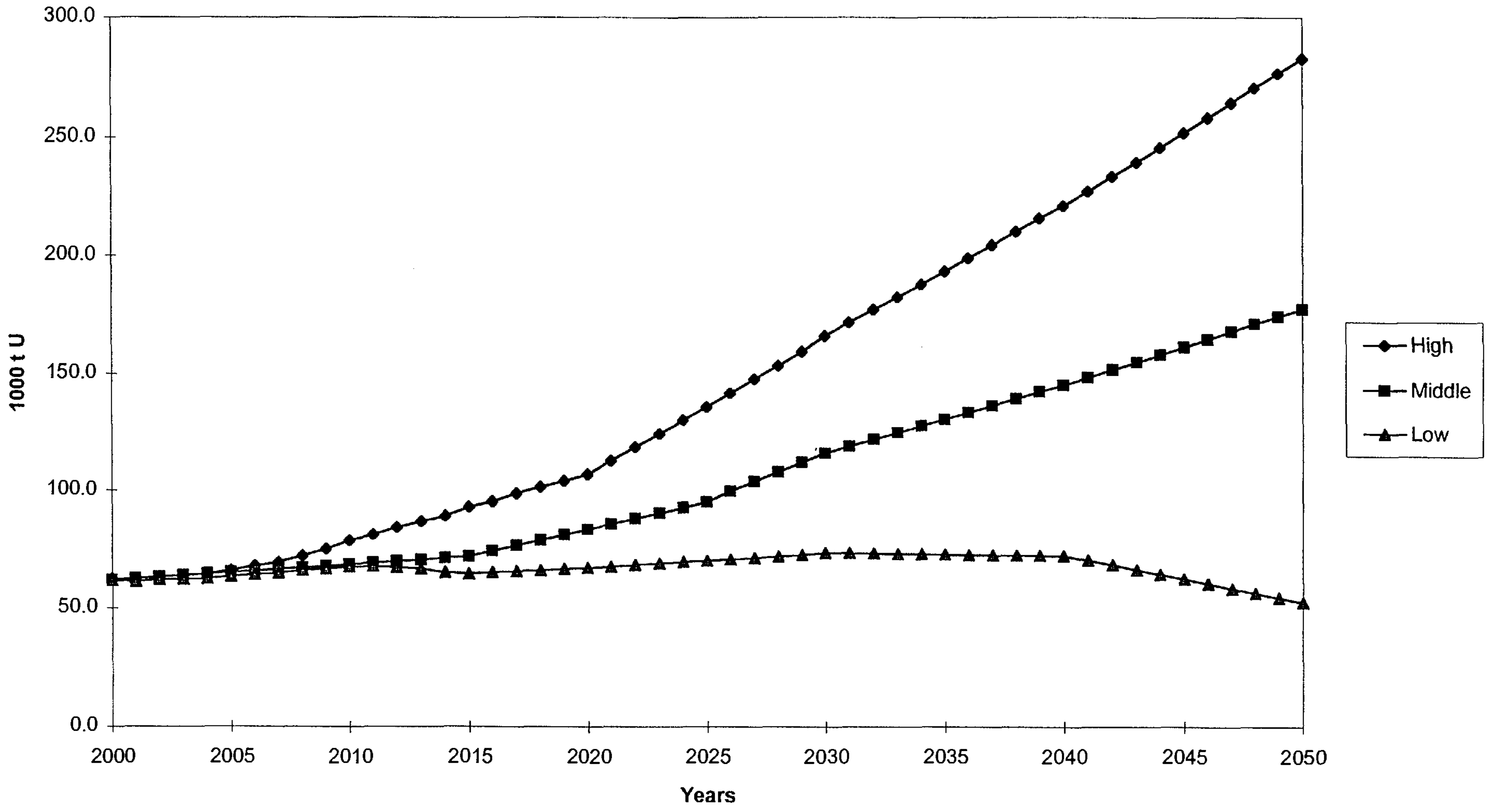


FIG. 5. Projections of annual uranium requirements 2000 to 2050.

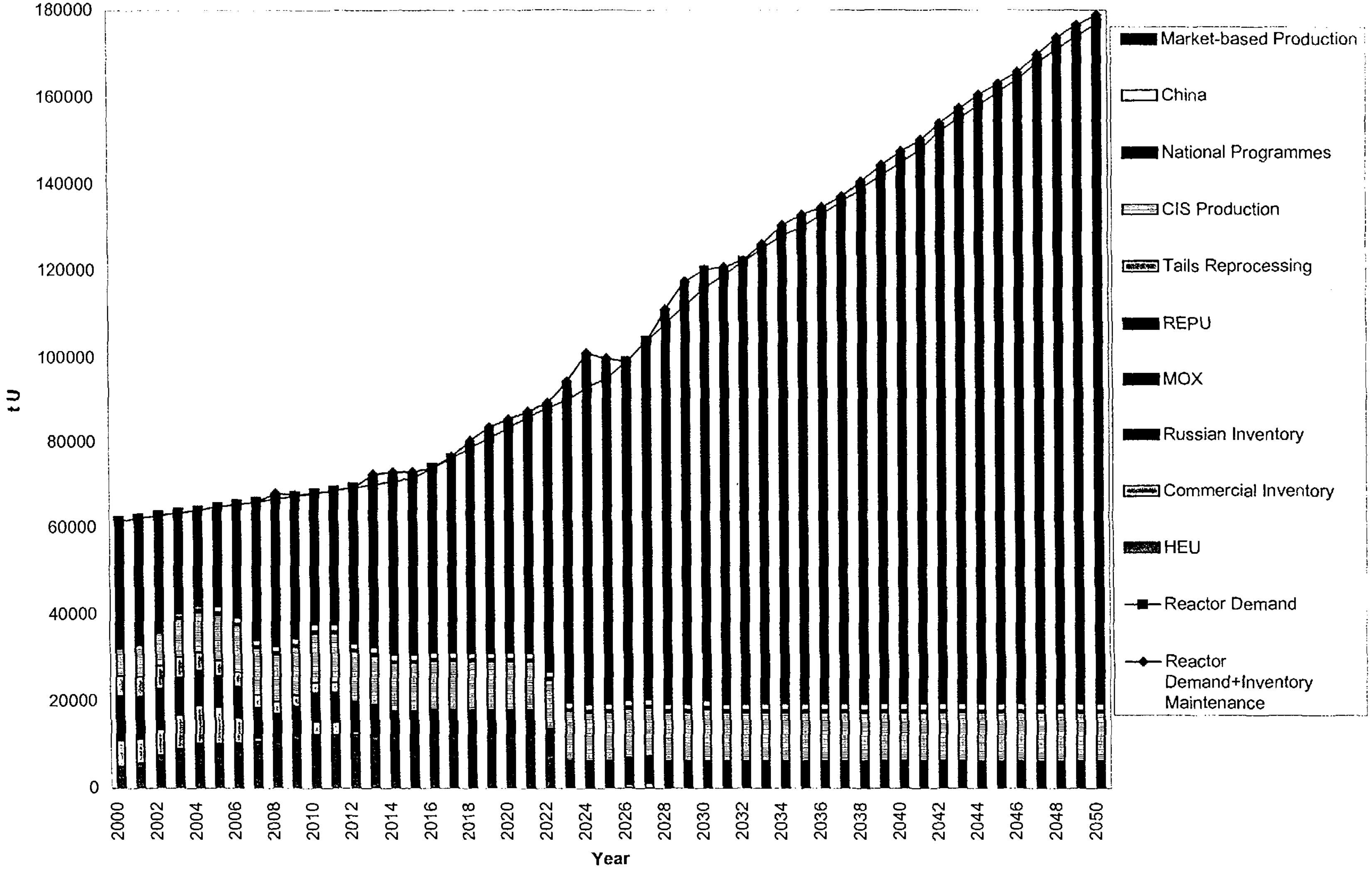


FIG. 6. Uranium supply-demand relationship 2000 through 2050 — middle demand case.

