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A Preliminary Assessment of Raw Material Inputs that Would be Required for Rapid Growth in Nuclear Generating Capacity

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The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

FOREWORD

The objective of this study, carried out under the auspices of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC), is to provide policy makers with an overview of raw material requirements for rapid growth in nuclear generating capacity. Rapid growth rates in nuclear generating capacity are considered essential over the long term in order to meet rising energy demand while limiting greenhouse gas emissions in the power generation sector. The study outline from the NDC specified that requirements arising from a very large ten-time expansion of nuclear generating capacity be examined.

This study was carried out by a Ad Hoc Group of Experts (Appendix A) who collected and analysed data and information available on current raw material requirements for the full nuclear fuel cycle and compared requirements arising from a hypothetical ten-time expansion of nuclear generating capacity with current rates of production and resource inventories of the required raw materials.

The conservative approach used in this study, which compares *future* raw material requirements for a significantly expanded fleet of nuclear reactors to *current* rates of production and resource inventories, does not consider geographical limitations to the flow of raw materials. That is, global resources are assumed to be available for use in any region. Any restriction to the flow of these materials, particularly those identified as materials of concern, could hinder the expansion of nuclear energy on the scale considered in this report. Nor does the report consider the impact of raw material demand arising from the growth of other electricity generating technologies. Such competition, although potentially significant, was considered beyond the scope of this study.

A major caveat associated with the conclusions of this report is the lack of direct input on raw material requirements from manufacturers of Gen III and Gen III+ reactors, the designs that will be used during at least the initial phase of the hypothetical build-up of nuclear generating capacity considered in this report. In addition, material requirements for advanced Gen IV reactors are not yet well known. The expert group also notes that new advanced designs, and in particular the nuclear fuel for these designs, could employ raw materials not considered in this report, some of which may be limited in availability.

As this report was being finalised, a tragic 9.0-magnitude earthquake and resulting tsunami struck Japan on 11 March 2011. Although it is too early to say how the resulting accident at the Fukushima Daiichi nuclear complex will affect global nuclear energy development, it is clear that public confidence in nuclear energy has been diminished. This in turn means issues related to public acceptance of the siting of fuel cycle facilities raised in this report will become even more challenging, at least in the short term.

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EXECUTIVE SUMMARY

The objective of this study, carried out under the auspices of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC), is to provide policy makers with an overview of raw material requirements for rapid growth in nuclear generating capacity. The study was carried out by an Ad Hoc Group of Experts who collected and analysed data and information available on raw material requirements for the full nuclear fuel cycle. These data were compared to current production rates and resource inventories as well as future requirements arising from the significant expansion of nuclear generating capacity.

The study assesses raw material requirements arising from a hypothetical ten-time expansion of nuclear technology which, in theory could take place in the latter half of the 21st century, according to global nuclear energy growth projections reviewed in this study and a simulation produced as part of this study. Owing to the limitations of available data on raw material requirements for new and advanced designs (Gen III, Gen III+ and Gen IV), a comprehensive inventory of material requirements was developed using Environmental Product Declaration reports based on Gen II reactor designs built in the 1970s. From this base and limited indirect published information, the expert group subjectively assessed the impact of material requirements for these new and emerging designs.

The study's conclusions highlight the general availability of the majority of raw material requirements to meet this hypothetical ten-time expansion of nuclear generating capacity, with one notable exception, uranium. As a result, the challenges associated with increasing the resource base and producing sufficient uranium from both conventional and unconventional resources to fuel a rapid expansion of global nuclear generating capacity on this scale are discussed in some detail. In consideration of these findings and sustainable development goals, it is concluded that a move to greater use of reprocessing and recycling of nuclear fuel, possibly combined with use of thorium as fuel, would be required to provide sufficient fuel for the lifetime of the hypothetical expanded fleet of nuclear reactors considered in this study. The final stages of development of the expanded fleet considered in this report would therefore likely need to focus on the construction of fast reactors in order to make the most efficient use of the available uranium resources.

With the exception of uranium, none of the raw materials identified in this report required for a ten-time expansion of nuclear generating capacity would consume more than 2% of the existing resource base. However, six other raw materials were identified as items of concern (bentonite, fluorite/fluospar, indium, manganese, zircon sand and gadolinium) because requirements for a ten-time expansion of the current nuclear fleet would consume a >4% share of current production capability. However, given that the development time for such a large fleet of reactors would span some seven decades, it is expected that production capability of most of these raw materials could be increased sufficiently to meet requirements of the expanded fleet, since the currently defined resource base for each one of these raw materials is considered sufficiently robust. Increased demand would likely increase prices, in turn stimulating additional exploration and production. Moreover, there is the possibility in some cases of substituting other materials and increasing recycling should requirements not be met.

Beyond raw material supplies, access to large volumes of water required for the operation of nuclear generating stations could be a limiting factor to rapid expansion in some areas, particularly if heat waves become more common, as currently expected with global warming. Careful planning and siting of new nuclear power plants with respect to water supply, combined with the use of closed-loop cooling systems, should ease the majority of these concerns in the near-term. Development of advanced reactors cooled by helium, sodium, lead or other means could alleviate this concern in the longer term. And although land requirements for the normal operation of nuclear power are small compared to other generating technologies, public resistance to siting such facilities could pose an issue in the development of the large nuclear fleet and support facilities considered in this report.

The report assumes that no barriers to the trade of raw materials exist. That is, requirements in one region can be met by resources from any other region. In order to meet projected raw material requirements arising from such a significant expansion of nuclear energy, governments are encouraged to continue to support or, as required, develop policies that discourage restrictions on the free international flow of natural resources. In many cases, natural resources of interest exist some distance from the region in which they would be required. Any restriction on the flow of these materials of interest, particularly those identified as materials of concern, could hinder the large expansion of nuclear energy considered in this report. Recent concerns over the near monopoly production of rare earths in China and restrictions on the export of these raw materials are an example of the type of restriction that could be detrimental to rapid global growth in nuclear generating capacity.

As mentioned, direct input from manufacturers of Gen III and GEN III+ nuclear reactors, the types that will be built during at least the initial phase of the build-up of nuclear generating capacity considered in this report, is not available due to commercial confidentiality concerns. In addition, requirements for advanced Gen IV reactors under development are not well known. Hence, conclusions derived concerning raw material requirements for these advanced technologies are based on subjective, indirect comparisons with well documented Gen II raw material requirements only. The expert group specifically notes that new types of nuclear fuel could employ raw materials not considered in this report, some of which may be limited in availability. On the other hand, several of the Gen IV designs under development could be capable of producing more nuclear fuel than they consume and would also be able to produce hydrogen for use as an energy carrier should its use, for example in transportation, become more common. Non-conventional applications such as water purification and desalination, district and process heat generation and hydrogen production in current and developing designs are noteworthy. Nuclear power plants do not just consume raw materials; they can also be used to produce process and district heat, potable water and hydrogen.

While analyses of resources and production in this study are based principally on data from 2007, the conclusions are considered to generally apply today, even though resource totals have evolved.

INTRODUCTION

Nuclear energy is one of a suite of low-carbon energy technologies. It is a proven technology with over 400 reactors in operation world-wide. Given the widely recognised need to reduce greenhouse gas emissions in order to minimise the impacts of climate change, and the recognition that electricity generation is currently a significant source of such emissions, many governments and utilities are considering either adding nuclear generating capacity to existing fleets or building reactors for the first time.

This combined with the view that electricity generation capacity will inevitably need to increase in the coming years, in particular to meet the needs of developing countries, raises the question of potential raw material limits to growth in nuclear generating capacity. Are there sufficient raw materials available to support growth in nuclear generating capacity? Are there any raw material constraints to developing this technology? If so, do they represent physical limits to the growth of nuclear generating capacity? It is these types of questions that led the NDC to investigate the question of raw material limits to the development of nuclear generating capacity. In order to capture all possible expansions, a conservative approach was adopted whereby a ten-time expansion of existing nuclear generating capacity was specifically addressed. This expansion is well beyond nuclear capacity requirements called for in order to reduce the impact of human induced climate change in current scenarios.

Documenting raw material requirements, not just for the operation of a nuclear reactor but for the entire fuel cycle, is a challenging task. Nuclear power plants (NPPs) are large and complex facilities. Providing fuel for the reactors is a multi-step and typically a multi-national process. Decommissioning nuclear fuel cycle facilities and the reactors themselves is a lengthy and complex process. Disposal of spent nuclear fuel has not yet been accomplished, but in several countries plans for deep geological disposal have been formulated and progress toward establishing repositories is ongoing. This final stage of the fuel cycle will also require raw material inputs.

Raw material requirements for the existing fleet of nuclear reactors have been well documented in Environmental Product Declarations, as outlined below. From this starting point, estimates of fuel cycle raw material requirements for a greatly expanded fleet of Gen II reactors can be developed. However, owing to commercial confidentiality concerns and associated restrictions on data, assessing the impacts of new technologies on raw material requirements documented for older technologies is more challenging. As a result, raw material requirements for advanced technologies were addressed on a subjective basis only.

ENVIRONMENTAL PRODUCT DECLARATION

Objective of Environmental Product Declarations

The environmental footprint, energy inputs and atmospheric emissions of a product have become an issue of increasing concern to consumers and producers alike. In the early 1990s, a few companies began to systematically compile information to address these issues, not just in the manufacture and use of their products, but through the entire spectrum of materials used in the manufacture, use and ultimately the disposal of a specific product. In order to provide this information in as open, detailed and methodical a fashion as possible, Life Cycle Inventories (LCIs) and later Life Cycle Assessments (LCAs), were developed to document in a comprehensive way all aspects of the complete life cycle of a given product.

As outside interest in these types of studies grew and expertise matured, pioneer practitioners of LCI and LCA came to realise the benefits gained by standardising and harmonising the work in order to compare similar products and to communicate results. This led to the development of a system for Environmental Product Declaration based on LCA in accordance with ISO 14025, known as the EPD® system today. It is managed by the International EPD Consortium. The standard requires common rules, known as Product Category Rules (PCRs), for different product categories. The Swedish power sector was involved in the early development of PCRs with European stakeholders that established functional units, system boundaries, calculation and cut-off rules, data quality standards and instructions for the structure and content of resulting declaration. In order to register an EPD it has to be verified by an independent party according to the standard.

EPDs are becoming more broadly recognised as a standardised and open means for companies to monitor and explain their environmental performance in a comprehensible, standardised fashion. The requirement for independent verification builds trust and enhances EPD credibility. Similar programs have also been initiated in other countries, including Denmark, Norway, Japan and South Korea.

Because of the cradle-to grave approach employed, EPDs provide companies with the means to enable product stewardship throughout the entire product chain (Kyläkorpi *et al.*, 2007). Demonstrating the environmental footprint and communicating the environmental performance of products in a credible and understandable way clearly meets a variety of producer, consumer and market needs. Moreover, because EPDs must comply with standardised methodological requirements, direct comparisons between EPDs produced by different companies engaged in the production of similar goods are possible. EPDs registered in different programs may not be comparable.

Because development of an EPD requires collecting and archiving large amounts of data, a modular approach has been adopted as a useful and flexible means of systematically collecting and storing data. Modular data storage also facilitates adding information and updating LCA-based information as an individual company's supply chain evolves, allowing informed, periodic assessments of the company's performance as well as the performance of companies supplying materials throughout the production life cycle chain. Established calculation rules ensure that similar procedures are used in the creation of EPDs for a wide range of products, goods and services.

Having now progressed beyond its developmental roots in Sweden, the formalised, international EPD® system[1] is based on a hierarchical approach following recognised standards ISO (International Organization for Standardization) 9001 (*Quality management systems*), ISO 14001 (*Environmental management systems*), ISO 14040 (*LCA - Principles and procedures*), ISO 14044 (*LCA - Requirements and guidelines*), ISO 14025 (*Type III environmental declarations*) and ISO 21930 (*Environmental declaration of building products*). As detailed in ISO 14025, EPD®s are designed to provide quantified environmental data using predetermined parameters and, where relevant, additional environmental information to allow objective comparisons of the environmental performance of goods and services having the same principal function. EPD®s are constructed in a neutral fashion and, as a result do not contain value-based judgements. By using standardised methods and rule-based procedures, it is possible to tally relevant environmental information throughout the supply chain of a given product as well as quantitatively documenting and displaying environmental improvements in the products and services achieved over time.

The International EPD® system requires that raw data on resource (raw material) consumption documented in the life cycle inventory work will be reported under the headings of Non-renewable and Renewable sources, each with subheadings of Material Resources, Energy Resources (used for energy conversion purposes) and Water Use. Standardised approaches require that all parameters for resource consumption are reported separately and expressed in grams (or multiples), with the exception of renewable energy resources used for the generation of electricity using hydro, wind and solar energy, which are to be expressed in mega joules (MJ). Water use is expressed in litres.

In addition, processes/activities that altogether do not contribute more than 1% of the total environmental impact for any impact category may also be omitted from the inventory analysis. In cases where process or plant specific data is not available, information from similar, generic sources may be used as a substitute, provided that the sum of the contribution to all parts of the life cycle to the separate impact categories from the use of generic data, instead of plant-specific data, does not exceed 10% of the total contribution to the impact categories. Moreover, similar products and services can also be included in the same declaration provided that the range of variation within each impact category does not exceed +/- 5%. EPD® rules also specify that no allocations can be made for recycling the products. One can however inform the readership about recycling separately.

To ensure that standards are maintained, external reviews (examination and approval) to verify that the data and declarations are in conformance with requirements are carried out by an independent party accepted by the body managing the EPD® program or an accredited certification body. External reviews are also carried out after a predetermined period of time (revision periods) to check the validity of the information. Those conducting an EPD® are required to have documented routines for checking and following-up on the validity of the information in the declaration and are required to inform the certification body if incorrect information or new information leading to major deviations from what is included in the declaration is discovered.

Nuclear Power Plant EPD®s

Electricity production has been an early subject of both LCA and EPD® because it is used in the manufacture of virtually all products. Information regarding resource (raw material) use in the production of electricity is therefore a fundamental, basic building block for LCAs and EPD®s of other products. In essence, EPD® practitioners require verified and standardised life cycle data input from electricity production in order to conduct EPD®s of other products. Because EPD®s facilitate

[1] EPD® is a registered trademark by the Swedish Environmental Management Council.

comparisons between different power sources, they foster in electricity producers an incentive to continually reduce both the use of resources and the impact of operations on the environment.

Vattenfall AB, a power generating company with roots in Sweden, produces and provides electricity and heat to customers in Sweden, Denmark, Germany, Finland, Poland and the United Kingdom. The company generates electricity principally through the use of fossil fuel, hydropower and nuclear energy (with a growing share of wind and biofuel). From early on, Vattenfall has been at the forefront of the development of LCI, LCA and EPD® studies. This long-term allocation of resources demonstrates the company's belief that these tools and procedures display its commitment to sustainable development. Vattenfall has conducted extensive work on LCA on all of the electricity generating technologies it employs, as well as on the transmission of the electricity that it provides to its customers. The LCAs lay the groundwork for the EPD®s developed for Vatenfall's hydro, nuclear wind and coal generating facilities. In total, Vattenfall has six EPD®s that are being maintained and updated continuously (Setterwall and Rydgren, 2004).

The EPD®s on Vattenfall's nuclear facilities were the first of a kind to be published. Although following the prescribed EPD method, electricity generated by NPPs is recognised as being distinct from other generation systems, owing to the fact that both the nuclear fuel cycle and the technology are complex, fuel is produced and refined at various locations, radioactive substances are formed during the process and the general public is concerned about accidents, long-lived radioactive waste, and the proliferation of nuclear weapons (Vattenfall AB, 2004). EPD®s of electricity generating facilities include information on land use, radiology and environmental risks, as specified in PCRs. All of Vattenfall's EPD®s on electricity generation have been verified by accredited, independent third party certification bodies.