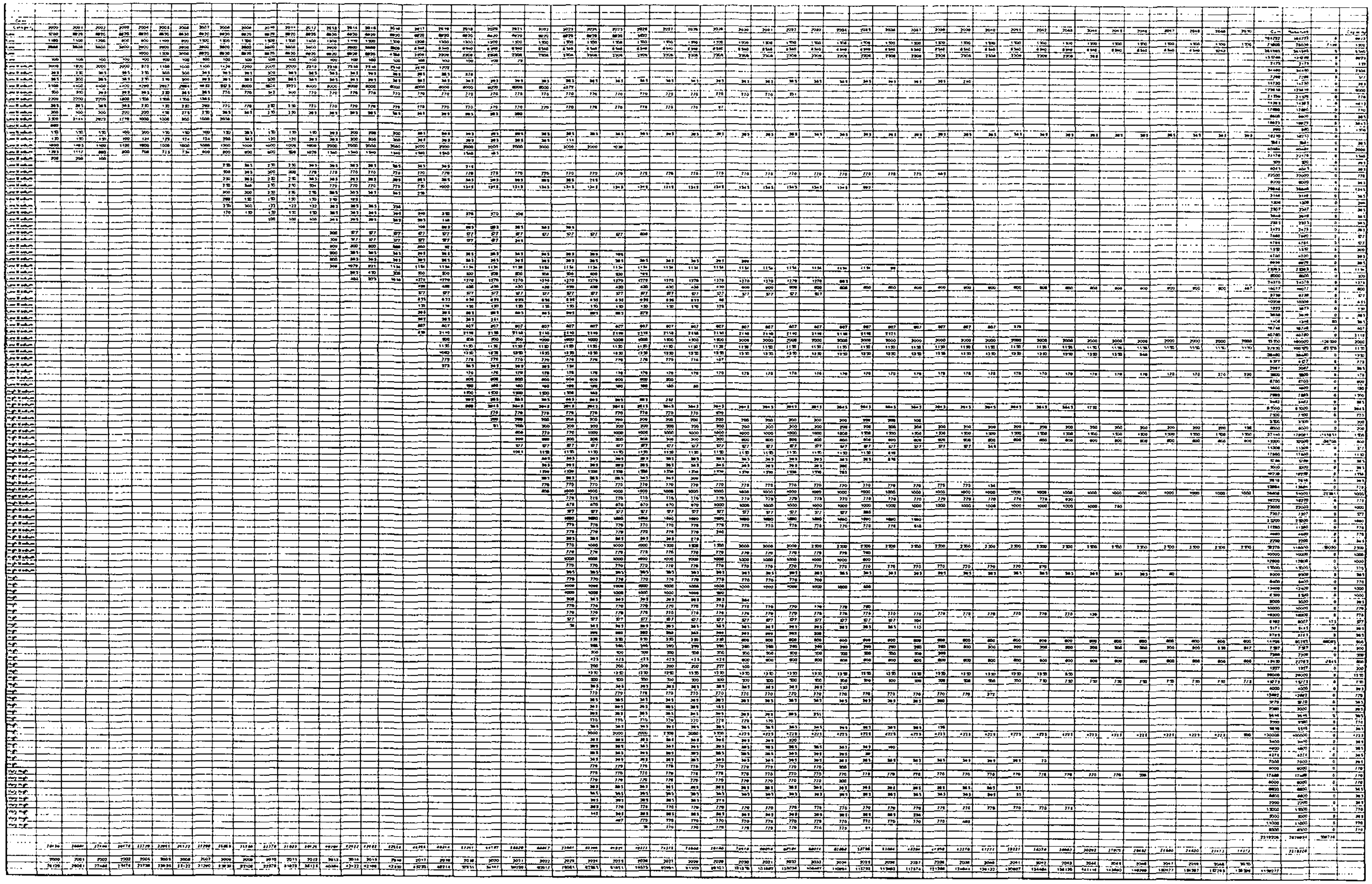


FIG. 7. Practical supply-demand balancing for market-based production — middle case study RAR.

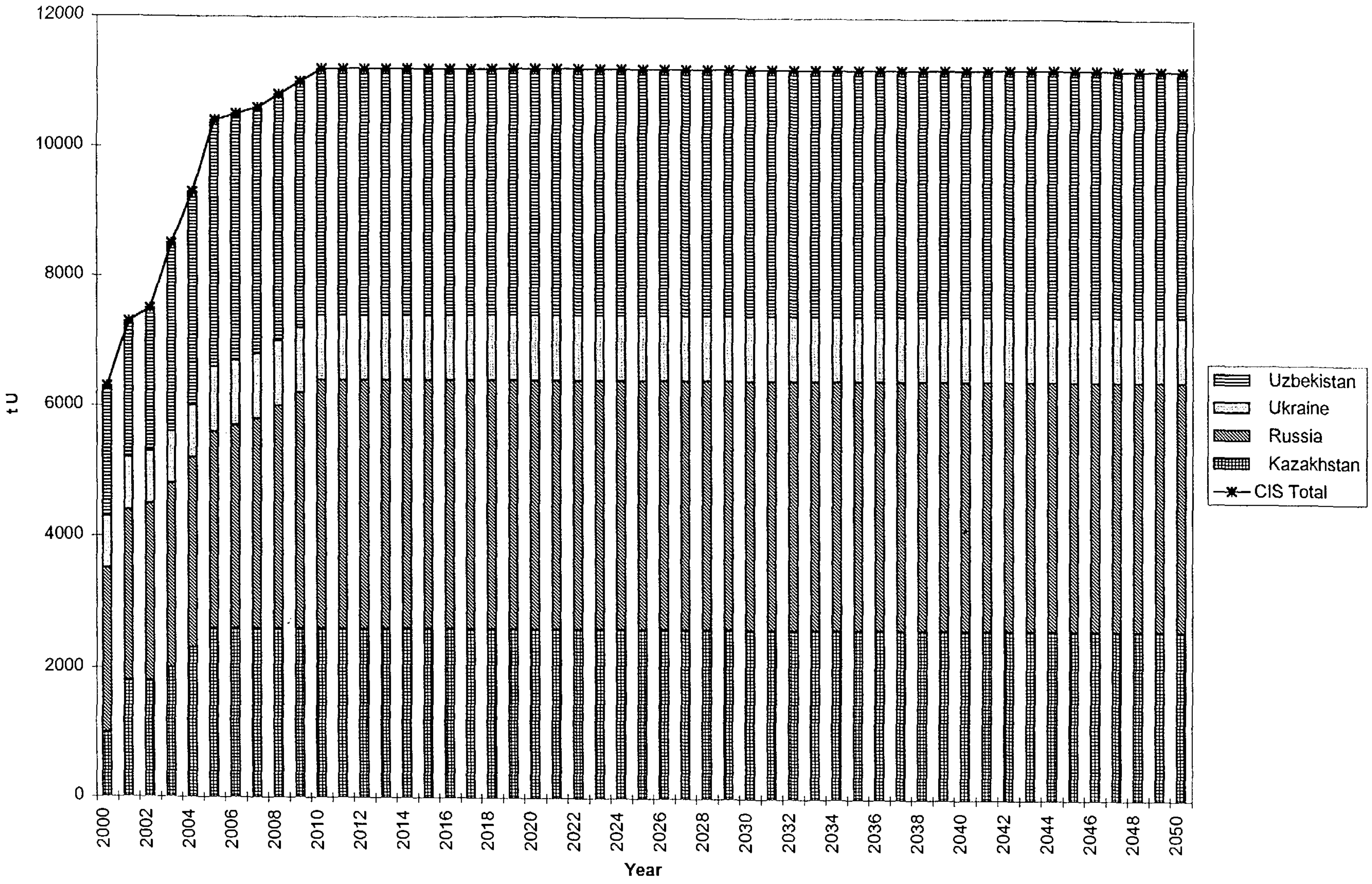


FIG. 8. Projection of annual CIS production to 2050 — conservation scenario.

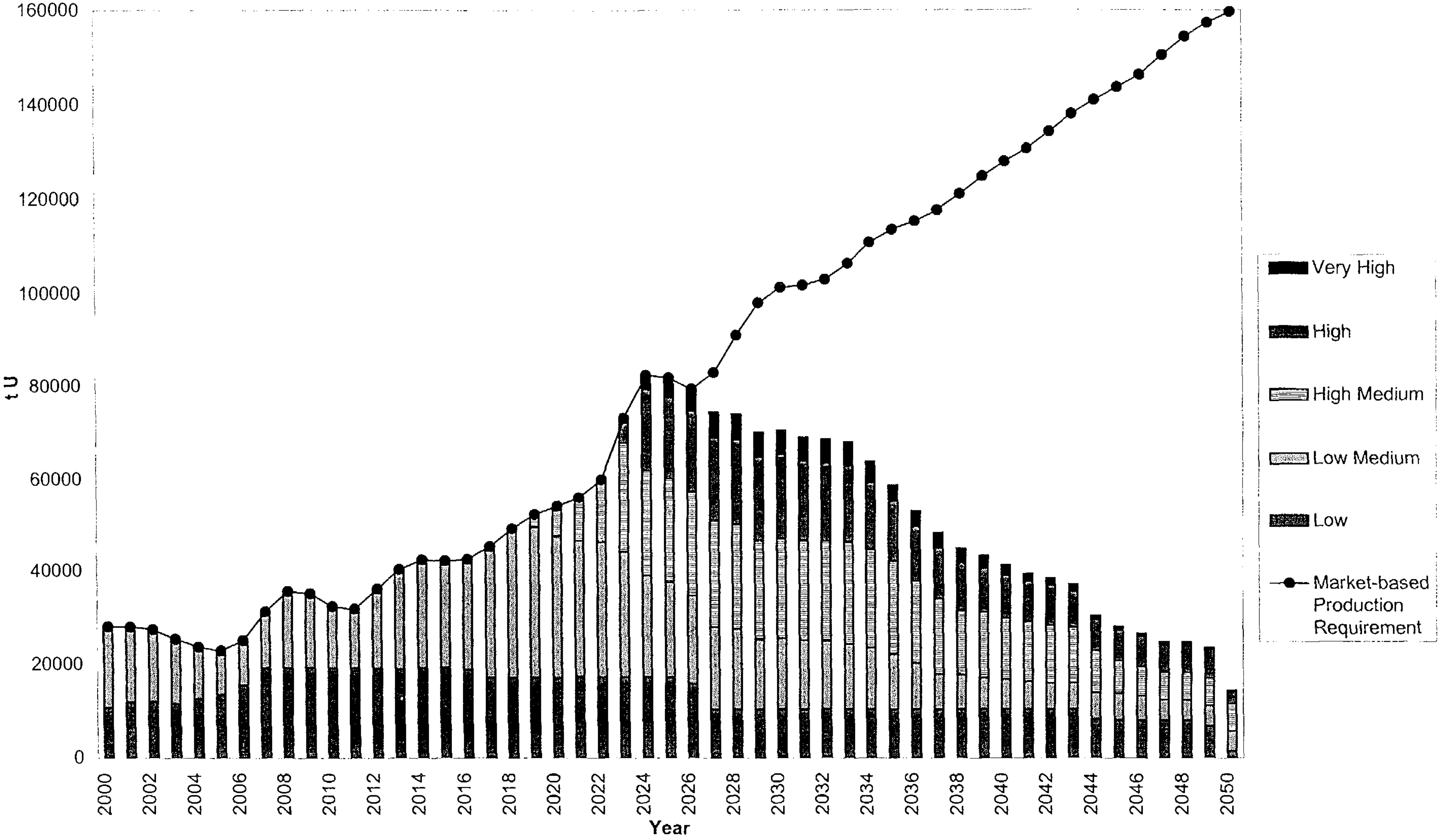


FIG. 9. Projection of market-based production from study RAR by cost category — middle demand case.

To understand the future of the nuclear fuel cycle, one must first understand its past. Fig.1 shows the relationship between Western production and reactor requirements from 1965 through 1998. Fig.2 shows a near-term comparison between production and requirements that also includes the former Soviet Union and the Eastern bloc countries. Early forecasts predicting a dominant role for nuclear power were overly optimistic. Consequently, in each year prior to 1983, Western production exceeded reactor requirements, leading to a significant inventory build up. 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. Draw down 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 clearly become the dominant supply source. Therefore, the objective of this report is to evaluate the adequacy of uranium supply to meet demand through 2050. The following steps were taken in completing the study:

- Establish annual world-wide reactor demand.
- 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.

2. DEMAND

Projecting worldwide reactor uranium requirements (demand) for the next 50 years requires detailed analysis involving a number of uncertainties. 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 burn up 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. The final step in the process is to project how these requirements will be met.

Several sources were used to project demand between 2000 and 2020. As shown in Fig.3, there is a broad range of opinions as to annual uranium requirements through 2020. 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 [1]. This study (hereafter referred to as the IIASA/WEC Study) provides a comprehensive analysis of energy use through 2050, which is used in this report to provide the basis for projection of long-term uranium requirements. Fig.4 presents the projection of nuclear electric generation developing in the IIASA/WEC study. These projections are the same as the "Nuclear variants" in "Key Issue Paper No. 1" presented at the IAEA's "International Symposium on Nuclear Fuel Cycle and Reactor Strategy: Adjusting to New Realities" held on 1-6 June 1997 [2]. Studies by the IAEA [3] and the International Institute for Applied Systems Analysis and the World Energy Council were used to extend demand projections to 2050. Information from these sources was combined to establish three demand projections that cover a broad range of assumptions as to worldwide economic growth and related growth in energy and nuclear power (Fig.5). The cumulative uranium requirements through 2050 for these demand cases and the economic assumptions on which they are based are as follows:

	Cumulative Requirements 2000 to 2050 (t U)	Economic Assumptions
Low demand case	3 390 000	Medium economic growth; phase out of nuclear power by 2100
Middle demand case	5 394 100	Medium economic growth; sustained but modest growth for nuclear power
High demand case	7 577 300	High economic growth; significant development for nuclear power

3 .URANIUM SUPPLY

3.1. Methodology

Uranium supply is broadly divided into two categories – primary and secondary supply. Secondary supply includes HEU, natural and low-enriched uranium inventory, MOX, reprocessed uranium (RepU) and re-enrichment of depleted uranium (tails). Primary supply includes all newly mined and processed uranium. In the middle demand case, in 2000, primary and secondary supply are projected to cover 58% and 42% of demand, respectively. However, by 2025 secondary supply's contribution is projected to drop to only 6% of demand. In the middle demand case, primary and secondary supply are projected to supply 89% and 11% of cumulative demand through 2050, respectively.

Primary supply is divided into two broad categories – that which is not constrained or controlled by market conditions, such as production in the CIS, China and the small national programmes, and production that is market-based. Market-based Production requirements are determined by subtracting the total of secondary supply and primary supply from the CIS, China and the national programmes from annual demand. Fig. 6 shows the role that each of the supply components is projected to play in filling the middle case demand.