British Energy (BE) is the United Kingdom's largest producer of electricity. It owns and operates eight nuclear power stations and a coal-fired plant. BE's nuclear fleet is comprised of seven advanced gas-cooled reactors (AGCRs) and one pressurised water reactor (PWR). BE also developed an EPD® for electricity produced at its Torness AGCR nuclear power station (British Energy, 2005). However, because the AGCR technology is being phased-out and is unlikely to be a part of future growth in nuclear generating capacity, it is not used in this study. Moreover, the Torness EPD® has not been certified by a third party.

Nordostschweizerische Kraftwerke AG (NOK) is the leading electricity producer in Switzerland and has been supplying electricity for more than 90 years. In late 2008, the NOK produced a certified EPD® of electricity produced at the Beznau nuclear power plant (Nordostschweizerische Kraftwerke AG, 2008). Because the release of this EPD® came late in the development of this study, the data from the Beznau EPD® is not used in a detailed way. The results do however provide some useful comparative information since the reactors are of similar vintage and design but the fuel procurement strategy employed is quite different from the strategy employed by Vattenfall, an aspect that is addressed in Section 4 of this report.

Vattenfall EPD® Method and System Boundaries

As mentioned, EPD®s present quantified raw material consumption and environmental information on the full lifecycle of a product. Data used in the initial stages of this study were taken from Vattenfall's published EPD®®s on nuclear electricity and underlying documents and calculations performed according to the rules of the EPD® system administered by the International EPD® Consortium (IEC, www.environdec.com). Vattenfall's EPD®s can also be downloaded from this site.

The EPD® system and its application are described in General Programme Instructions. The hierarchic structure of the fundamental documents used in the preparation of an EPD® for electricity within the EPD® system is:

- Product Category Rules, PCR CPC17 (Product Category Rules (PCR) for preparing an Environmental Product Declaration (EPD®) for Electricity, Steam, and Hot and Cold Water Generation and Distribution)
- General Programme Instructions for environmental product declaration, EPD®.
- ISO 14025 on Type III environmental declarations
- ISO 14040 and ISO 14044 on Life Cycle Assessments (LCA)

The life cycle assessment documents resource (raw material) use and emissions from all processes contributing to the generation of electricity at Vattenfall's Ringhals nuclear power plant in the operating year 2006 (Vattenfall AB, 2007), including all aspects of the nuclear fuel cycle and the method proposed to dispose of spent nuclear fuel in Sweden. The Ringhals power plant consists of one boiling-water reactor (BWR; Ringhals 1) and three pressurised-water reactors (PWRs). All four reactors are light-water Gen II designs that were commissioned between 1975 and 1983. The Ringhals power plant had a total installed capacity of about 3 550 MW at the time of the assessment.

The declared product of the EPD® is 1 kWh of electricity (the functional unit) generated and distributed to the customer during the reference year 2006. Since the technical service life of the Ringhals NPPs is 50 years, resource use, emissions and waste are allocated over this service life period. The resulting EPD® "ecoprofile" quantifies all resources (raw materials) used throughout the life cycle of the facility and fuel cycle, expressed in grams per kilowatt hour (g/kWh) of electricity delivered to the customer. Input from this Vattenfall EPD formed the core of the database developed for this project.

Material resources included in the project database represent an inventory of all raw materials required for the manufacture of building materials and materials used in the operation of facilities in the nuclear fuel cycle, the construction, operation and decommissioning of the nuclear power plant itself and the construction and operation of the deep geological repository, following the specifications of the proposed Swedish repository for spent nuclear fuel (Figure 1). Also included are natural resources for energy ware used in the manufacturing process of materials used in fuel fabrication, electricity generation, waste management and transportation. Required quantities of lead in ore, copper in ore, bauxite, iron in ore, limestone, wood, lignite, crude oil, coal and natural gas used in the construction, operation and planned decommissioning of the nuclear power plant are included, as well as resources required for the production of chemicals used in these processes (Vattenfall AB, 2007). However, materials used in the construction and decommissioning of facilities in the production of nuclear fuel (i.e. mines, mills, conversion, enrichment and fuel production facilities) are not included in the EPD® (Figure 2).

Figure 1. Steps in the nuclear fuel cycle for the Ringhals NPP included in the 2007 Vattenfall EPD®

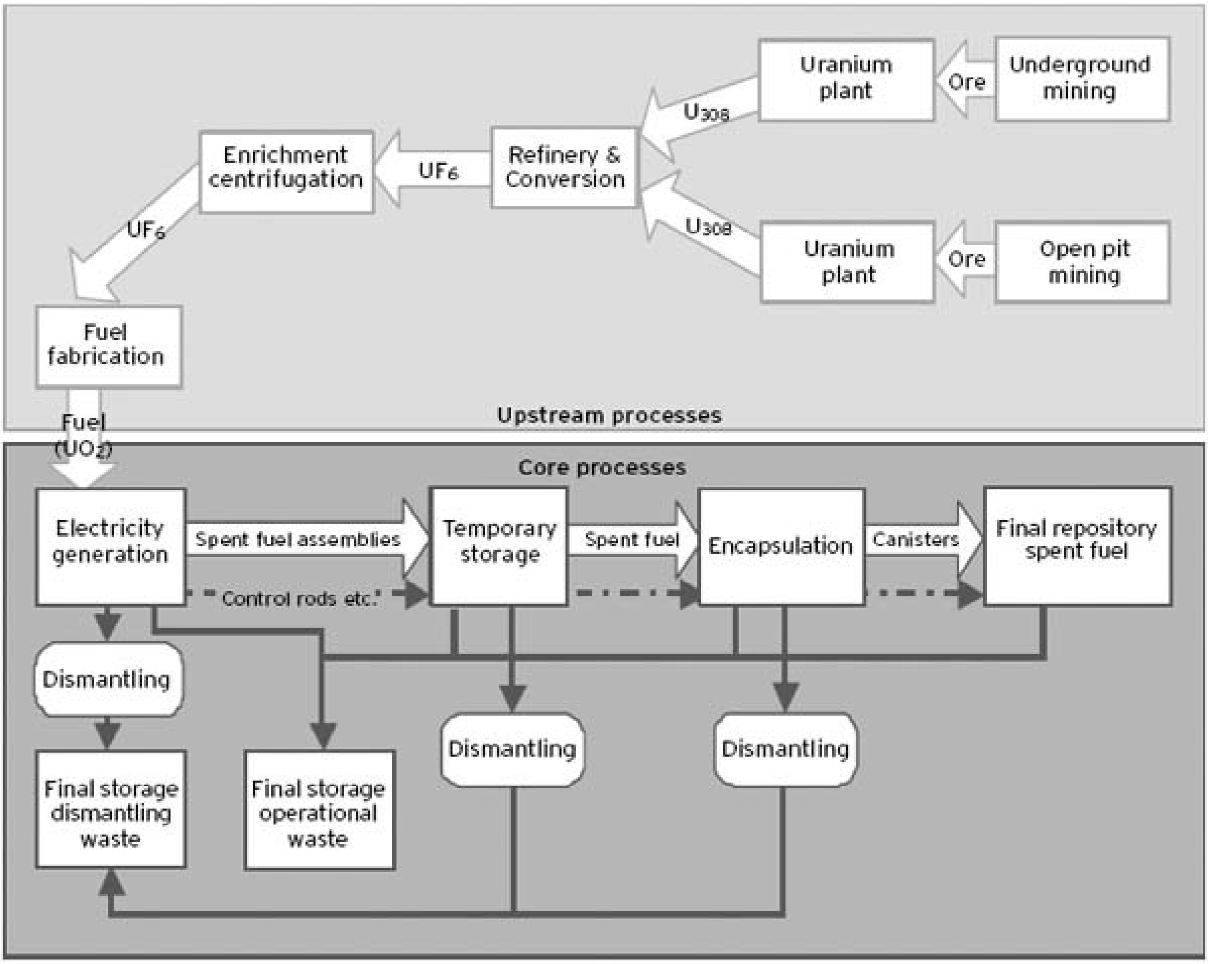
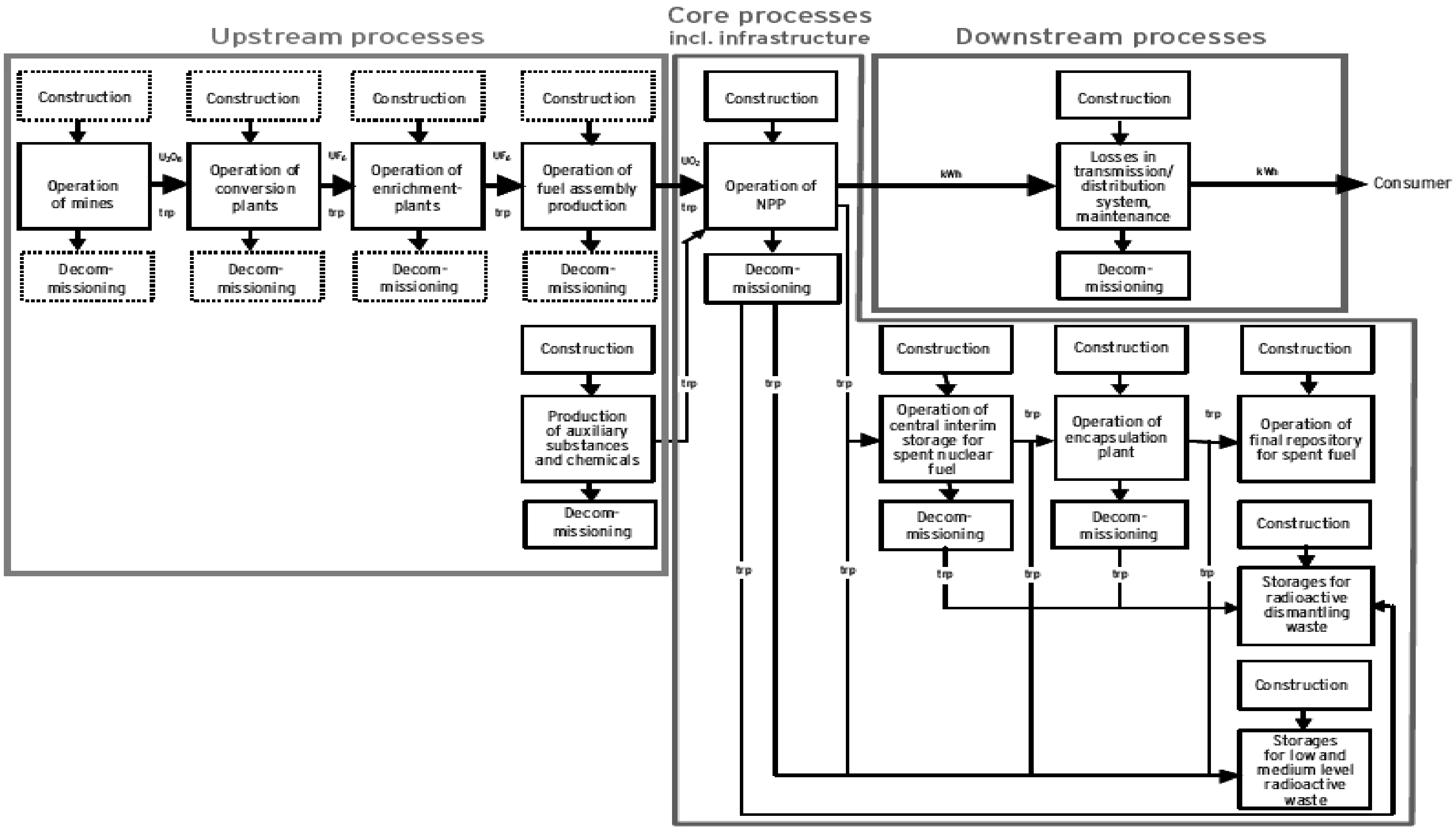


Figure 2. Components of the upstream portion nuclear fuel cycle for the Ringhals NPP included in the Vattenfall EPD® – those not included are indicated by dashed line boundaries



Although the first (2004) EPD® produced by Vattenfall, originally based on the 2002 operating year, provides a comprehensive starting point for analysing raw material requirements for the operation of a Gen II NPP, some information and data gaps exist, as noted above. As this study progressed, it was decided that as far as possible with the available data, the focus should be placed on material requirements for PWRs, given the dominance of this design in the current fleet of NPPs and the likelihood that this type of design will dominate new build, at least in the early stages. In order to provide this focus and to include as much pertinent data as possible, Vattenfall provided an updated (2007) dataset exclusive to the Ringhals nuclear power station (3 PWRs and 1 BWR), including all items analysed, even if these materials were not reported in the EPD® due to the 1% rule noted above (i.e. specialty materials used in small quantities, <1% of the total, that were not included in the 2004 report are included in the updated dataset).

Because EPD®s are maintained and adjusted according to changes in the supply chain and new information, the updated and more comprehensive database used in this study also includes all post-2002 additions and changes. Moreover, because of the modular nature of the database developed by Vattenfall, the updated dataset included a breakdown of the amount of each raw material required in each step of the NPP life cycle (i.e. mining, conversion, enrichment, fuel fabrication, operation of the NPP, construction and decommissioning of the NPP, operation of waste facilities and construction and decommissioning of the waste facilities).

At the time that the new data was submitted by Vattenfall (March 2008), power uprates had been completed at Ringhals. Table 1 shows the uprated power output of the three Ringhals PWR reactors along with other characteristics of the NPP and information on Ringhals 1, a boiling water reactor.

Table 1. Technical aspects of the Ringhals NPPs

	Power output (MWe)	Annual average generation (TWh)	Average efficiency based on the thermal energy in the reactor	Total fuel load* (ton UO_2)	Average energy avail-ability last 5 years(%)	Commis-sioned (year)
Ringhals 1 (BWR)	857	6	33.7	127	84	1976
Ringhals 2 (PWR)	867	6.5	32.7	82	89	1975
Ringhals 3 (PWR)	1 040	7	34.8	82	88	1981
Ringhals 4 (PWR)	907	7	32.7	82	89	1983

* Approximately 20% of the fuel in R1 and 25% in R2, 3 & 4 is exchanged with fresh fuel every year.

Table 2. Details the mix of suppliers in the nuclear fuel chain included in the updated dataset based on existing contracts negotiated for materials required between 2007 and 2011

Company	Facility, location	Operation
Rössing Uranium Ltd	Rössing Namibia	Open pit mine
BHP Billiton	Olympic Dam, Australia	Underground mine
Cameco	Blind River, Canada Port Hope, Canada	Refining Conversion
Urenco Ltd. (UCL)	Capenhurst, Great Britain	Enrichment (centrifugation)
TENEX (sales organisation) UEIP ECP	 Novouralsk, Russia Zelenogorsk, Russia	 Enrichment (centrifugation) Enrichment (centrifugation)
Areva	Lingen, Germany	Fuel fabrication

Although not analysed in this study, data on life cycle emissions are also included in EPD®s. For the Vattenfall EPD®, data on resource use and emissions were mainly retrieved from the following sources:

Table 3. Data sources for Ringhals EPD

	Data from
Ringhals' operation	Environmental management system of the NPP
Ringhals' construction	Construction drawings, design plans and other archived documents plus experts at the site
Suppliers in the nuclear fuel chain see table above	Experts at the respective suppliers and public environmental reports
Operation of waste facilities for radioactive waste	From environmental reports (for existing storages) and from current planning at SKB (for plants not yet built)
Construction of waste facilities for radioactive waste	Construction drawings, design plans and other archived documents plus experts at SKB*
Manufacturing of construction materials, components and operation chemicals and auxiliary materials, generation of electricity and production of fuels	Database ecoinvent ver. 1.3

* Swedish Nuclear Fuel and Waste Management Co.

Total greenhouse gas emissions for the production of electricity in 2006 at Vattenfall's Righals nuclear power plant amounted to 3.7 g CO_2 equivalent (Global Warming Potential over an assigned lifetime of 100 years).