Assessing the adequacy of uranium resources to satisfy Market-based Production requirements is the main focus of this report. Resources are categorized by confidence levels using IAEA/NEA terminology, from the highest confidence known conventional, resources (RAR + EAR-I) to lower confidence undiscovered resources (EAR-II and Speculative Resources). Production centres and their associated resources are also ranked by projected production cost within the cost categories shown in Table I.

TABLE I. PRODUCTION COST CATEGORIES

Cost Category	**$/kg U**	**$/lb. U_3O_8**
Low	≤ 34	≤ 13
Low Medium	> 34-52	> 13-20
High Medium	≥ 52-78	≥ 20-30
High Cost	≥ 78-130	≥ 30-50
Very High	> 130	> 50

The order in which individual production centres are projected to begin operations to satisfy Market-based Production requirements is based on a combination of confidence level, production capacity and cost. It has been assumed that the lowest cost producer in the highest resource confidence category operating at capacity will fill the first increment of demand, followed 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. Fig.7 is a spreadsheet that shows how the next higher-cost production centres are added as needed to satisfy annual increases in Market-based Production requirements. *It is important to emphasize that 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.*

3.2. Secondary Supply Assumptions

Projecting the potential contributions from secondary supply sources is a key step in determining Market-based supply requirements. Following are the basic assumptions on which projections of secondary supply are based. Details on these assumptions and other aspects of secondary supply are included in the longer version of this report.

— ***Highly enriched uranium from surplus defence inventories (HEU).*** It is assumed that the current agreements between the governments of the USA and Russia will be expanded to increase availability of low-enriched uranium derived from Russian HEU through 2022. Commercialization of US HEU will extend through 2023. HEU contribution is projected to total 249 500 t U in the base case.

— ***Commercial inventory.*** Inventory held by Western utilities, uranium producers and government agencies is projected to total 168 500 t U equivalent, including strategic and discretionary/excess inventory. Draw down of utility and US government inventories is projected to end in 2006 and 2014, respectively. Uranium producers are assumed to maintain inventory levels equal to two-thirds of the previous years' requirements. Draw down of producer inventory will fluctuate accordingly.

— ***Russian inventory.*** Draw down of Russian natural and low-enriched uranium inventory with fluctuate depending on HEU deliveries. As the contribution of HEU increases, inventory draw down will steadily decrease, and will finally end in 2014, after a cumulative contribution of 47 000 t U.

— ***Mixed oxide fuel (MOX) and reprocessed uranium (RepU).*** MOX use is projected to grow steadily through 2012 after which usage will stabilize at 3600 t U equivalent through 2050. Use of RepU is assumed to grow gradually through 2016 after which it is capped at 2500 t U equivalent through 2050.

— ***Depleted uranium stockpiles (tails).*** Tails re-enrichment is constrained by availability of low-cost SWUs and by safeguards limitations on transferring large quantities of depleted uranium to Russian enrichment plants and leaving the secondary tails in Russia. Therefore, tails re-enrichment is scheduled to end in 2011 after having contributed a cumulative total of 43 000 t U equivalent.

3.3. Non-Market Based Primary Supply Assumptions.

It is assumed throughout this study that the uranium production industry world-wide is gradually adopting market-based economic principles. This assumption has been the main guideline in determining the contributions from the CIS, China and the national programmes.

— ***Commonwealth of Independent States.*** This study considers two categories of production from the CIS. Production from existing facilities, with minor expansion potential, is assigned to the "CIS Production" category. Fig. 8 shows the projected annual contributions from the four CIS producing countries - Kazakhstan, Russia, Ukraine and Uzbekistan - in this category. Resources not directly associated with current facilities are available to satisfy Market-based Production requirements. These resources are assumed to begin operations when they are cost-justified to help satisfy Market-based Production requirements.

— ***China.*** China's production has the potential to expand from the current annual level of 400 t U to 1380 t U by 2005. For purposes of this study, China's output is capped at 1380 t U per year between 2005 and 2050.

— ***National Programmes.*** Countries that currently maintain small programmes dedicated to meeting domestic reactor requirements include Brazil, Czech Republic, France, India, Pakistan, Romania and Spain. The Czech Republic, France and Spain are scheduled to shut down their programmes between 2001 and 2003. It is assumed that the remaining programmes will continue to produce at approximately their current levels through 2050.

3.4. Market-Based Production

3.4.1. Reasonably Assured Resources (RAR) – Middle Demand Case

The adequacy of resources to satisfy Market-based Production requirements has been evaluated for three demand cases at different resource confidence levels. Consultants that contributed to the study were able to attribute 3.276 million t U to 125 deposits about which they have specific information, compared to 3.128 million t U RAR listed in the IAEA/NEA 1999 Red Book [4]. The difference between the two totals is largely attributable to conservative reporting by some countries that did not include deposits with well-documented resources which are not recoverable at current market prices. RAR directly attributable by the consultants to specific resources are termed "Study RAR". More specific information is publicly known about the geology, mining methods and production costs for these resources, and this knowledge is used as the first step in assessing resource adequacy. Fig.9 projects production cost trends as output derived from Study RAR expands to meet growing requirements for Market-based Production. As shown in Fig.9, Study RAR will be adequate to satisfy Market-based Production requirements through 2026, after which lower confidence resources will play an increasingly important role. Fig.9 also indicates that resources in the low and low medium-cost categories will be adequate to satisfy Market-based Production requirements through about 2018. Therefore, market prices could remain at or below $52/kgU through 2018, provided supply and demand relationships are similar to the middle demand case.

Since a great deal of information is known about Study RAR, they are accorded the highest confidence level of all of the resource categories and are projected to be among the first resources to be exploited as demand increases with time. Because of the level of detailed information available on Study RAR, they are very useful in modelling projected changes in the uranium production industry through 2026. Table II shows the role that different mining and extraction methods are projected to play in satisfying Market-based Production requirements throughout the next 25 years. In situ leach (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 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 annual production.

TABLE II. 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%

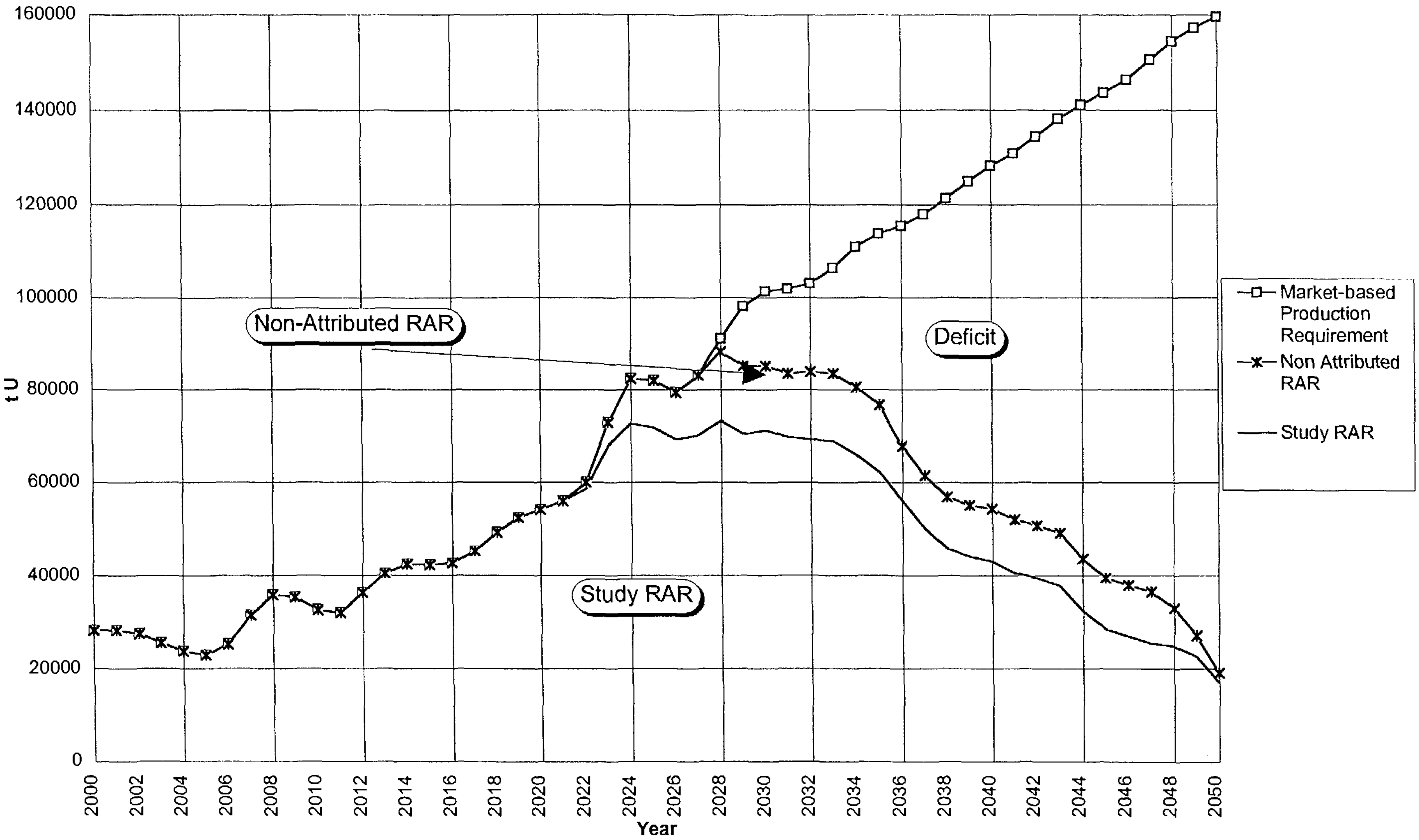


FIG. 10. Total RAR-derived production compared with market-based production requirement — middle demand case.

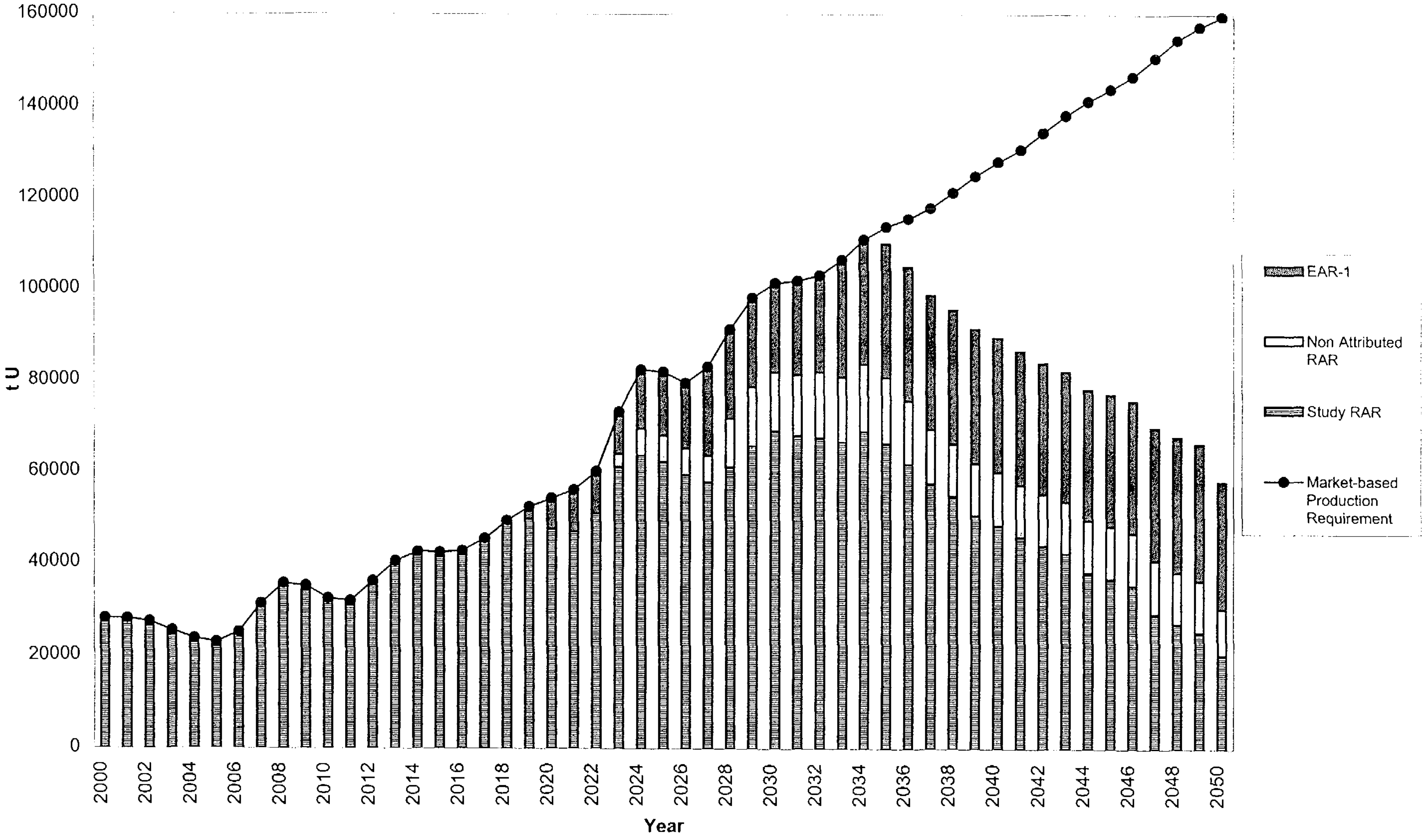


FIG. 11. Resource contribution by confidence level through EAR-1 — middle demand case.