Conclusion

Life cycle raw material requirements for Gen II reactors and the associated fuel cycle are documented in EPD®s. These data provide a comprehensive starting point for an assessment of raw material requirements arising from rapid expansion of global nuclear generating capacity. Owing to the dominance of PWRs in the existing fleet and their expected dominance at least during the initial build-up of capacity considered in this report, it was decided to focus, to the extent possible, on material requirements arising from PWRs. Hence, a detailed dataset from the Ringhals NPS (75% PWR and 25% BWR) was selected as a basis for this project. Although raw materials used in the construction and decommissioning of facilities in the production of nuclear fuel are not included in the Ringhals EPD® dataset, the influence of raw material requirements arising from these facilities are not considered large enough to significantly impact on the overall conclusions of the report.

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ESTIMATING RAW MATERIAL REQUIREMENTS ARISING FROM A HYPOTHETICAL LARGE (TEN-TIME) EXPANSION OF NUCLEAR GENERATING CAPACITY

Assumptions

As outlined in Section 2, a database for this project on raw material requirements was developed from Vattenfall's EPD® and updated in March 2008, focusing on material requirements for electricity production at the four unit Ringhals nuclear power station (NPS). To estimate raw material requirements for the ten-time expansion in nuclear generating capacity specified in the project outline, raw material requirements for the Ringhals NPS production were scaled up to the total 2006 world nuclear electricity production of 2 659.7 TWh (International Atomic Energy Agency, 2007), then multiplied by ten to provide a rough simulation of a ten-time expansion of global nuclear generating capacity (Table 3). This approach implicitly assumes that the entire expanded global nuclear fleet would consist of Generation II reactors of the type currently in operation at the Ringhals NPS (75% PWRs and 25% BWRs). Data on production of the required raw materials and the known resource base of each raw material was then added to the database (principally derived from the USGS in 2007 and 2008). Calculated raw material requirements for a dramatically expanded global nuclear fleet were then compared to global annual production figures as a first cut gauge of the impact such a large scale expansion of nuclear power would have on the global production capacities.

The results of this exercise (Table 4) suggest that only one raw material would be in short supply: uranium. That is, current rates of uranium production would fall short of meeting requirements stemming from a ten-time expansion of nuclear generating capacity. This is not surprising, given that freshly mined uranium currently has met only about 60% to 70% of annual reactor requirements in the past several years, the remainder being derived from sources of previously mined uranium (so-called "secondary sources"). World uranium production in 2006 would have to increase by more than 15 times to meet uranium requirements in this simulation of an overnight tenfold nuclear generating capacity increase using a once-through fuel cycle.

Although no other raw material requirements would exceed production or currently defined resources in this hypothetical, overnight ten-time expansion, requirements for six other raw materials (bentonite, fluorite and fluorspar, indium, manganese, zircon sand and gadolinium) could have an impact on current production since requirements would exceed 4% of total global production capability (86%, 25%, 11%, 23%, 9%, 7% and 4%, respectively).

All remaining raw material requirements for a ten-time global nuclear generating capacity expansion fall below 4% of current production, suggesting that even under this conservative hypothetical scenario of rapid expansion of nuclear generating capacity sufficient quantities could be produced to meet the life cycle needs of the expanded fleet of reactors.

It should be noted that resource and production figures for some raw materials were not available (aluminum, boron carbide, carbon, olivine, quartzite, rock , salt, shale, sodium hypochlorite, sodium sulphate, soil, sulfur, talc, volcanic rock, lignite and peat) but none of these substances are considered to be in short supply. In addition to assuming that the expanded fleet of NPPs would be composed entirely of GEN II reactor designs of the vintage currently in operation at the Ringhals NPS, the preliminary simulation further assumes that the expansion would take place overnight. To provide a more realistic time frame for this expansion of the global nuclear fleet, a second simulation was preformed.

Table 4. Raw material requirements arising from a ten-time expansion of nuclear generating capacity compared to global production and resources*

Raw Material	Reactor					Production and Resources	
	Ringhals g/kWh	2005 Gen tonnes (if all of Ringhals)	Ringhals type X 10	% of yearly prod (if all of Ringhals type)	% Resources	World production Tonnes/year	World Reserves Tonnes
Aluminium in ore	8.85E-04	2.35E+03	2.35E+04	0.06		3.80E+07	
Bauxite	2.13E-03	5.67E+03	5.67E+04	0.04	2.36E-04	1.37E+08	2.40E+10
Bentonite	3.21E-01	8.54E+05	8.54E+06	86.24		9.90E+06	"extremely large"
Borax	1.04E-07	2.77E-01	2.77E+00	0.00	6.75E-07	4.35E+06	4.10E+08
Boron Carbide	1.91E-06	5.09E+00	5.09E+01	1.34		3.80E+03	
Cadmium	1.36E-06	3.63E+00	3.63E+01	0.19	6.15E-03	1.89E+04	5.90E+05
Clay (other than bentonite)	8.26E-02	2.20E+05	2.20E+06				
Calcite	2.16E-01	5.73E+05	5.73E+06				
Caliche	3.82E-10	1.02E-03	1.02E-02			Enormous	No limits known
Carbon	1.91E-06	5.09E+00	5.09E+01	0.01		1.00E+06	
Chromium in ore[1]	4.96E-04	1.32E+03	1.32E+04	0.24	1.10E-04	5.39E+06	1.20E+10
Coal[3]	1.24E-02	3.30E+04	3.30E+05	0.01	4.24E-06	4.97E+09	7.77E+12
Copper in ore	9.03E-03	2.40E+04	2.40E+05	1.65	1.04E-02	1.46E+07	2.30E+09
Crude oil[3]	1.09E-02	2.90E+04	2.90E+05	0.01	1.59E-04	3.62E+09	1.82E+11
Chrysotile	6.54E-07	1.74E+00	1.74E+01	0.00	8.69E-06	2.33E+06	2.00E+08
Cinnabar	7.54E-08	2.01E-01	2.01E+00	0.13	8.35E-04	1.50E+03	2.40E+05
Cobalt	7.28E-09	1.94E-02	1.94E-01	0.00	2.76E-06	6.23E+04	7.00E+06
Colemanite	5.59E-07	1.49E+00	1.49E+01	0.60	8.75E-01	2.50E+03	1.70E+03
Diatomite	1.38E-10	3.66E-04	3.66E-03	0.00	3.98E-07	2.20E+03	9.20E+05
Dolomite	2.63E-03	7.00E+03	7.00E+04			Enormous	No limits known
Feldspar	1.10E-10	2.93E-04	2.93E-03	0.00		1.29E+06	No limits known
Ferromanganese	9.47E-10	2.52E-03	2.52E-02	0.00	5.86E-06	9.79E+03	4.30E+05

Fluorite	4.21E-02	1.12E+05	1.12E+06	24.83	4.87E-01	4.51E+06	2.30E+08
Fluorine in ore	2.57E-04	6.83E+02	6.83E+03				
Fluorspar	2.10E-02	5.58E+04	5.58E+05	10.99	1.12E-01	5.08E+06	5.00E+08
Gadoliniumoxide GdO3	6.70E-06	1.78E+01	1.78E+02	4.46	4.46E-03	4.00E+03	4.00E+06
Gravel and sand	1.50E+00	3.99E+06	3.99E+07			Enormous	No limits known
Gypsum	1.09E-06	2.91E+00	2.91E+01	0.00		1.10E+08	"Large"
Hafnium	6.06E-07	1.61E+00	1.61E+01	0.09	1.61E-03	1.80E+04	1.00E+06
Helium	3.18E-07	8.46E-01	8.46E+00	0.00	1.61E-06	4.26E+06	5.24E+08
Indium	4.09E-06	1.09E+01	1.09E+02	22.67	1.81E+00	4.80E+02	6.00E+03
Iron in ore	2.55E-01	6.78E+05	6.78E+06	0.68	4.84E-03	1.00E+09	1.40E+11
Kieserite	5.78E-07	1.54E+00	1.54E+01				virtually unlimited
Lead in ore	3.91E-03	1.04E+04	1.04E+05	3.17	1.55E-01	3.28E+06	6.70E+07
Limestone	3.52E-03	9.37E+03	9.37E+04		1.28E+08	Enormous	No limits known
Magnesium in ore or water	6.68E-04	1.78E+03	1.78E+04	0.39		4.60E+06	virtually unlimited
Manganese in ore	3.42E-02	9.08E+04	9.08E+05	8.26	1.75E-02	1.10E+07	5.20E+09
Molybden	6.01E-05	1.60E+02	1.60E+03	0.86	8.41E-03	1.85E+05	1.90E+07
Natural gas[3]	2.02E-02	5.37E+04	5.37E+05	0.02	3.81E-04	2.23E+09	1.41E+11
Nickel in ore	9.21E-04	2.45E+03	2.45E+04	1.48	1.75E-02	1.66E+06	1.40E+08
Niobium	9.63E-06	2.56E+01	2.56E+02	0.57	8.54E-03	4.50E+04	3.00E+06
Olivine	4.19E-08	1.11E-01	1.11E+00				No limits known
Palladium in ore	2.18E-09	5.80E-03	5.80E-02	0.00	7.26E-08	1.90E+05	8.00E+07
Phosphorous in ore	1.03E-03	2.73E+03	2.73E+04	0.02	5.46E-05	1.45E+08	5.00E+10
Platinum in ore	7.24E-11	1.92E-04	1.92E-03	0.00	2.41E-09	2.20E+05	8.00E+07
Potassium chloride	3.62E-05	9.63E+01	9.63E+02	0.00	5.67E-06	3.10E+07	1.70E+10
Quartzite	5.43E-04	1.44E+03	1.44E+04			Enormous	No limits known
Rhenium in ore	4.03E-11	1.07E-04	1.07E-03	0.00	1.07E-08	3.30E+04	1.00E+07
Rhodium in ore	6.18E-11	1.64E-04	1.64E-03	0.01	2.05E-09	1.50E+01	8.00E+07
Rock (blasted masses)	5.14E+00	1.37E+07	1.37E+08			Enormous	No limits known
Salt	4.06E-02	1.08E+05	1.08E+06	0.45		2.40E+08	No limits known
Selenium[1]	6.78E-08	1.80E-01	1.80E+00	0.13	1.06E-03	1.40E+03	1.70E+05

Shale	2.06E-07	5.48E-01	5.48E+00				
Silver in ore	2.18E-05	5.81E+01	5.81E+02	2.98	1.02E-01	1.95E+04	5.70E+05
Soda (Sodium carbonate)	1.05E-12	2.80E-06	2.80E-05	0.00	6.99E-11	1.17E+04	4.00E+07
Sodium hypochlorite[1]	6.74E-04	1.79E+03	1.79E+04				
Sodium sulphate	1.50E-03	3.98E+03	3.98E+04	1.21		3.30E+06	sufficient for centuries
Soil	1.11E+00	2.94E+06	2.94E+07				
Stibnite (antimon)	1.43E-11	3.81E-05	3.81E-04	0.00	8.85E-09	1.35E+05	4.30E+06
Sulphur	1.23E-04	3.27E+02	3.27E+03	0.01		5.71E+07	
Talc	8.01E-07	2.13E+00	2.13E+01	0.00		8.10E+06	large
Tin in ore	5.19E-07	1.38E+00	1.38E+01	0.00	1.25E-04	2.80E+05	1.10E+07
Titanium in ore	2.18E-04	5.80E+02	5.80E+03	0.11	4.46E-04	5.40E+06	1.30E+09
Titanium dioxide	3.08E-03	8.20E+03	8.20E+04	2.35	1.86E-02	3.49E+06	4.40E+08
Ulexite	1.32E-07	3.51E-01	3.51E+00	0.00	8.56E-07	4.86E+06	4.10E+08
Volcanic rock, basalt	1.46E-03	3.89E+03	3.89E+04				
Zinc in ore	1.48E-04	3.94E+02	3.94E+03	0.04	8.20E-04	1.05E+07	4.80E+08
Zircon sand[1]	2.26E-03	6.02E+03	6.02E+04	6.55	1.00E-01	9.20E+05	6.00E+07
Non-renewable energyware:							
Coal	3.22E-01	8.56E+05	8.56E+06	0.17	8.56E-04	4.97E+09	1.00E+12
Crude oil	4.83E-01	1.28E+06	1.28E+07	0.35	7.06E-03	3.62E+09	1.82E+11
Lignite, dry substance	2.40E-01	6.39E+05	6.39E+06				
Natural gas	2.33E-01	6.19E+05	6.19E+06	0.28	4.39E-03	2.23E+09	1.41E+11
Peat	6.95E-05						
Uranium in ore[2]	2.01E-02	5.35E+04	5.35E+05	1305.15	1.13E+01	4.10E+04	4.74E+06
Renewable energyware:			Land[4] (m^2)		2.12E-05		
Hydro-electricity	1.53E-03		Water		2.16E+02		
Wood, dry substance	4.14E-02						
Wood (mould wood, wet)	4.13E-02		See Note 1				

Biofuel as wood	4.41E-02	See Note 2
Wind electricity	3.03E-05	See Note 3
		See Note 4
Use of recycled material:		See Note 5
Aluminum scrap	8.43E-05	
Copper scrap	1.12E-02	
Lead scrap	5.53E-05	
Steel scrap	6.99E-03	
Metals combined		
Waste oil		
Rock/excavated material		
Paper		

Total world nuclear production (TWh)		**Value in the calculations above (kWh)**
2005	**2006**	
2626.1	2659.7	2.6597E+12

Note 1) Not followed from the cradle.
Note 2) 2.27 (10^{-2}) g/kWh is used for fuel the Ringhals and Forsmark stations and 2.71 (10^{-2}) g/kWh is used for fuel the Torness station; the rest is used in other NPPs supplying electricity elsewhere in the nuclear fuel cycle.
Note 3) Used as feedstock for materials, not as energyware.
Note 4) For Forsmark 75.0% of the land is the generating facility (1 254 ha, the largest component being the 890 ha cooling seawater surface plume) while the mines represent the major part (24.0%) of the remainder.
Note 5) The Ringhals power station itself covers an area of about 1.5 km2; whereas Torness covers an area of about 1.3 km2, of which about 30 ha is permanently used for operational activities.

*See Appendix B for Database links

Nuclear Energy Growth Rates and Fuel Needs

Nuclear Energy Development Scenarios

World nuclear electricity generation in 2007 was just over 2 600 TWhe (about 370 GWe installed capacity), representing about 15% of the total electricity generation in the world. Under certain world growth scenarios a ten-time increase in the total world production of nuclear electricity to 26 000 TWhe is forecast to take place within the current century. Several studies by authoritative agencies have projected the possible global demand for electricity and the portion generated by NPPs (Centre of Geopolitics of Energy and Raw Materials, 2002; International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), 1995; Nakicenovic *et al*., 1998; International Atomic Energy Agency (IAEA), 1996, 1997; International Energy Agency (IEA), 1999; Nuclear Energy Agency (NEA), 2002; Nakicenovic and Swart (Intergovernmental Panel on Climate Change, IPCC), 2000; Clarke *et al*. (Climate Change Science Program, CCSP), 2007; Kim and Edmonds (CCSP), 2008). These studies estimated the growth (or phase out) of nuclear electricity generation in different regions of the world using different projections of population growth, possible constraints on CO_2 emissions, maturity of technology development and technology transfer, costs of electricity generation, and other factors.

An example of the range of potential energy demand futures is illustrated in the IIASA/WEC study (1995) which was used by the Generation-IV Fuel Cycle Cross Cut Group (Gen-IV FCCG) to examine the fuel cycle implications for alternative nuclear power scenarios in terms of Generation-IV reactors goals (Gen-IV FCCG, 2002). The IIASA/WEC study included six patterns of how energy demand will grow and how it will be met. A given pattern was assumed to prevail in all world regions when producing the global aggregate. All patterns provide for substantial social and economic development with growth in quantity and quality of energy services provided and with improving energy efficiencies and environmental compatibility. The styles and drivers of development for the different patterns are described as follows:

- Pattern (Case) A - (with three scenarios) is one of high economic growth and assumed high degrees of technological ingenuity
  - Scenario A1: high availability of oil and gas
  - Scenario A2: return to coal; scarce oil and gas
  - Scenario A3: nuclear and renewables; fossil phaseout
- Pattern (Case) B - (single scenario) is the middle course –with more modest energy demand, slower technological innovation, and less uniform rates of economic growth among developing countries.
- Pattern (Case) C- (with two scenarios) is an ecologically driven pattern with assumed unprecedented progressive international co-operation focused on environmental protection and international equity and relying on North to South technology and institutional transfers
  - Scenario C1: renewables grow dramatically; fossil reduction, and nuclear phaseout
  - Scenario C2: nuclear ascendance, fossil reduction

Figure 3 shows the six patterns for global deployments of nuclear electricity as predicted by the IIASA/WEC study. The figure also shows the ten-time increase in nuclear energy generation and whether or when it might be achieved under the different scenarios. Of interest here is the IIASA/WEC Case B scenario which has been used as the base case by the Gen-IV FCCG and it is also used as the base case for the current study. As shown in Figure 3, a ten-time increase in nuclear energy generation is achieved starting in the year 2085. This scenario is consistent with more recent studies such as the IPCC and CCSP. Figures 4 and 5 compare IIASA/WEC Case B nuclear energy deployment to some of the scenarios described in the IPCC and CCSP studies, respectively.

Figure 3. IIASA/WEC nuclear energy demand scenarios

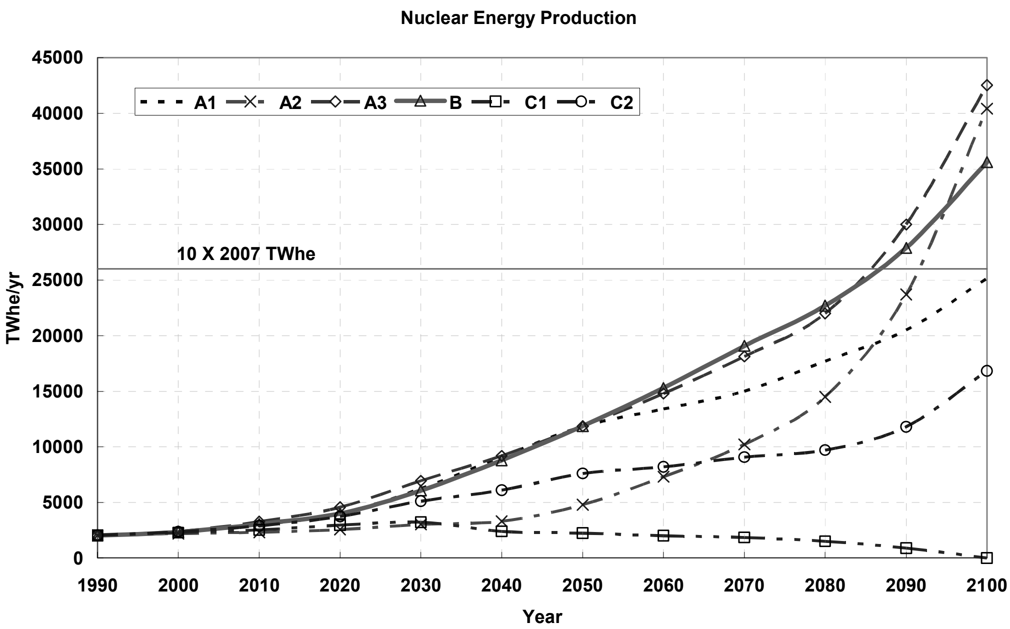


Figure 4. Comparison between IIASA/WEC B scenario and selected IPCC-SRES scenarios

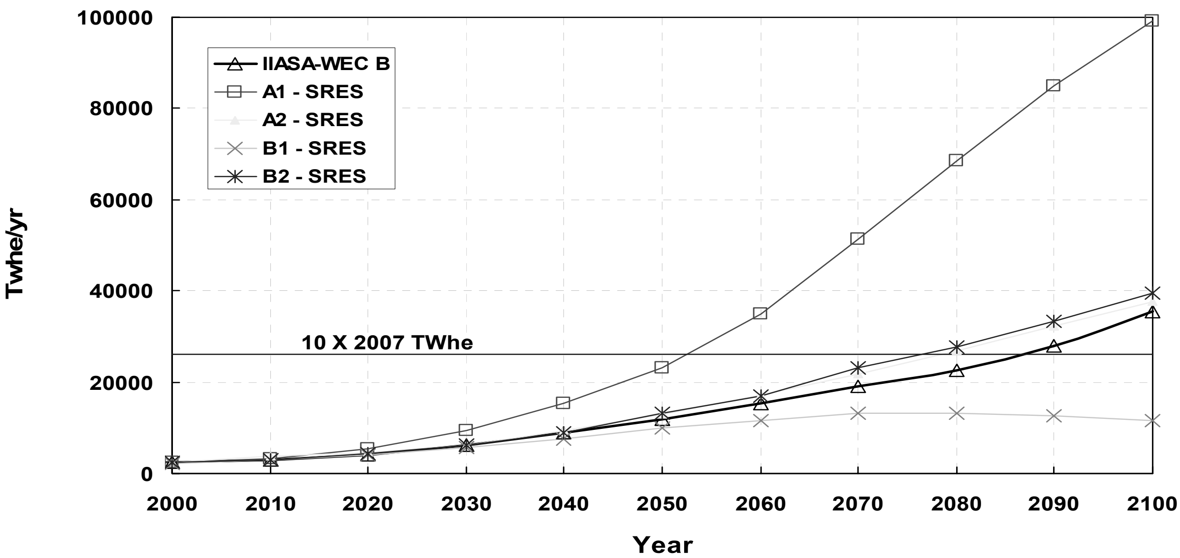
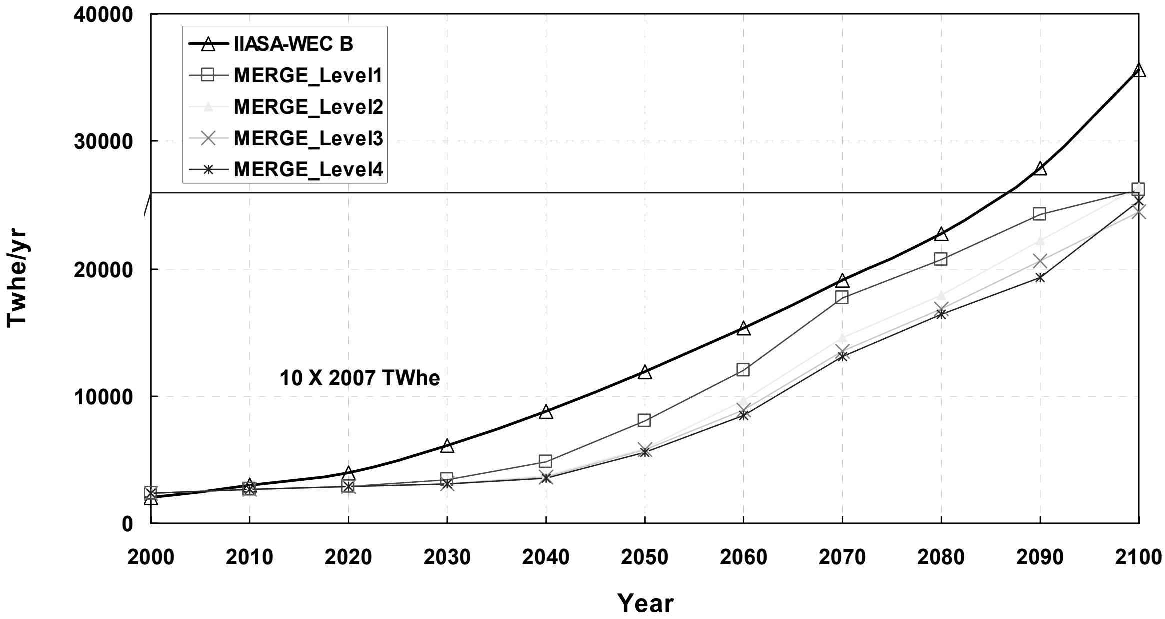
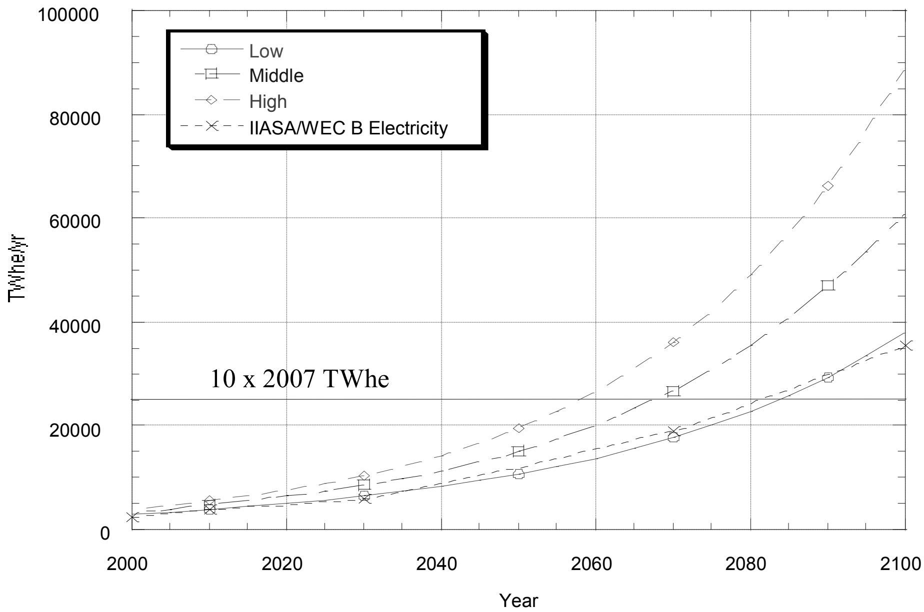


Figure 5. Comparison between IIASA/WEC B scenario and selected CCSP scenarios



Notice that the demand scenarios shown in Figures 3 to 6 do not include the possible use of nuclear reactors in non-traditional electricity sector. There are possible future use of nuclear reactors in non-conventional applications such as water purification and desalination, district and process heat generation, and hydrogen production. Yacout *et al*., (2004) discuss possible growth rates in nuclear energy that includes demand to meet some or all of these non-conventional nuclear energy applications. Figure 6 portrays such possible demand scenarios compared to the IIASA/WEC scenario B nuclear energy demand for electricity. The 'Low' scenario clearly represents a lower bound estimate for nuclear energy demand in business-as-usual cases. The 'Middle' scenario represents an initially scenario B (IIASA/WEC) demand where hydrogen production starts to add nuclear energy demand from mid century on. Finally, scenario 'High' represents an ambitious nuclear energy demand development reaching 90 000 TWhe/yr by the end of this century to be compared to 2007 generation of 2 600 TWhe/yr. More details about the assumptions taken in these scenarios are provided by Yacout *et al*. (2004). The figure also shows the possibility of achieving the ten-time increase in nuclear energy production as early as the year 2058.

Figure 6. Global nuclear energy deployment scenarios including non-conventional applications



Integrated Fuel Cycle Modelling Tools

Over the past few years, simulation of the dynamic behaviour of the nuclear fuel cycle scenarios has taken increasing importance as a tool for the assessment of the integrated nuclear energy systems options and its development pathways. Increasingly, interest is shown in the development and use of those tools. Various fuel cycle assessment codes are currently available or under development in different parts of the world (Yacout *et al*., 2005, 2006; Van Den Durpel *et al*., 2003; Jacobson *et al*. 2007; Schneider *et al*., 2005; Boucher and Grouiller, 2005; Millington, 2003; Mehmet, 2007; Ichimura, 2003). Those codes vary in their details of simulating the nuclear fuel cycle and their abilities to predict the associated infrastructure deployment over time. Figure 7 is an illustration of detailed fuel cycle components and possible mass flows which are considered in more or less details by the different systems codes.

The assessment tool of interest here is the DANESS ('Dynamic Analysis of Nuclear Energy System Strategies') code (DANESS, ANL). DANESS is an integrated dynamic nuclear process model for the analysis of today's and future nuclear energy systems on a fuel batch, reactor, and country, regional or even worldwide level.[2] The DANESS model allows simulating up to 10 different NPP-types and up to 10 different fuel types in one simulation. Starting from the NPP park and fuel cycle situation in 1990, DANESS analyses energy-demand driven nuclear energy system scenarios over time and allows the simulation of changing NPP-parks and fuel cycle options. The energy demand is hereby given as an energy-demand scenario or as a specific NPP-park evolution. New NPPs are introduced based on the energy demand and the economic and technological ability to build new NPPs. The technological development of NPPs and fuel cycle facilities is modelled to simulate delays in availability of technology. Levelised fuel cycle costs are calculated for each nuclear fuel batch for each type of NPP over time and are combined with capital cost models for NPPs and fuel cycle facilities to arrive at energy generation costs per reactor and, by aggregation, into a cost of energy for

[2] DANESS is an integrated dynamic nuclear process model for the analysis of today's and future energy systems on a fuel batch, reactor, and country, or even worldwide level (Fig. 8).

the whole nuclear energy system. Cash-flows are also calculated per NPP and fuel cycle facility allowing the investigation of the detailed economics of nuclear energy systems. The waste arising from the NPPs and fuel cycle facilities is traced throughout their respective lifetime and the storage and conditioning as well as disposal of this waste is modelled explicitly including the isotopic composition, radioactivity, radiotoxicity and decay heat evolution over time for such waste. DANESS is composed of different interconnected sub-models each of those intended to perform a specific part of the simulation. Figure 8 depicts the overall architecture of the DANESS-model.