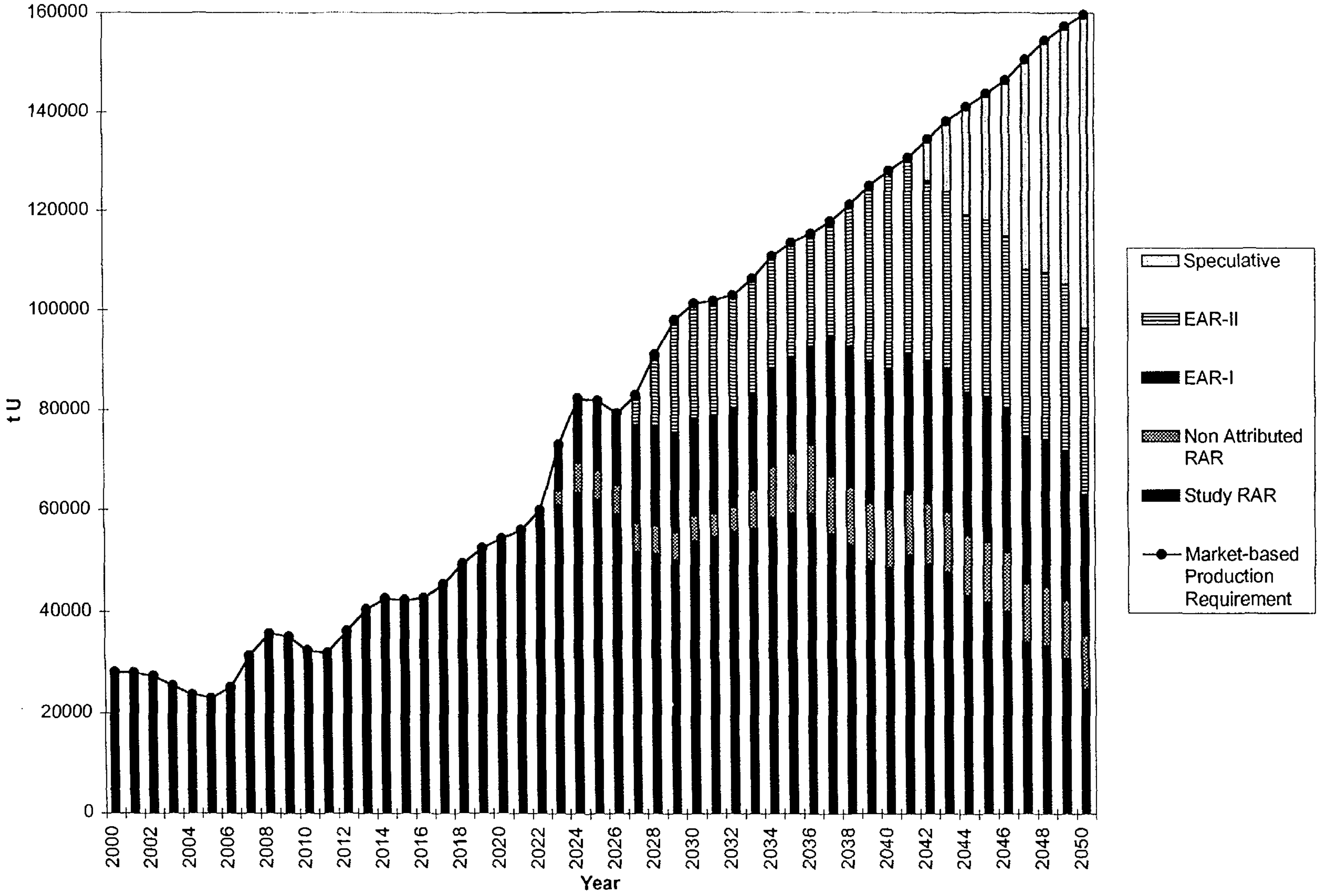


FIG. 12. Resource contribution by confidence level through EAR-II — middle demand case.

Table III is a summary of the changing contribution of different geologic deposit types over time. The unconformity-related deposits in Australia and Canada will clearly dominate production through 2015, with a significant contribution from the Olympic Dam breccia complex. Beyond 2015, other deposit types will have to be developed in greater numbers to satisfy Market-based Production requirements.

TABLE III. 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%
Collapse breccia pipe				2%	2%	2%
Metamorphic						1%
By Product	1%	1%	0.5%	0.5%	1%	0.5%

RAR not directly attributed by the study consultants to known deposits are termed Non-attributed RAR. As shown in Fig.10, adding Non-attributed RAR to the production stream only satisfies Market-based Production requirements through 2027 compared to 2026 when limited to Study RAR.

3.4.2. Estimated additional resources – category I (EAR-I) – middle demand case

EAR-I constitutes 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". Fig.11 shows the relative contributions of Study and Non-attributed RAR and EAR-I (known resources). As shown in Fig.11, with the addition of EAR-I, known resources are adequate to satisfy Market-based Production requirements through 2034, or 7 years longer than the scenario restricted to RAR (Fig.9). Table IV compares the affect of successively adding lower confidence levels of resources to the production stream, starting with Study RAR and progressing through Non-attributed RAR and finally to EAR-1.

TABLE IV. COMPARISON OF THE AFFECT OF ADDING LOWER CONFIDENCE RESOURCES TO THE MARKET-BASED PRODUCTION STREAM – MIDDLE DEMAND CASE

	Study RAR	Total RAR	RAR+EAR-I
Market-based Production requirement (t U)	4 158 280	4 158 280	4 158 280
Cumulative production (t U)	2 319 210	2 617 860	3 313 780
Cumulative deficit*(t U)	1 839 070	1 540 410	844 500
Potential unutilized resources	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	NA	2019

*Deficit between Market-based Production requirements and cumulative production

As noted in Table IV, in the middle demand case, cumulative production derived from known resources is adequate to satisfy 80% of Market-based Production requirements through 2050. EAR-I are not projected to be cost-justified until about 2019 in the middle demand case. Therefore, their introduction into the production stream will not significantly change market price trends compared to the scenario limited to RAR. For example introduction of EAR-I only delays by two years (2021 compared to 2019) the point at which high medium-cost resources ($52 to $78/kgU) will be cost justified. Table IV includes the category "unutilized resources", which addresses the fact that 698 440 t U or 17% of known resources available to meet Market-based Production requirements will not have been utilized by 2050. Unutilized resources are typically associated with high-cost production centres with large resource bases that are cost-justified too late in the study period for their resources to be depleted by 2050 (assuming practical production capacities).

3.4.3. Estimated additional resources – category II (EAR-II) – middle demand case

Production derived from known resources is projected to satisfy only about 80% of Market-based Production requirements in the middle demand case. Therefore, lower confidence undiscovered resources will be needed to fill the gap between known resources and production requirements. *Having to rely on undiscovered resources to fill the projected supply gap substantially increases the uncertainties and risks. This cautionary note should be borne in mind throughout the remaining discussion of utilization of undiscovered resources.*

By definition, EAR-II, though part of the undiscovered resources category, are believed to occur in well-defined geological trends or areas of mineralization with known deposits, so they clearly carry less risk and uncertainty than Speculative Resources. Nevertheless, the true potential of EAR-II must still be proven by exploration and development programmes. Fig.12 shows the projected contribution of RAR through EAR-II between 2000 and 2050, and how the gap between Market-based Production requirements and production narrows with the addition of progressively lower confidence resources. Table V compares changes in production and cost parameters as lower confidence resources are added to the production stream.

TABLE V. COMPARISON OF PRODUCTION AND COST PARAMETERS – RAR THROUGH 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*(t U)	1 540 420	844 500	306 740
Potential unutilized Resources	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	2019	2019
First year EAR-II cost-justified	NA	NA	2027

*Deficit between Market-based Production requirements and cumulative production.

As shown in this comparison and in Fig.11, the addition of EAR-II would cover Market-based Production requirements through 2041 and would reduce the deficit between production and requirements to 306 740 t U, assuming that their potential is confirmed by exploration. Also of significance is the fact that potentially unutilized resources are projected to total nearly 2.4 million t U, or eight times the projected deficit. More efficient use of only a portion of the unutilized resources could entirely eliminate the gap between supply and requirements in the middle demand case.

3.5. Adequacy Of Supply – Low And High Demand Cases

Up to this point we have considered the adequacy of supply in the middle demand case. The widely varying opinions concerning the future of nuclear power dictate that we also examine the adequacy of supply for the low and high demand cases. RAR are projected to be adequate to satisfy Market-based Production requirements in the low demand case, but, quite the opposite is true for the high demand case. Cumulative reactor requirements are projected to increase from 5.4 million t U in the middle demand case to nearly 7.6 million t U in the high case. Market-based Production would be expected to fill most of that increase. Since we are dealing with the same resource base in both demand cases, satisfying the accelerated demand schedule in the high case requires accelerated utilization of resources. Therefore, not surprisingly, the deficits between production and requirements that characterize the middle demand case increase substantially in the high case.