Figure 7. Schematic of a nuclear fuel cycle system

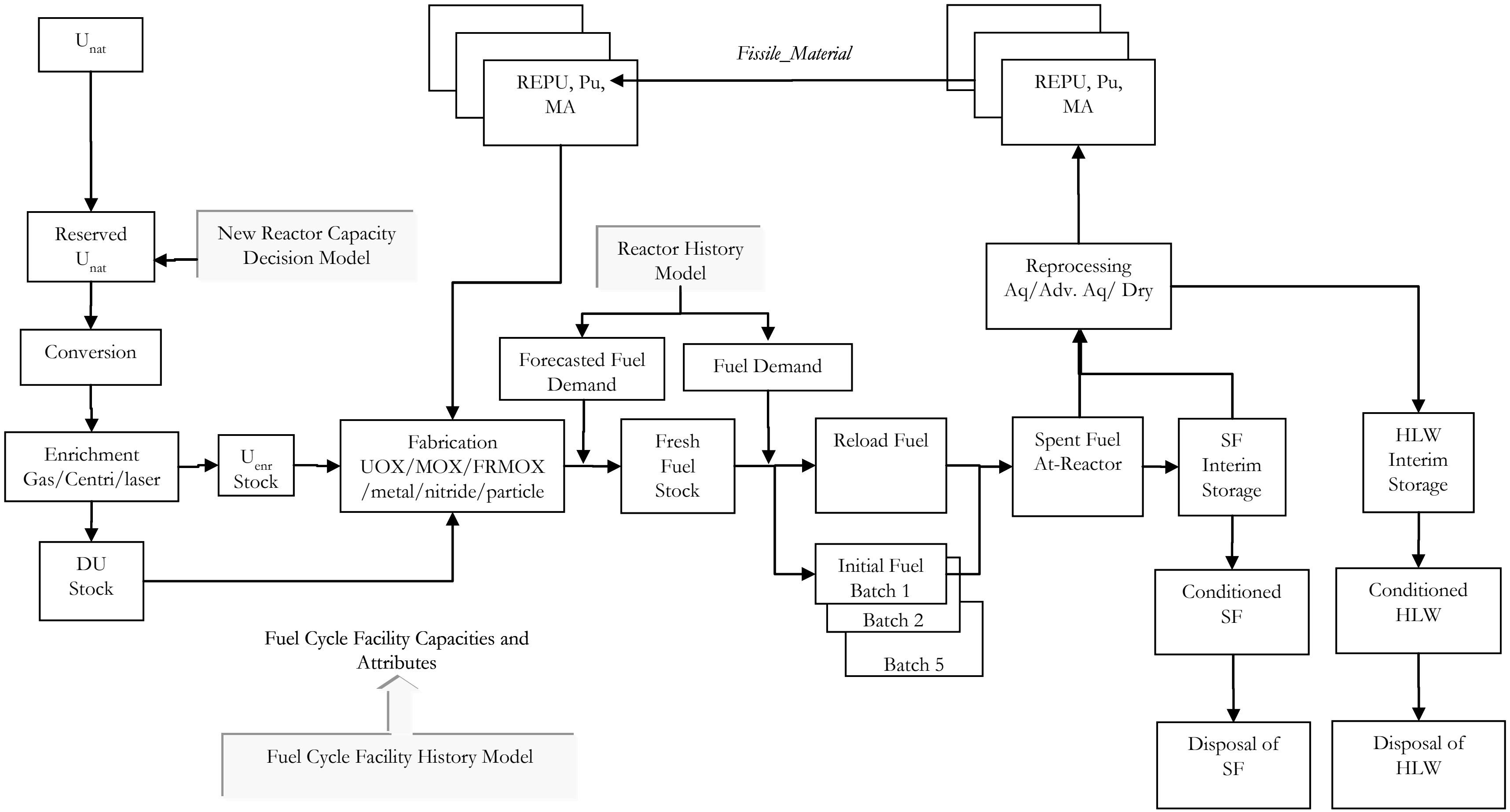
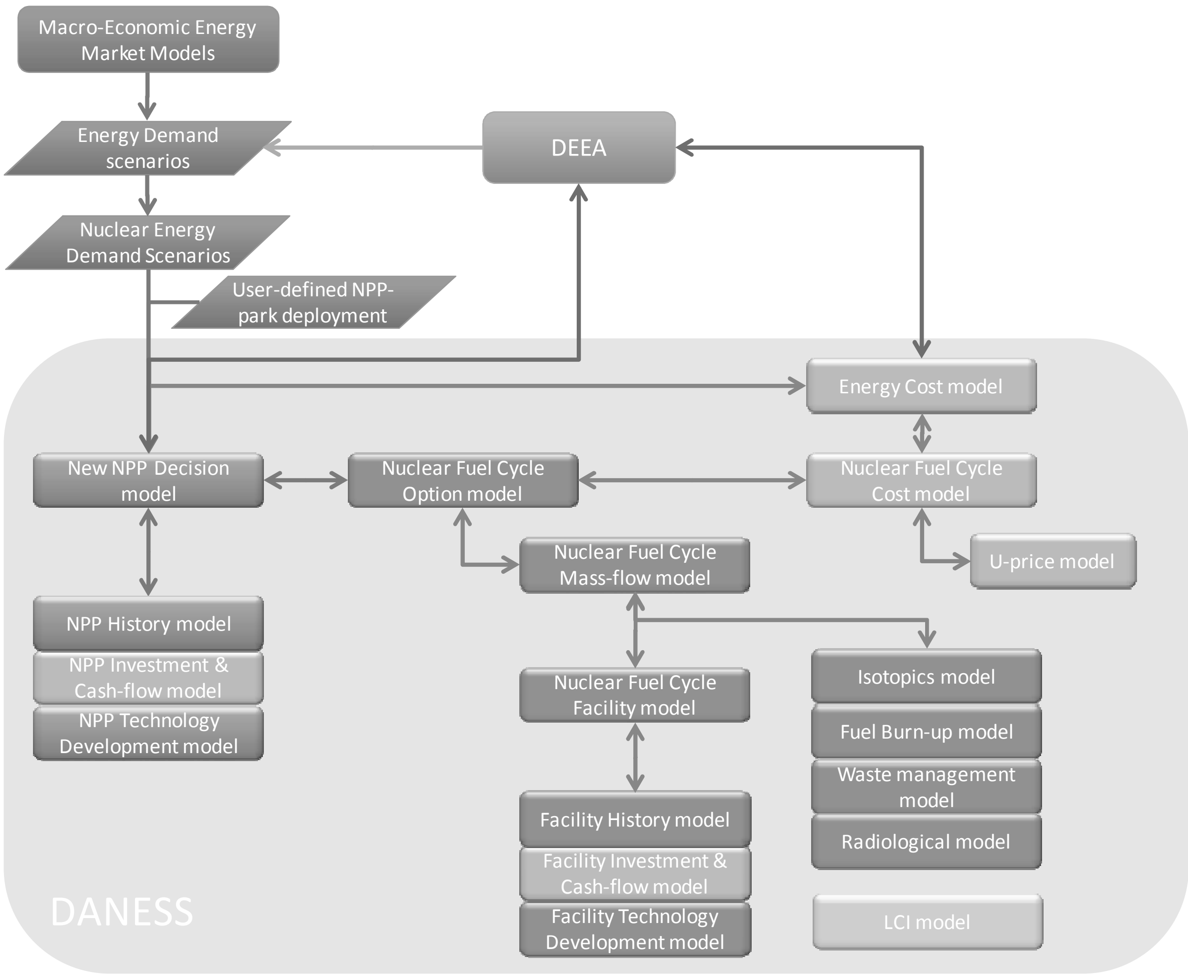


Figure 8. DANESS integrated system model



Fuel cycle facilities also have different characteristics and several technological options per fuel cycle step are available. The user may choose, for instance, that UOX fuel is reprocessed using aqueous reprocessing technology, MOX using advanced aqueous and metallic fast reactor fuel using dry reprocessing technologies. These technologies may have different loss fractions (per element), different transit times, costs, etc. Again, each fuel cycle facility that is considered in the simulation follows a life-path from ordering until decommissioning where the expenses at each moment are traced. The technologies follow a technology development path covering 9 technological readiness levels where the duration of each step may be different among technologies and can evolve in time.

The DANESS-model checks the availability of fissile material for the different fuel and reactor combinations and will order new fuel cycle facilities or will change the reactor park composition or fuel cycle options according to the criteria set forward by the user. More details on DANESS is available via the DANESS-manual accessible on the DANESS website (www.DANESS.anl.gov).

Scenario Calculations for Fuel Requirements

As mentioned, the scenario selected for this study corresponds to Case B world aggregate nuclear energy demand growth produced in the IIASA/WEC projections. The deployment is thought of as the "global nuclear energy park" with no regional segmentation of energy demand or mass flows. In attempting to satisfy the pre-specified demand, the simulated deployment of new power plants is constrained only by internal mass flows which determine fissile availability - i.e., plants cannot start producing power unless they can be fuelled - drawing on either virgin ore, or on fissile available in discharged fuel assemblies, or fissile remaining in enrichment tails and recovered irradiated uranium, or in new fissile bred in previously-deployed power plants. The sources to be exploited are specified as input to the scenario. To meet the demand specified by the scenario, only deployment of LWRs is considered here which makes the availability of uranium ore resources the only possible constraint on deployment of reactors. The properties of a typical LWR design that is considered here is shown in Table 5. The mass flow properties and the charge and discharge fuel isotopic compositions of the reactor are specified as input to the simulation. DANESS modelling of new capacity additions constrains plant start-up in two ways. First, the construction and licensing lag times must have been completed. Second there must be fuel available sufficient to begin operations. The fuel requirement comprises not only the initial working inventory of the power plant itself, but also forward fuelling for a specified number of reload batches. The physical inertial elements of the supply infrastructure are accounted for - including licensing and construction lag times for fuel cycle infrastructure elements and for power plants. The time lags for interim storage between links of the fuel cycle are also accounted for. Market economic penetration is not modelled; both the dates of commercial availability of various power plant types and the fractional mix of plant types to be used to satisfy new demand are pre-specified as input to the specific scenario case being evaluated. In this sense, the scenarios serve to illustrate what could be physically achievable.

Table 5. Reactor and fuel attributes

Reactors	PWR	BWR	ALWR		HTGR	FR (CR=0.5)
Thermal Power (MWth)	2647	2647	2647		600	843
Electric Power (MWe)	900	900	900		284	320
Thermal Efficiency (%)	34	34	34		47	38
Capacity Factor (%)	90	90	90		90	85
Technical Lifetime (yr)	50	50	50		50	50
Fuels						
	UOX	UOX	UOX		MOX	Particle
Average Burnup (GWd/tHM)	50	40	50	50	120	Metal
# fuel batches	5	5	5	3	7	120
Cycle Length (mo)	12	12	12		12	12
Initial U (t/tIHM)	1	1	1		0	1
Initial Enrichment (%)	4.2	3.7	4.2	0.25	15.5	0
Initial DU (t/tIHM)	0	0	0	0.91903	0	
Initial REPU (t/tIHM)	0	0	0	0	0	0.061
Initial Pu (t/tIHM)	0	0	0	0.08097	0	0.5936
Initial MA (t/tIHM)	0	0	0	0	0	0.2919
Spent U (t/tIHM)	0.93545	0.94576	0.93545	0.88753	0.85917	0.0535
Spent enrichment (%)	0.82	0.8	0.82	0.15	4.8	0.5936
Spent Pu (t/tIHM)	0.012	0.1085	0.012	0.05512	0.01883	
Spent MA (t/tIHM)	0.00125	0.00114	0.00125	0.0074	0.002	0.2365
Spent FP (t/tIHM)	0.0513	0.04225	0.0513	0.04996	0.12	0.0452

Figure 9 shows production of deployed global nuclear energy compared to the input energy demand as specified by the IIASA/WEC-B scenario. The smooth matching between energy demand and energy production is achieved through DANESS forecasting of energy demand and planning for building LWRs to meet demand. The corresponding deployed reactor capacity in GWe is shown in Figure 10 where each reactor capacity is one GWe and reactor capacity factor is assumed to be 0.85. The figure shows an initial global nuclear reactor capacity of about 350 GWe that is composed mainly of Gen-II LWRs combined with a small fraction of Russian WWER reactors and a small population of CANDU reactors. This population of Gen-II reactors shuts down gradually as it reaches the end of its operational time. Once a Gen-II type reactor is shutdown it is replaced by a Gen-III reactor that has a lifetime of 60 years. It is assumed here that licensing extension is granted to all Gen-II reactors to operate to 60 years. Once all Gen-2 reactors are phased out, all deployed nuclear reactors become Gen-III LWRs (ALWRs) type reactors by the year 2050. Figures 10 – 13 show the mass flows associated with the deployment of LWRs in addition to key capacities such as enrichment and fabrication rates. Mass flows include the amount of generated depleted uranium, natural uranium consumption rates, in addition to spent fuel and high level waste production rates.

Figure 9. DANESS calculated nuclear energy production vs. energy demand for the IIASA/WEC-B scenarios

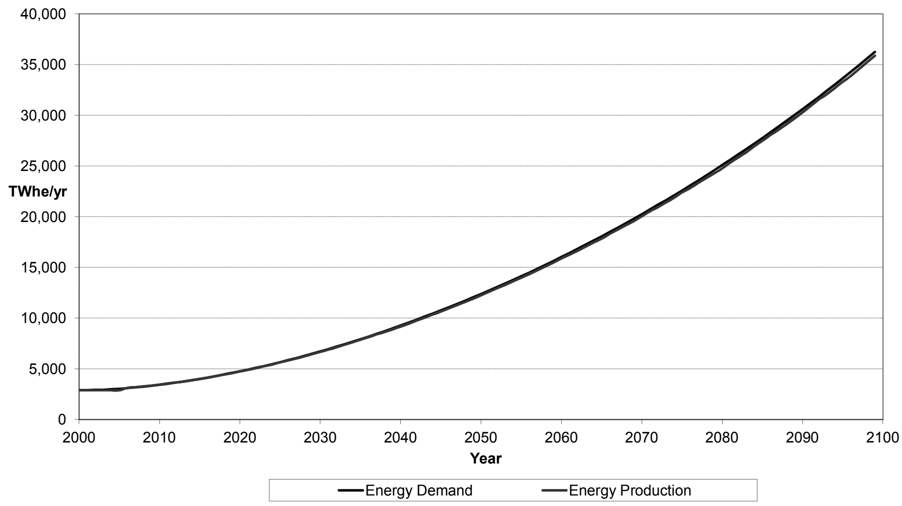


Figure 10. Deployed reactor capacity

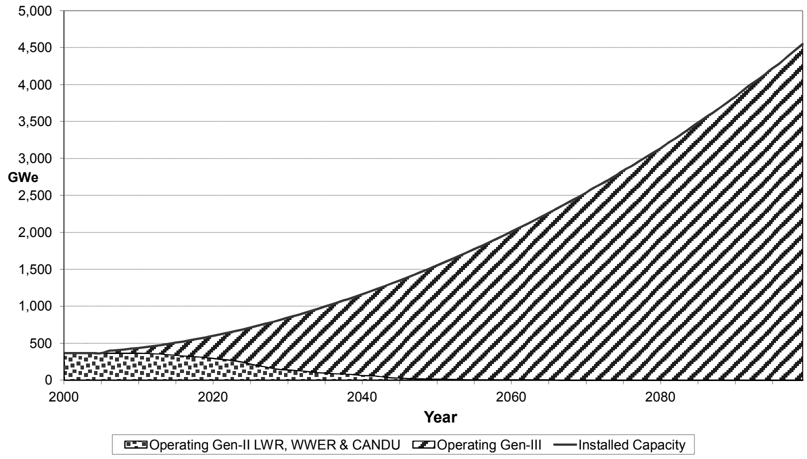


Figure 11. Evolution of inventories of generated depleted uranium (DU) and natural uranium in addition to annual rates of fuel fabrication and enrichment rates for a once-through fuel cycle

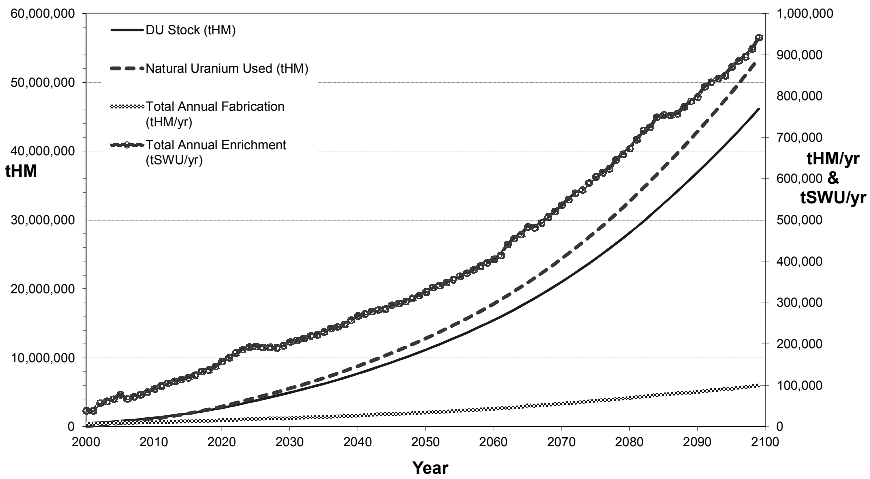


Figure 12. Annual rates of natural uranium consumption and enrichment for a once-through fuel cycle

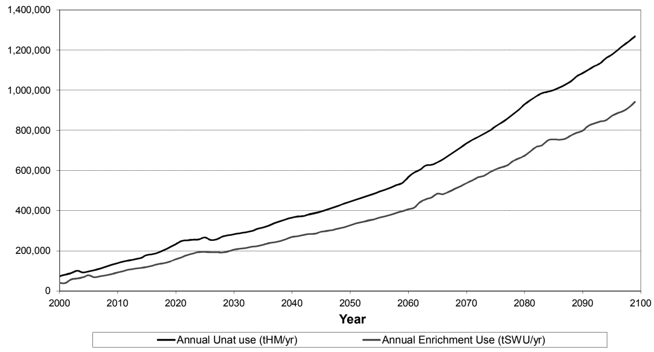
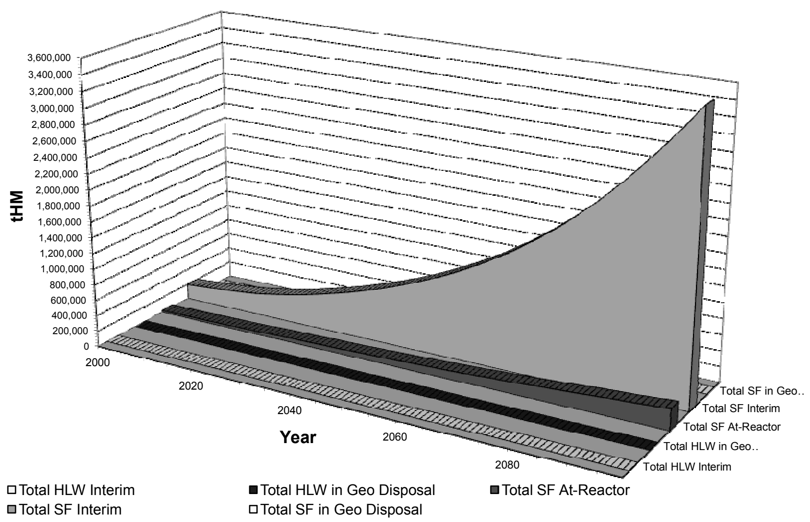


Figure 13. Evolution of spent fuel and high level waste inventories as a function of time for a once-through fuel cycle



Conclusion

A number of institutions have produced simulations of growth in nuclear generating capacity that see a possible ten-time development of nuclear generating capacity and associated electricity generation compared to the scale in operation today, although the timing of development varies. Review and analysis of these development scenarios suggest that the most realistic timing of the ten-time development of nuclear electricity generation is the Case B IIASA/WEC projection that sees this target reached in 2085.

Examination of the evolution of fuel cycle requirements for development of a global reactor fleet of this scale shows the need for extensive fuel resources and spent fuel storage and disposal facilities should the fleet exclusively employ a once-through fuel cycle.

Also of note are scenarios of potentially more rapid growth in nuclear generating capacity in consideration of non-conventional applications such as water purification and desalination, district and process heat generation and hydrogen production. As a result, the consumption of raw materials to build, operate and decommission NPPs to produce electricity should also take into consideration the potential applications to produce potable water and heat, as well as hydrogen as an energy carrier.

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FUEL FOR AN EXPANDED REACTOR FLEET

As outlined in preceding sections, a preliminary analysis of material requirements arising from a rapid, ten-time increase in nuclear electricity generating capacity indicates that uranium would be in short supply. This is not surprising, given that reactor requirements for uranium in the currently operating fleet of NPPs have exceeded uranium mine production by about 40% over the past several years. Since the early 1990s, this difference has been made up by drawing upon sources of previously mined uranium, so-called “secondary supplies” (uranium mined between 1945 and 1990 that is held in various forms by the civil industry, governments and the military).

In Section 3 above, the scenario of nuclear capacity expansion selected for this study shows that a ten-time expansion of nuclear generating capacity could be achieved as early as 2085. This is comparable with other estimates of rapid expansion of nuclear generating capacity. According to the Nuclear Century Outlook developed by the World Nuclear Association (WNA; http://www.world-nuclear.org/outlook/clean_energy_need.html), high case nuclear generating capacity is projected to reach 3 488 GWe by 2060 and over 11 000 GWe by 2100. Interpolating the post 2060 growth rate based on the year 2100 expanded generating capacity indicates that a ten-fold expansion of global generating capacity would be surpassed in 2062.

The Nuclear Energy Outlook, the first of a kind for the OECD Nuclear Energy Agency (NEA, 2008a), includes a high case projection to over 1 400 GWe by 2050. Although this projection does not extend to the scale envisioned in this project, extension of the rapid late stage rate of growth in the NEO indicates that the ten-time level of generating capacity would be achieved in 2083. Both the WNA and the NEA maintain that such growth rates are realistic and achievable. In combination, they suggest that global generating capacity ten-times greater than mid-2008 could be achieved in about 50 to 80 years.

If the expanded fleet were to entirely consist of Gen II PWRs (75%) and BWRs (25%) from the Ringhals NPP operating at between 88% and 89% availability, typical annual uranium consumption calculated from EPD® data would amount to about 145 tU/GWe, not including first core requirements. Annual uranium requirements of a fleet of nuclear reactors generating 3 720 GWe would then amount to some 540 000 tU. In the nuclear energy growth rate outlined in section 3 of this report, annual uranium consumption would amount to 183.6 tU/GWe (including first core requirements) assuming a 60 year lifetime for reactors. At this rate, annual uranium requirements for a 3 720 GWe reactor fleet would total about 683 000 tU. This is a substantial increase over recent global uranium mine production that has amounted to about 40 000 tU/yr between 2004 and 2007. The following section examines the ability of the uranium mining sector to expand to the scale deemed required to support a ten-time expansion of global nuclear generating capacity. This would require increasing recent uranium mine output by over 17 times.

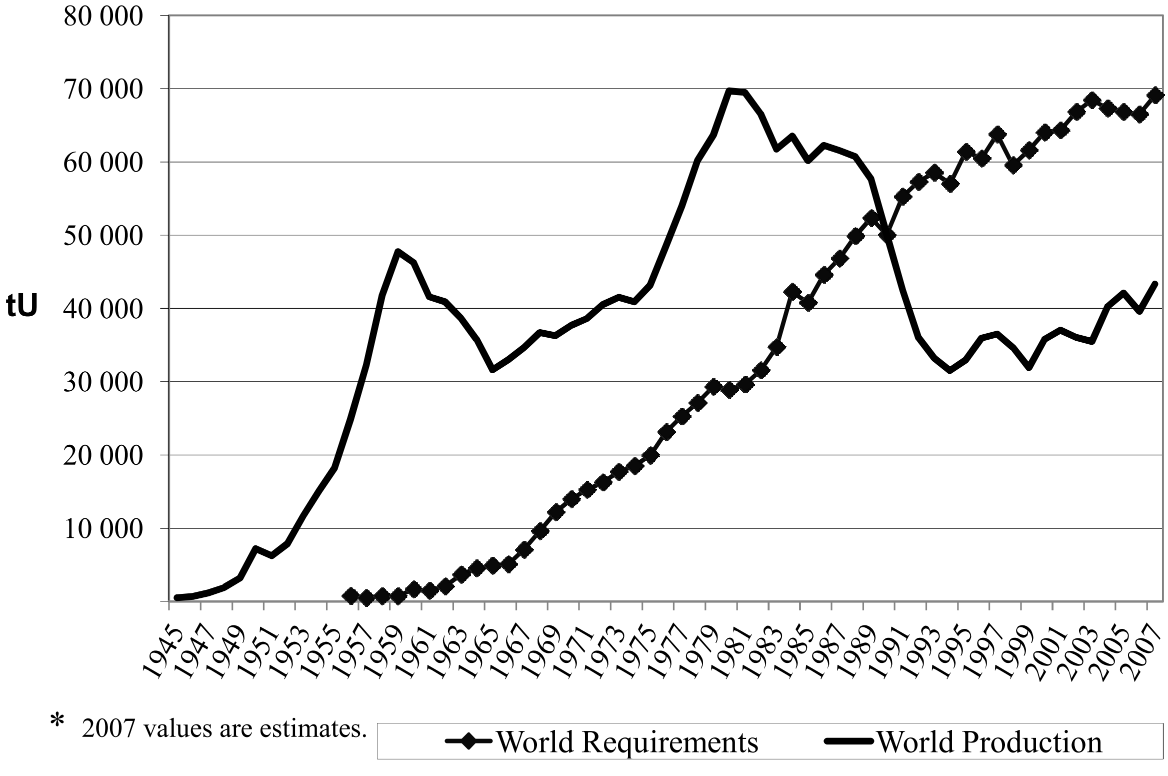
History of Uranium Supply

In general, market conditions drive the development of uranium mines and production. Many aspects of the current uranium market have been shaped by a 20 year period of low prices (~1983-

2003) that followed a period high prices and intense exploration and production. This period of heightened activity reached its peak in the 1970s when expectations of significant growth in nuclear generation were held by many. This expectation was not realised, principally owing to plummeting confidence in civil nuclear energy following the Three Mile Island and Chernobyl accidents. Since uranium production in these early years greatly exceeded subsequent requirements (Figure 14), the market was oversupplied and a large inventory of uranium accumulated. This inventory has been a key factor in keeping prices low until 2003, as the ability to draw from inventory sources greatly reduced demand for freshly mined material. These two decades of low uranium prices led to the closure of all but the lowest cost mining facilities, market consolidation and sharply reduced investment in exploration and mine development.

Although this inventory of so-called "secondary supplies" has been drawn upon for a number of years, it is not precisely known how much material remains that could eventually be brought to the market. Although some governments and organisations disclose inventory holdings, information on commercial inventories is not publicly available. The size of military inventories, their suitability for use in the civil sector and their availability, are also not well known. One recent estimate (Capus, 2007) concluded that commercial inventories had been generally depleted of any sizeable excess but that government inventories, although likely sizeable, were not well known, particularly those held by the Russian Federation. Although secondary supplies are now necessary to balance uranium supply and demand and will likely remain important for several years, available evidence suggests that they are not likely of the size necessary to be a significant component of the material required to fuel such a significant expansion of nuclear energy on the scale envisioned in this project. Therefore, the bulk of the uranium required to fuel such an expansion employing a once-through fuel cycle will have to be increasingly comprised of freshly mined material.

Figure 14. Annual Uranium Production and Requirements (1945-2007*)



* 2007 values are estimates.

Uranium Exploration and Resources

Conventional Uranium Resources

Worldwide exploration and mine development expenditures in 2006 amounted to USD 774 million, an increase of more than 250% compared to 2004 expenditures, as uranium market prices strengthened considerably (NEA, 2008b). Although the majority of global exploration activities remain concentrated in areas with the best prospects for the discovery of low-cost deposits (those with potential for unconformity-related and *in situ* leaching (ISL) amenable sandstone deposits), primarily in close proximity to known resources, recent high prices have stimulated "grass roots" (areas not previously explored) exploration, as well as heightened exploration activities in regions known to have good potential based on past work.

As exploration activity increases, so too does the resource base, despite continuous draw-down through ongoing mine production. As of 1st January 2007, total Identified Resources (that is, those deposits delineated by sufficient direct measurement to conduct pre-feasibility and sometimes feasibility studies) rose to about 5 469 000 tU in the <USD 130/kgU category (an increase of 15% compared to 2005). Though a portion of these increases relate to new discoveries, the majority result from re-evaluations of previously Identified Resources in light of the effects of higher uranium prices on cut-off grades. Total Undiscovered Resources (those that are expected to occur based on geological knowledge of previously discovered deposits and regional geological mapping) amounted to more than 10 500 000 tU, increasing by 485 000 tU from the total reported in 2005, even though some countries, including some major producers (e.g. Australia and Namibia), do not report resource estimates in this category. Hence, as of 1st January 2007 total Known Conventional Resources amounted to 5 469 000 tU, with an additional 10 500 000 tU thought to be available in areas that have been the subject of some past exploration, based on current understanding of geological formations hosting uranium mineralisation in sufficient concentration to be economically mined. This amounts to a total potential resource base of about 16 000 000 tU (NEA, 2008b). Uranium prices must be sufficiently high to stimulate the additional exploration required to convert Undiscovered into Identified Resources if all these in-ground resources are to be mined and brought to the market.

It is however important to note that resource figures are dynamic and related to commodity prices. The uranium resource figures cited above are a "snapshot" of the available information on resources of economic interest and are not an inventory of the total amount of uranium contained in the earth's crust (one estimate (Schneider and Sailor, 2008) of the total potentially available suggests that as much as 80 trillion tU, although much of this would likely be sub-economic occurrences of low - grade uranium). Should favourable market conditions continue to stimulate exploration, additional discoveries can be expected, as was the case during past periods of heightened exploration. For example, Australia's Identified Resources increased by over 200 750 tU between January 2007 and August 2007 as a result of deposit extensions and new discoveries (NEA, 2008b). Promising early exploration results suggest that additional discoveries are likely forthcoming in several other countries, including Canada, Namibia, Niger and South Africa.

Unconventional Uranium Resources

While uranium exploration has surged recently and new conventional uranium resources (those where uranium is recoverable as a primary product, a co-product or an important by-product) are being identified, the work required to define resources of economic interest in the category of "unconventional resources" is only just being renewed. Unconventional resources, those from which uranium is recoverable as a minor by-product, such as uranium associated with phosphate rocks are expected to be considerable.

Historically, uranium produced as a by-product of phosphoric acid production for fertiliser is the only unconventional resource category from which a significant amount of uranium has been recovered (Barthel, 2007). Processing of Moroccan phosphate rocks in Belgium produced about 690 tU between 1975 and 1999 and about 17 150 tU were recovered in the United States from phosphate rocks in Florida between 1954 and 1962. As much as 40 000 tU were also recovered from processing marine organic deposits (essentially concentrations of ancient fish bones) in Kazakhstan (NEA, 2008b). Although current costs of production are not well known, estimated production costs for a 50 tU/year project, including capital and investment, ranged between USD 40/kgU and USD 115/kgU in the United States in the 1980s (McCarn, 1998). Regulatory requirements have matured since the 1980s and these requirements and licensing procedures would likely increase production costs by an unknown, but likely significant amount. Since U extraction from phosphate rocks is not ongoing it is evidently not currently economically attractive. However, should nuclear capacity build at the pace considered in this report, this form of production could once again become an important source of uranium.

A recent summary of the information available on unconventional uranium resources concluded that the total uranium reported as unconventional resources, dominated by phosphate rocks in Morocco (>85%), amounts to about 7.3 – 7.6 million tU (NEA, 2008b). However, since this total does not include information from countries known to contain these types of deposits it is considered to be a conservative estimate.

Other estimates of uranium resources associated with marine and organic phosphorites outline the existence of almost 9 million tU in four countries alone; Jordan, Mexico, Morocco and the United States (IAEA, 2001) and a global total amounting to 22 million tU (De Voto and Stevens, 1979). Clearly these figures should be considered as part of a general mineral inventory since they do not conform to resource reporting standards. The development of more rigorous estimates of uranium in phosphate rocks and the costs of recovering the contained uranium would be timely given that uranium market prices may once again justify the economic exploitation of these deposits.

A potential additional unconventional uranium resource is seawater, which contains over 4 billion tU. However, because of the low concentration of uranium in seawater (3-4 ppb), it has been estimated that it would require the processing of about 350 000t of water to produce a single kg of uranium. Between 2001 and 2003 however, Japanese researchers tested an alternative approach, a braid type recovery system directly moored to the ocean floor, recovering about 1.5 gU over a 30 day test period (Tamada *et al*., 2006). The recovery factor of such a system is estimated to be about 1 200 tU/year at a recovery cost of over USD 700/kgU. Research is continuing with the goal of improving the recovery factor and reducing cost.

Uranium Requirements of the Expanded Fleet

As outlined above, uranium requirements under a scenario of rapid growth in nuclear generating capacity will increase significantly. To support a ten-time increase in global generating capacity, uranium requirements would need to increase by 17 times to meet expected annual requirements of over 683 000 tU. Growth in annual uranium requirements under the WNA and NEA high growth scenarios and the DANESS simulation are depicted in Figure 15. The development of cumulative uranium requirements in the same three scenario projections is depicted in Figure 16. For reference, horizontal lines added to Figure 16 show the 2007 levels of Identified Resources (IR) and estimates of Undiscovered Resources (Und).