Table VI compares production and cost parameters for known resources in the middle and high demand cases. The deficit between cumulative Market-based Production requirements and production derived from known resources more than triples in the high demand case. Known resources are projected to be adequate to satisfy requirements through 2025 in the high case compared to 3034 in the middle case. And, production centres in the high medium-cost category will be cost-justified in 2015 in the high demand case compared to 2021 in the middle case, potentially advancing the projected increase in the uranium market price by six years.

TABLE VI. COMPARISON OF RESOURCE UTILIZATION PARAMETERS - MIDDLE AND HIGH DEMAND CASES, BASED ON PRODUCTION DERIVED FROM KNOWN RESOURCES

	Middle Demand Case	High Demand Case
Market-based Production requirement (t U)	4 158 280	6 406 190
First year of deficit compared with Market-based Production requirement	2035	2026
Cumulative production (t U)	3 313 780	3 455 840
Cumulative deficit*(t U)	844 500	2 950 350
Potential unutilized resources	698 440	556 710
First year high medium cost required	2021	2015
First year high cost required	2027	2022
First year EAR-I cost-justified	2019	2013

*Deficit between Market-based Production requirements and cumulative production

Fig.12 shows the contribution to annual production from different confidence level resources through EAR-II for the high demand case. With the addition of EAR-II to the production stream, there are actually sufficient resources available to nearly satisfy Market-based production requirements. However, about 1.9 million t U of the resources will not be utilized because they will not be cost-justified early enough to be fully depleted by 2050. Unutilized resources account for the gap between annual production and production requirements shown on Fig.12. With the inclusion of EAR-II, potentially unutilized resources are nearly equal to the deficit between cumulative production and Market-based Production requirements. In other words, resources are adequate to satisfy requirements *if* production capacity could be increased to fully utilize the resources.

3.6. Speculative And Unconventional Resources

As noted in Figs 11 and 12, in both the middle and high demand cases, even with the addition of lower confidence EAR-II, there remains a gap between production and Market-based Production requirements. *However, it is important to emphasize that the gap does not result from a true shortage of supply potential.* Instead, it results mainly from unutilized resources, which in turn are attributable to the fact that there are relatively few large, low-cost deposits in the resource base that have not already been developed. Instead, the resource base is dominated by relatively small deposits with limited production capacity or by large, but high-cost deposits that are cost-justified too late in the study period to receive maximum benefit from their resources.

In addition to EAR-II, as noted in Table VII, contributors to the Red Book also report 8.67 million t U of Speculative Resources (SR) that are based on indirect evidence and geological extrapolation. Like EAR-II, however, SR are conceptual, undiscovered resources that will require extensive exploration that results in discoveries before they can be moved to higher confidence categories.

TABLE VII. LEADING COUNTRIES IN REPORTED SPECULATIVE RESOURCES

	<\$130/kgU (1000 t U)	Total (1000 t U)
Canada	700	700
China	*	1770
Kazakhstan	500	500
Mongolia	1390	1390
Russia	544	1000
South Africa	*	1113
United States	858	2198
Total	3992	8671

* Not reported.

If exploration does not bear out the potential of the SR, unconventional resources offer a substantial, albeit very high-cost, supplement to undiscovered resources. Table VIII summarizes estimates of unconventional resources and the deposit types with which they are associated.

TABLE VIII. UNCONVENTIONAL RESOURCES – MINERAL INVENTORY

Deposit Type	Estimated Resources (1000 t U)
Phosphorite Deposits	9000
Black Shale Deposits	4000 – 5000
Lignite and Coal Deposits	70
Total	13 400 - 14 000

The message from Tables VII and VIII is that there is no shortage of potential uranium resources. The magnitude of projected SR listed in Table VII indicates that 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 sustainable 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. In addition, though they are high (or very high) cost and have potential environmental problems, the unconventional resources represent an enormous potential supply of uranium.

4. EXPLORATION REQUIREMENTS

In the middle demand case, we have established that known resources are adequate to satisfy 96% of Market-based Production requirements, and it is unutilized resources and not a true shortage of resources that accounts for the gap between production and requirements. The same is true in the high demand case if EAR-II are added to the resource base. As previously noted, unutilized resources are mainly attributable to high-cost deposits with large resource bases that are not cost-justified early enough for their resources to be depleted by 2050. Production capacities could potentially be expanded for some of these projects, but expansion potential is limited and it is not the answer to the unutilized resources problem. Instead, the real challenge for the future will be to find large, relatively low-cost deposits that can be brought into production by at least 2025, so that their resources will be fully utilized within the remaining 25 years of the study period.

Historical discovery costs through 1998 in Australia and Canada, two areas with long-standing exploration programmes, ranged from $0.50 to $1.60/ kgU. Discovery costs between 1989 and 1999 increased to between $3.90 and $6.90/kgU, as exploration was forced to target deeper and/or more subtle prospects. All it would take would be the discovery of another deposit similar to McArthur River or Jabiluka to substantially reduce the recent costs, but the message is clear - the easy discoveries have been made. While it is not practical to broadly apply historical discovery costs to future exploration programmes, we can project a range of expenditures needed to meet future resource requirements. For example, 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 IX shows order of magnitude exploration expenditures at a range of discovery costs that could be required to ensure discovery of sufficient resources to offset the projected high demand case deficit.

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

Discovery Cost ($/kg U)	Required Exploration Expenditure (billion $)
0.50	1.20
1.00	2.39
2.00	4.78
3.00	7.18
4.00	9.57

To meet the challenge of overcoming resource deficits, exploration expenditures will have to begin to increase significantly within the next five years to ensure that discoveries are made early enough to accommodate the long lead time between discovery and production. Otherwise, there is the probability that the resources will not be fully utilized by 2050. 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 was developed that could detect conductive zones at depth. Exploration drilling focused on one such conductive zone encountered encouraging, but sub-economic mineralization, in 1985. 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.

Future discoveries can be expected to experience lead times comparable to those experienced by McArthur River. 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 IX cannot be evenly spread throughout the 50-year study period. Instead, they need to come early enough that the resulting discoveries can contribute to production requirements in a timely manner.

5. RISK AND UNCERTAINTY

Up to this point, a resource base has been projected at each confidence level, and the adequacy of those resources to meet Market-based Production requirements has been assessed. There is, however, no absolute certainty that all of the resources will be available, and there is equal uncertainty as to the availability of secondary supply. Therefore, sensitivity studies have been completed that evaluate the impact of increases or decreases in the various supply components.

5.1. HEU

The HEU base case includes 250 t Russian HEU that are not included in the current Russian-US Agreement. This additional material extends by 10 years the availability of uranium derived from Russian HEU. There is every reason to believe that the two superpowers will extend the current agreement, and there is the potential that even more HEU could become available for commercialization with further bilateral reductions in nuclear weapons. However, there is also the possibility that HEU availability will be limited to the current Agreement which ends in 2013.

Therefore, in addition to the base case, high and low HEU scenarios are considered in order to evaluate the impact of limiting or increasing HEU availability. The low case conforms to the existing Agreement and ends HEU availability in 2013, while the high case extends availability through 2040 compared to 2023 for the base case. Table X shows the impact that changes in HEU availability will have in the middle demand case assuming that production is limited to known resources.

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

	Base Case HEU	Low HEU Case	High HEU Case
First year of deficit compared with Market-based Production requirement	2035	2034	2036
Market-based Production requirement	4 158 280	4 256 210	4 048 230
Cumulative production (t U)	3 313 780	3 340 370	3 246 230
Cumulative deficit* (t U)	844 500	915 840	801 990
Potential unutilized Resources	698 440	672 870	764 410
First year high medium cost required	2021	2019	2021

*Deficit between Market-based Production requirements and cumulative production

As noted in Table X, varying HEU availability has limited impact on the middle demand case. Adequacy of known resources to satisfy requirements only changes by one year on either side of the base case. The deficit between production and requirements varies by only 2 to 3% from the base case. Increasing HEU availability will not change the cost/price projection, while limiting it to the current Agreement will only advance by two years the need for high medium-cost projects to begin filling requirements.