Figure 15. Evolution of annual uranium requirements under the NEO and WNA high case scenarios and the DANESS simulation of a ten-time increase in global nuclear generating capacity or electricity production

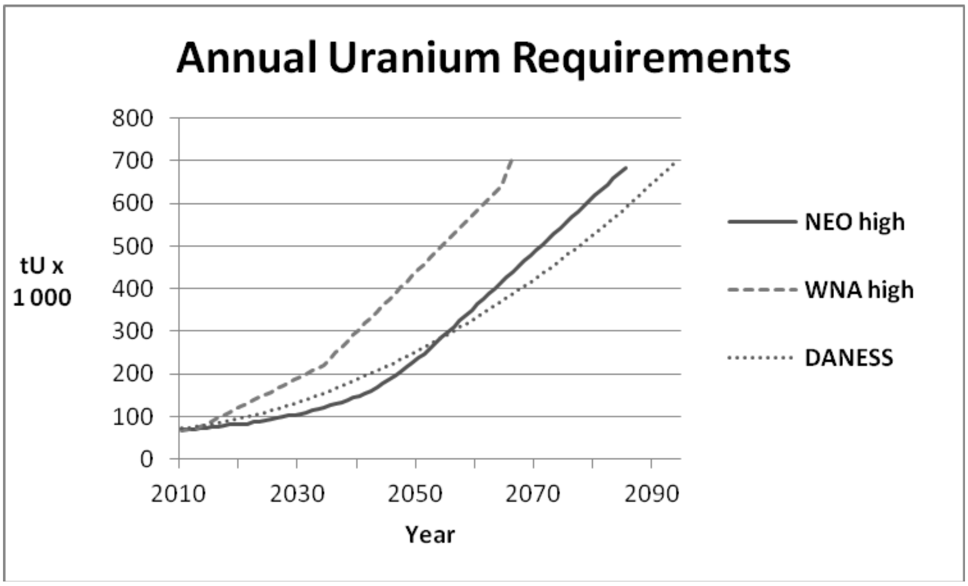
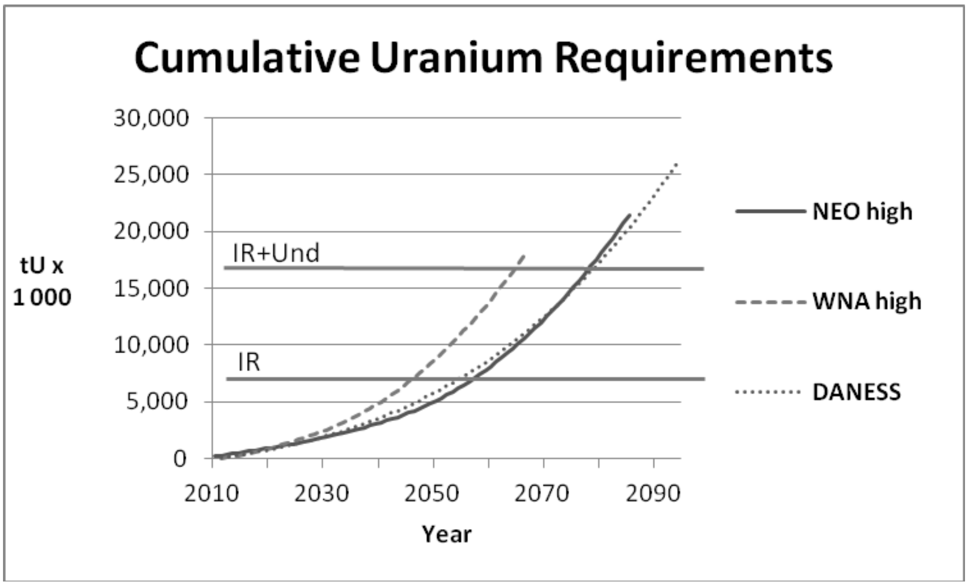


Figure 16. Evolution of cumulative uranium requirements under the NEO and WNA high case scenarios and the DANESS simulation of a ten-time increase in global nuclear generating capacity or electricity production.

(Blue horizontal lines demarcate levels of currently Identified and Undiscovered uranium resources)



The shape of the curves in the above two figures are determined by the rate at which nuclear generating capacity is added in the projection scenarios, since uranium requirements are held steady at 183.6 tU/GWe/year. For the WNA high case scenario projection, only three data points are provided (2030, 2060 and 2100) and steady growth rates are assumed between each of these data points. In the high case NEO scenario projection, data points are available for each year and the build-up in generating capacity is expected to be more rapid in the period from 2030 to 2050. Growth rates for this period are extended at a fixed rate to 2085 to allow global generating capacity to build up to the target figure of 3 720 GWe. The DANESS simulation described in the previous chapter indicates slightly more time would be required to build to the target capacity. Because the build-up rates to the target capacity vary in the three projections, reaching the requirements of 683 000 tU per annum figure is achieved at slightly different times.

Because of the variation in the build-up rates to the target of global nuclear generating capacity for this study, the 2007 total uranium resource base is consumed at slightly different rates, as depicted in Figure 16. Under the WNA scenario, Identified Resources are consumed by 2038, whereas in the NEA high case they are not completely exhausted until 2050. In the DANESS simulation, the uranium resource base would be exhausted by 2045. Adding Undiscovered Resources to Identified Resources stretches the exhaustion dates to 2060 in the WNA model, 2075 in the NEA model and 2074 in the DANESS simulation. Since reactors built during this ramp-up of capacity are expected to have lifetimes of 60 years or more, this indicates that even with a strong market and development of the 2007 total uranium resource base, it would appear that there is likely to be insufficient freshly mined uranium to fuel this expanded fleet of reactors on a once-through life cycle basis. In addition, yearly requirements of 680 000 tU or more would continue for several decades.

With strong uranium demand and consequent rising market prices underpinning the ramp-up of the generating capacity, unconventional uranium resources could contribute to the projected short-fall, potentially delivering as much as 22 million tU to the market. This would add another 35 years of fuel to a fleet of reactors with a generating capacity of 3 720 GWe. Although a significant increase, it is still not enough to provide fuel for the entire lifetime of reactors built in the latter years of this ramp-up to the ten-fold increase in nuclear generating capacity.

As noted by McMurray (2005), despite global historical exploration expenditures amounting to a total of about USD billion, "…there remain large areas around the world that are only sparsely explored. The answer to the question "have we found it all" is an emphatic no." He further notes that the list of potential exploration targets is long and that additions to the resource base will take place with exploration investment and experienced people using the investment wisely. Mudd and Diesendorf (2008) note that although uranium is commonly perceived to be a finite resource, the two previous periods of intense exploration (1940s and 1970s) stimulated by increasing demand resulted in the delineation of resources far in excess of what was required. Yet although there is a strong potential of identifying additional resources, it is not possible at this time to say where these conventional resources may be found and whether they can be economically extracted.

As discussed above, seawater is another possible source of uranium to fuel this expanded nuclear fleet, due to the large volume of uranium contained (over 4 billion tU) and its inexhaustible nature. However, because of the low concentration of uranium in seawater (3-4 ppb), and limited effort to date to develop the technology, recovery costs of current systems are too high to be competitive with freshly mined uranium. Regardless of the cost of production, development of a technology suitable for the large scale extraction of U from seawater will inform future fuel cycle decisions since the resource is so extensive that concerns about limited U supply, regardless of the fleet envisaged, will be eliminated. It is nonetheless possible that with rising prices at least some of these significant resources could be extracted. Although this could become an important source of uranium, production would have to be significant to satisfy an important part of the increased demand arising from such a large fleet of nuclear reactors considered. At this time, production on such a scale is not feasible.

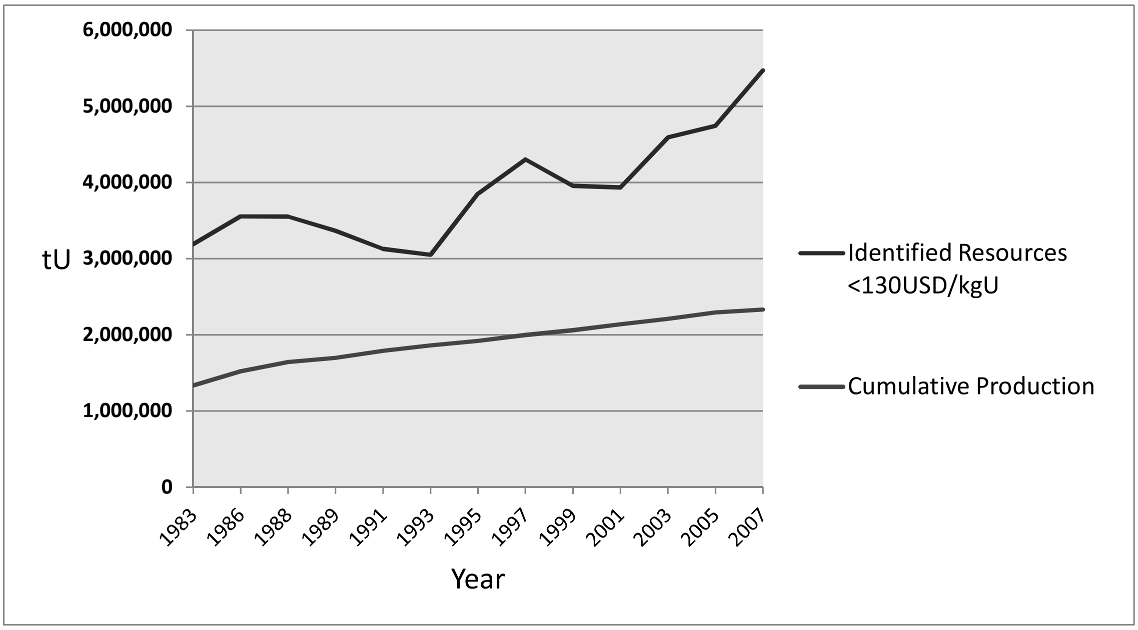
Uranium Resource Figures

One of the limitations of the approach described above is that the uranium resource base is treated as being static. That is, regardless of the year that the resource tally used was made, no consideration was given to the ability, and in times of increasing demand, the likelihood, that the uranium resource base will increase. In the past, more exploration has invariably led to the identification of more resources of economic interest. With the increase in uranium prices since 2003, known conventional resources increased by 3% in 2005 (NEA, 2006b) and an additional 15% in 2007 (NEA, 2008b). With continuing strong demand and high prices, there is no reason why such growth should not continue.

Uranium resource figures cited in the Uranium, Resources, Production and Demand series (NEA, 2006b and 2008b) are not estimates of the absolute amount of mineable uranium available in the earth's crust. Instead they represent that amount identified at a specific time based on the geographic extent of the exploration conducted to that date. Figures published at any given time are more a reflection of the amount of exploration that has taken place; not the absolute amount of mineable uranium available on planet earth. The uranium industry has only just recently emerged from a prolonged period of low prices, during which prices were too low to stimulate investment in exploration, with the exception of limited work in the immediate vicinity of operating mines and known deposits of economic interest.

The history of uranium mining illustrates the dynamic nature of uranium resource figures. As documented in the Red Book Retrospective (NEA, 2006a), over 2.3 million tU have been mined since 1945. However, the uranium resource base has not been depleted and in general has increased. Since 1983, the time that resource categories equivalent to those used today were adopted, resources have increased despite continuous draw-down by production, despite periodic declines in some categories during times when prices were low (Figure 17). Of particular note is the rapid increase in resources since the increase in market prices in 2003.

Figure 17. Evolution of uranium resources available at <130 USD/kgU compared to cumulative production



In terms of Identified Resources, it is also noteworthy that the figures provided in these global uranium resource assessments are conservative. In order to be included in this tally, a great deal of direct measurement and evaluation of each deposit is required, particularly when classifying by cost of production as required in the Red Book classification scheme. With as many as 600 junior companies recently involved in uranium exploration, in addition to the major producers, it is likely that significant resources are known that are not yet classified and reported, since it takes time, expertise and investment to conduct the required level of analyses to report figures by the standards required. On the other hand, a small portion of all the resources included in the tally are now not accessible for mining due to political decisions and public resistance.

In terms of the history of mineral extraction, uranium is a relative new commodity of interest. Large areas of countries with potential for uranium resources of economic interest have either not yet been explored or were explored only in a cursory fashion using outdated techniques. The potential for technological advances should not be overlooked. It has been estimated that only 25% of the current identified resource base in northern Saskatchewan could have been discovered in the first phase of exploration, since deep geophysical exploration techniques and geological models used in recent discoveries were not known in this earlier phase of exploration (MacDonald, 2003). Low prices have limited application of these techniques until only recently, but in the most recent phase of uranium exploration these techniques and models are being more widely used.

To add to the underestimation of resources, some countries have not been the subject of consistent and continuous assessment. For example, in the case of the United States, a significant portion of the resource base was some time ago classified as Estimated Additional Resources II (now termed Prognosticated Resources, part of the Undiscovered Resources category), owing to insufficient need to systematically assess the large volume of drilling results at that time. With reassessment, a portion of this total would likely be reclassified as Inferred Resources, leading to a potentially significant increase in Identified Resources in one country alone.

Prognosticated and Speculative Resources are also likely underestimated. These so-called Undiscovered Resources are estimated following procedures outlined in an IAEA Technical Report (IAEA, 1992). As noted above, some countries that host significant uranium resources (e.g. Australia, Namibia) do not report Undiscovered Resources. Others, because of many years of depressed demand and market prices, have not devoted sufficient effort and expertise to conduct systematic evaluations, in some cases for several years. The continuation of strong market conditions may motivate governments in these countries to increase efforts in this area. If so, additions to the category of Undiscovered Resources can be expected.

For these and other reasons, it can be concluded that published uranium resource figures likely significantly underestimate the size of the total global uranium resource. Although uranium resources are not unlimited, the exact size of the complete global resource inventory available for mining remains to be determined. Recent exploration efforts at Olympic Dam, site of the world's largest uranium deposit discovered to date provides an insightful case in point. Despite drilling continuously for two years with as many as 15 drilling rigs, it was not possible to define the entire extent of the deposit (Fitzgerald, 2006).

Uranium Production

In 2006, uranium was produced in 20 different countries; one more than in 2004 as the Islamic Republic of Iran started production in 2006. However, three of these countries (France, Germany and Hungary) only produced small amounts of uranium recovered during mine remediation efforts. Two countries, Canada and Australia, accounted for 44% of world production in 2006 and just eight countries, Canada (25%), Australia (19%), Kazakhstan (13%), Niger (9%), the Russian Federation (8%), Namibia (8%), Uzbekistan (6%) and the United States (5%), accounted for about 93% of world production in 2006 (NEA, 2008b).

Overall, world uranium production increased from 40 188 tU in 2004 to 41 943 tU in 2005 before declining by about 6% to 39 603 tU in 2006. Unofficial figures for 2007 indicate that uranium production increased to about 41 200 tU and is expected to increase further in 2008, perhaps to as much as 45 000 tU, as production is being ramped-up at existing centres and the new production centres are brought on line in response to higher prices.

The revived uranium market since 2003 has not only driven increased exploration activity and production it has also stimulated plans to expand existing production centres and to develop new ones. By 2020, if all of these plans come to fruition, uranium production could increase to over 100 000 tU/yr (NEA, 2008b). However, strong market conditions will be needed if these planned developments are to be commissioned in a timely fashion. It is important to note that mine development times (the time between discovery and first production) have increased considerably over the last several decades, in many jurisdictions now amounting to 10 years or more, one of the reasons that mine production cannot be expected to increase rapidly.

Although resources may not be a limiting factor in the longer term, given likely changes in the market associated with rising demand and as yet unrealised potential, there are significant challenges associated with increasing uranium production to over 680 000 tU/yr and sustaining that level of production for decades. Investment requirements in exploration and mine development will be significant, as will requirements to train personnel and develop infrastructure in remote regions not currently involved in mineral extraction. Technical issues will need to be overcome, as it is possible that new deposits will be located in more challenging geological settings for mining than is the case today. Should the deposit be low grade, significant challenges will arise in terms of waste management, simply because volume of waste increases as grades decline, except with production by ISL. Efficiencies will need to be developed to mine the low grade deposits in ways that minimise energy use and greenhouse gas emissions. And given the degree of public resistance to uranium mining today, much greater effort will be needed to demonstrate that these new large and potentially numerous mines do not pose significant hazards to people or the environment. Public resistance to uranium mining will need to be addressed in order to fully capitalise on the resources available. Although each one of these challenges can in theory be overcome, they are significant.