5.2. MOX, REPU and re-enrichment of depleted uranium

Technical and political considerations could limit availability of secondary supply from MOX, RepU and re-enrichment of depleted uranium (tails). Anti-plutonium sentiment could end MOX use as early as 2005. The current trend towards higher burnup could decrease availability of economically attractive spent fuel by 2010, which is the basis for the low RepU case. Uncertainty as to availability of US tails for re-enrichment could reduce the overall contribution from tails re-enrichment by nearly half. Therefore, in addition to the base case, low case projections were made for each of these supply sources, the combined results of which are summarized in Table XI.

TABLE XI. COMPARISON OF PRODUCTION AND COST PARAMETERS – COMBINED BASE CASE AND LOW CASES FOR MOX, REPU AND TAILS: ASSUMES PRODUCTION BASED ON 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	4 158 280	4 432 550
Cumulative production (t U)	3 313 780	3 364 400
Cumulative deficit* (t U)	844 500	1 068 150
First year high medium cost required	2021	2019

*Deficit between production and requirements

The combined low cases result in a potential cumulative reduction in supply from MOX, RepU and tails of 270 200 t U compared to the total of their base cases. Even so, the potential reductions have limited impact on supply-demand relationships. For example, though the deficit between Market-based Production requirements and cumulative production from known resources increases by about 25% in the low case, cost-justified high medium-cost projects will be needed only two years earlier. Accordingly, the impact on market price trends of going to the low case will be minimal.

5.3. Impact of environmental and political opposition

Opposition to uranium mining from environmental or political groups presents a potentially serious obstacle to resource development and utilization. It is estimated that environmental and/or political opposition could result in deferral or even abandonment of up to 10% of RAR. As we look ahead 50 years, there is no way to forecast potential changes in public or governmental attitudes toward uranium mining. As shown in Table XII, we can, however, evaluate the impact on supply-demand relationships if projects that currently have the *potential* for environmental or political opposition are removed from the resource base.

TABLE XII. COMPARISON OF PRODUCTION AND COST PARAMETERS WITH AND WITHOUT RESOURCES SUBJECT TO ENVIRONMENTAL AND POLITICAL OPPOSITION: ASSUMES PRODUCTION BASED ON KNOWN RESOURCES, MIDDLE DEMAND CASE

	With Projects Subject to Opposition	Without Projects Subject to Opposition
Market-based Production requirement	4 158 280	4 158 280
Available resources	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*(t U)	844 500	1 177 120
First year high medium cost required	2021	2019

*Deficit between Market-based Production requirement and cumulative production

As shown in Table XII without the resources subject to environmental or political opposition, known resources are only adequate to cover Market-based Production requirements until 2029 compared to 2035 if these 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, however, relatively minor. The potential impact of environmental or political opposition on the overall resource base is included as a cautionary note. It is, however, not intended to prejudge whether such opposition will have any permanent impact on the resource base.

However, it must be concluded that uranium production may only be successfully conducted when the community is convinced that environmental impacts are reduced to acceptable level with properly planned, developed, operated and closed project.

6. PRODUCTION COSTS AND MARKET PRICE IMPLICATIONS

For each combination of supply and demand, we have noted the dates when high medium-cost production ($52-$78/kgU) is projected to be required to satisfy Market-based Production requirements. As the role of secondary supply is reduced, uranium market price trends will more and more begin to parallel production cost trends; prices will have to increase to support increasing production costs. Table XIII summarizes the years in which market prices are projected to increase to the next higher cost category to cover production costs for the middle and high demand cases assuming varying resource bases.

As noted in Table XIII, in the middle demand case, with production derived from known resources, high medium-cost projects will first be needed to fill requirements in 2021. It follows, therefore, that the spot market price will have to increase to >$52/kgU in 2021 to support the need for projects with higher production costs.

TABLE XIII. PROJECTIONS OF WHEN PROJECTS IN 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

7. ENVIRONMENTAL IMPLICATIONS OF THE USE OF NUCLEAR POWER

The debate surrounding the future of nuclear power is not likely to be resolved in the very near future. 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 XIV 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.

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

	Reactor Demand (1000 t U)	Carbon Dioxide Saved (billion tonnes)
Low Demand Case	3390	135
Middle Demand Case	5394	216
High Demand Case	7577	303

8. CONCLUSIONS

In 2000, primary and secondary supply are projected to satisfy 58% and 42% of reactor uranium requirements, respectively in the middle demand case. By 2025, primary supply sources are expected to cover 94% of requirements, and the role of Market-based Production is projected to grow from satisfying 45% of requirements in 2000 to 86% in 2025. Known resources are adequate to cover about 96% of Market-based Production requirements in the middle demand case. However, because of resource distribution and production capacity limitations, not all resources will have been depleted by 2050, leaving a cumulative deficit between production and requirements of nearly 850 000 t U. This deficit expands 3.5-fold in the high demand case. Even with the addition of undiscovered EAR-II, there will still be a deficit between production and Market-based Production requirements of about 307 000 t U in the middle demand case.

The challenge for the uranium production industry will be to discover large, relatively low-cost deposits to fill the projected deficits. Plentiful secondary supply has depressed uranium market prices, which in turn has diminished incentive to undertake the exploration programmes needed to offset these deficits. Estimates of EAR-II + Speculative Resources are more than adequate to offset the projected deficits. In addition, unconventional resources such as uranium-bearing phosphorite and coal and lignite deposits offer a very high-cost supplement to undiscovered conventional resources.

Therefore, there is not a true shortage of potential resources. However, these undiscovered resources must be converted to discoveries, which must then be developed in a timely matter to ensure that their resources can be fully utilized to offset the projected deficits. Lead times between the beginning of exploration and production can range between 15 and 20 years. Therefore, the market price must increase sufficiently for producers to be willing to take the financial risks associated with exploring for and developing new uranium resources. The increase in market price should make it possible for industry to discover new low cost resources. It will also then be necessary for industry to continue to demonstrate that it can produce uranium in an environmentally acceptable manner.

ACKNOWLEDGEMENTS

This paper is based on the report "ANALYSIS OF URANIUM SUPPLY TO 2050" to be published by the International Atomic Energy Agency. The report was prepared for the IAEA by A.Boitsov (Russian Federation), G.Capus (France), F.Dahlkamp (Germany), S.Kidd (Uranium Institute), H.Miyada (Japan), W.Symanski (USA), J.McMurray (USA), I.Vera (OECD/Nuclear Energy Agency), and D.Underhill (IAEA). The IAEA wishes to express its appreciation to all those who were involved in the drafting and review and is particularly grateful to J.McMurray for his major contribution.

REFERENCES

[1] NAKICENOVIC, N., GRÜBER, A., and MCDONALD, A., Global Energy Perspectives, International Institute for Applied Systems Analysis and World Energy Council, Cambridge University Press (1998).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Key Issue Paper No.1: Global Energy Outlook, Symposium on Nuclear Fuel Cycle and Reactor Strategies; Adjusting to New Realities, Vienna, Austria (1997).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, "Energy, electricity and nuclear power estimates for the period up to 2020", Reference Data Series No. 1, April 1999 Edition, Vienna.

[4] OECD/NUCLEAR ATOMIC ENERGY AGENCY - INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 1999 - Resources, Production and Demand, OECD, Paris (2000).