As mentioned above, there are also unconventional sources of uranium that could be developed to increase uranium supply, given strong demand and high prices. Phosphate producers in the United States are considering re-opening such operations and Jordan is considering beginning uranium production in this manner, given recent increases in uranium prices. Past estimates of uranium contained in phosphate rocks amount to as much as 22 million tonnes, although much exploration work is required to confirm this figure. However, the uranium potential of the extensive, near shore, continental shelf phosphate rocks has not generally been included in these assessments. The cost of producing uranium in this fashion was competitive with conventional mining operations in the past, and given strong demand and high prices for the commodity and the possibility of cost reducing technological breakthroughs, such extraction processes could be used in the future to provide additional sources of uranium.

The Potential Contribution of Secondary Sources

As noted above, uranium production has consistently exceeded commercial requirements (Figure 14) since the dawn of commercial nuclear power applications in the late-1950s through to about 1990, although details on the amounts mined were not initially publicly available for some countries. A more complete picture emerged following the political and economic reorganisation in Eastern Europe and the former Soviet Union in the early-1990s, as more information on the production and use of uranium in the former Soviet Union became available. However, some uncertainty remains regarding the magnitude of the inventories accumulated as well as the availability of uranium from other potential sources.

Data from past editions of the series "Uranium Resources Production and Demand" (NEA, 2006a), along with information recently provided by member states, provides a rough indication of the possible upper bound of potentially commercially-available inventories. Cumulative production through 2006 is estimated to have amounted to about 2 325 000 tU, whereas cumulative reactor requirements through 2006 amounted to about 1 700 000 tU (NEA, 2008b). This leaves an estimated remaining stock of about 625 000 tU, the upper limit of what could potentially become available to the commercial sector. This base of already mined uranium has essentially been distributed into two segments, with the majority used and/or reserved for the military sector and the remainder stockpiled by the civilian sector and government. Since the end of the Cold War, increasing amounts of uranium, previously reserved for the military, have been released to the commercial market. However, a significant portion of this element of the previously mined uranium inventory will for the foreseeable future likely be reserved for military purposes.

Civilian inventories include strategic stocks, pipeline inventory and excess stocks available to the market. Utilities are believed to hold the majority of civilian stocks because many have policies that require carrying the equivalent of one to two years of natural uranium requirements. Capus (2007) estimated excess commercial stocks to amount to 40 000 tU in 2005. Although commercial inventories are generally considered to be depleted of any sizeable excess, recent data suggest that they are actively being re-built (NEA, 2008b) although the strategy will likely evolve as utilities adjust stockpile levels according to changes in the price of uranium. As with material held by the military, the size of some government portions of these inventories is not well known, particularly in the Russian Federation. Although the inventory of enriched uranium product and natural uranium held by the Russian Federation is never officially reported, it is believed to be substantial.

Stocks of uranium, previously dedicated to military applications in both the United States and the Russian Federation, have been made available for commercial applications, introducing an important source of uranium to the market. Under the existing agreement between the United States and the Russian Federation, which ends in 2013, the equivalent of about 9 000 tU/yr in the form of low enriched uranium (LEU) is being delivered to the market by down blending highly enriched uranium (HEU) declared surplus by the military (NEA, 2008c). Pool (2007) estimates that when this program is completed about 40% of the Russian HEU will have been converted to LEU. Although there remains potential for additional quantities of HEU and natural uranium held in various forms by the military sector to become available to the commercial market, it is not possible to say with certainty how much or when such supplies could be released. Capus (2007) estimates that between 2005 and 2050 the equivalent of 96 000 tU arising from HEU in the United States and the Russian Federation could be delivered to the commercial market.

A recent overview of inventories of recyclable fissile and fertile materials, based on a literature survey and estimates by experts (NEA, 2007), concludes that a considerable amount of previously mined uranium is already currently or potentially available to the commercial market. As of the end of 2005, the total inventory of separated recyclable fissile materials amounted to 645 000 t natural U equivalent. This total is comprised of 230 tHM of ex-military HEU (70 000 tU equivalent), 70 tHM of ex-military plutonium (Pu; 15 000 tU equivalent), 320 tHM of Pu (60 000 tU equivalent), 45 000 tHM of reprocessed U (50 000 tU equivalent), and 1 600 000 tHM of enrichment tails (450 000 tU equivalent). Although converting enrichment tails, the most significant portion of this inventory, to reactor fuel would require a significant ramp-up of existing conversion and enrichment capabilities, this category alone could potentially contribute as much as 450 000 tU to fuel the growth of nuclear generating capacity considered in this study. While not insignificant, this amount is less than 1 year of fuel supply in the latter years of the nuclear generating capacity build-up envisioned in this study. Capus (2007) notes however that the most economic portion of this tails inventory, the “rich” portion, amounts to a maximum of about 110 000 tU equivalent.

This inventory does not include possible future programs to convert additional surplus military HEU and Pu to forms suitable for commercial reactor fuel (the figures cited above include only the HEU and Pu currently committed for conversion to reactor fuel by the military). Also not included is some 200 000 tHM of spent fuel currently in storage awaiting final disposition. It is estimated that the current inventory of spent fuel contains potentially re-useable fissile material amounting to some 1 700 t of Pu and 190 000 tU equivalent that could be recycled with current reactor and fuel cycle technology (NEA, 2007). In 2008, reprocessed and recycled uranium and plutonium provided the equivalent of 3 000 tU/yr, while tails re-enrichment provided the equivalent of about 2 000 to 3 000 tU/yr (NEA, 2008c), less than 10% of global demand.

Efficiencies of Uranium Use, Reprocessing and Recycling

As outlined by Tourbach (2007), if the LWR reactor fleet described in this study adopted operating efficiency procedures, as well as reprocessing and recycling practises, significant uranium savings could be achieved, amounting in his scenario to as much as:

- 5% by extending the burn-up and fractional loading,
- 20% by reducing the ^{235}U content in depleted uranium (i.e. specifying lower uranium tails assays)
- 20% by recycling the irradiated uranium and plutonium,
- 5 to 10% by improving the reactor performance (heavy reflector, thermal efficiency, etc.), and
- 5 to 10% by improving the conversion ratio in the reactor.

This is not the total savings that could be achieved by these practices; only the amount that could be achieved as outlined in Tourbach’s scenario. Nonetheless, it shows that the introduction of these practices, regardless of timing, could lead to a considerable extension of the time that existing uranium resource base could provide fuel for an enlarged fleet of existing designs. It is likely that all available savings would be required to continue to fuel the expanded nuclear fleet along with significant investment (e.g. producing reprocessed uranium requires dedicated conversion and enrichment facilities).

However, if the reactor fleet envisaged is comprised of increasing numbers of fast neutron reactors (FRs), potentially from Gen IV designs currently under development (see Section 6.3), at some point uranium requirements would begin to decline as these designs are commercialized and deployed, even as nuclear generating capacity is being built-up. Several Gen IV designs are being developed to produce more fuel than they consume (in theory capable of producing as much as 60 times more fuel than they consume through multiple reprocessing and recycling options). However, before these multiple fuel cycles and advanced designs can be deployed, considerable research effort and financing must be devoted to the development and demonstration of safe and economic operations of these designs currently under development.

Tourbach (2007) considers the adoption of such measures in a study of fuel requirements and CO_2 emissions reductions achieved through an aggressive development scenario of a global nuclear generating capacity rising to 3 130 GWe by 2050 and 9 150 GWe by 2115. Assuming uranium consumption of 180 tU/yr/GWe for Gen II (1970s) reactors and 10% less for Gen III designs (evolutionary designs marketed today), a 0.20% tails assay and a fleet comprised entirely of 1 000 MWe reactors, uranium consumption is shown to rapidly increase to the point that the 2005 uranium resource base (NEA 2006b), both conventional and unconventional, is consumed between 2055 and 2075. The recommended development scenario considers that an overall 40% reduction of U consumption could be achieved as early as 2015 by reducing tails assays from 0.25% to 0.10% (a 20% saving), reprocessing and re-enrichment of used nuclear fuel (10% saving) and recycling Pu through the use of MOX fuel (10% saving). In this fashion, U requirements are reduced to 100 tU/GWe/yr. In addition, with the introduction of Gen IV reactors by 2045, and their exclusive construction from 2055 onwards, uranium requirements are seen to be eventually reduced to negligible quantities.

As noted in Section 2 above, Nordostschweizerische Kraftwerke AG (NOK) recently (2008) produced a certified EPD® of electricity produced at the Beznau nuclear power plant in Switzerland. This EPD® provides information on the impact that reprocessing and recycling can have on uranium requirements. During the 2006/07 reference year for the EPD®, NOK utilised a mixture of fuels for the reactor: conventional UO_2, mixed oxide fuel (MOX), and enriched reprocessed uranium fuel derived from the downblending HEU declared surplus by the former Soviet Union to LEU suitable for use in civil light water reactors like Beznau. Over 75% of the fuel used in Beznau during the reference year was from the latter two categories of recycled material. As a result, annual uranium requirements at Beznau (35 tU/GWe) are more than four times less than Ringhals (145 tU/GWe), where no recycled uranium is used (a small amount of re-enriched uranium, <0.01% of the uranium used to fuel the Ringhals NPS, is used in other NPPs supplying electricity to the nuclear fuel cycle in the Vattenfall supply chain).

In summary, U requirements for the rapidly expanded nuclear fleet considered in this report could be reduced from 683 000 tU/yr to about 273 000 tU/yr or more by adopting operating efficiency procedures, as well as reprocessing and recycling practises. Existing inventories of some 650 000 tU equivalent would also help fuel the greatly expanded fleet considered in this report, but not for more than a few years. Implementing either one of these options would require significant investment.

Thorium

Thorium is a naturally-occurring, slightly radioactive metal, which can be found in small amounts in most rocks and soils, where it is about three times more abundant than uranium. Soil commonly contains an average of around 6 parts per million (ppm) of thorium. Like uranium, thorium can be used as a nuclear fuel. Although not fissile itself, ^{232}Th will absorb thermal neutrons to produce ^{233}U, which is fissile (and long-lived). The used fuel can then be unloaded from the reactor; the ^{233}U can be chemically separated from the thorium and be used as fuel for another reactor.

Thorium fuel has better thermal and physical properties as well as irradiation performance than uranium fuel. The melting point of thorium dioxide is, for example, about 500 °C higher than that of uranium oxide. This difference allows having higher temperatures in the reactor core and provides an added margin of safety in the event of a temporary power surge or loss of coolant in a reactor. Another possible advantage of the thorium fuel cycle is related to the long term management of spent-fuel. A smaller quantity of high level, spent fuel with fission products that have shorter half-lives is produced by thorium fuel cycles in comparison to the uranium-plutonium fuel cycles. This results into less demand for the repository lifetime as well as space requirements. In addition, spent thorium fuel includes ^{232}U, which is radioactive through the emission of gamma rays. This makes it difficult to divert thorium for non-peaceful purposes.

However, there are some significant challenges associated with the thorium fuel cycle. In the case of an open cycle, the main issue is the long breeding interval of the thorium cycle (conversion of ^{232}Th to ^{233}U through ^{233}Pa) compared to the uranium cycle (conversion of ^{238}U to ^{239}Pu through ^{239}Np). This leads to the accumulation of ^{233}Pa because it has a relatively long half-live (26.9 days) that is significantly longer than that of ^{239}Np. ^{233}Pa is a significant neutron absorber and thus spoils the quality of the fuel.

In the case of the closed thorium cycle, the main issue is the strong gamma emission of ^{228}Th daughter products. ^{228}Th is a daughter product of ^{232}U and thus the issue of strong gamma-emitters is present both in the case of thorium and uranium recycling. The most energetic gamma rays are produced by ^{208}Tl (2.6 MeV). Thus, remote handling would be necessary for fuel fabrication of recycled materials in a closed thorium cycle.

The most common source of thorium is the rare earth phosphate mineral monazite, which can contain up to about 12% thorium, although content typically averages about 6-7%. Monazite is found in igneous and other rocks but the richest concentrations are in placer deposits, concentrated by wave and current action with other heavy minerals. World monazite resources are estimated to be about 12 million tonnes, two-thirds of which are in heavy mineral sands deposits on the south and east coasts of India. There are also substantial deposits in several other countries (Table 6). Thorium recovery from monazite usually involves leaching with sodium hydroxide at 140°C followed by a complex process to precipitate pure ThO_2.

The publication *Uranium 2007: Resources, Production and Demand* (NEA, 2008b) provided a figure of 4.4 million tonnes of total known and estimated resources thorium, but it is recognised that this is not inclusive. Data for reasonably assured and inferred resources recoverable at a cost of USD 80/kg Th or less are provided in Table 6, although it should be noted that some of the tonnages of Th listed are based on assumptions and surrogate data for mineral sands, not direct geological data in the same way as most mineral resources.

Over the last decades there has been interest in several countries to use thorium as a nuclear fuel since it is more abundant in the Earth's crust than uranium. Basic research and development as well as operation of reactors with thorium fuel have been mostly conducted in Germany, India, Japan, Russia, the UK and the USA. Some examples of experience with thorium fuel include:

- Germany : The 15 MWe AVR (Arbeitsgemeinschaft Versuchsreaktor) experimental pebble bed reactor at Jülich operated between 1967-1988 partly as a test bed for various fuel pebbles, including thorium. The 300 MWe THTR (Thorium High Temperature Reactor) in Germany was developed from the AVR and operated between 1983 and 1989 with 674 000 pebbles, over half containing Th/HEU fuel. In addition to these high temperature reactors thorium fuel was tested at the 60 MWe BWR in Lingen.

Table 6. Estimated world thorium resources

(Reasonably assured and inferred resources recoverable at up to USD 80/kg Th)

Country	**Tonnes**	**% of total**
Australia	489 000	19
USA	400 000	15
Turkey	344 000	13
India	319 000	12
Venezuela	300 000	12
Brazil	302 000	12
Norway	132 000	5
Egypt	100 000	4
Russia	75 000	3
Greenland	54 000	2
Canada	44 000	2
South Africa	18 000	1
Other countries	33 000	1
World total	**2 610 000**	

- UK: Thorium fuel elements with a 10:1 Th/U (HEU) ratio were irradiated in the 20 MWth Dragon reactor at Winfrith, UK, for 741 full power days. Dragon was run between 1964 and 1973 as an OECD/Euratom cooperation project, involving Austria, Denmark, Sweden, Norway and Switzerland in addition to the UK.

- USA: Thorium fuel was tested in one light water reactor (Shippingport) and two gas-cooled reactors. Shippingport operated as a Light Water Breeding Reactor between August 1977 and October 1982, when the station was finally shut down. General Atomics' Peach Bottom high-temperature, graphite-moderated, helium-cooled reactor in the USA operated between 1967 and 1974 at 110 MWth, using high-enriched uranium with thorium. The Fort St Vrain reactor, the only commercial thorium-fuelled nuclear plant in the USA, was a high-temperature (700°C), graphite-moderated, helium-cooled reactor with a Th/HEU fuel designed to operate at 842 MWth (330 MWe). The fuel was arranged in hexagonal columns ('prisms') rather than as pebbles. Almost 25 tonnes of thorium was used as fuel for the reactor, and this achieved 170 GWd/t burn-up.

- Canada: AECL has more than 50 years experience with thorium-based fuels, including burn-up to 47 GWd/t. Some 25 tests have been performed in three research reactors and one pre-commercial reactor.

- India: The Kamini 30 kWth experimental neutron-source research reactor using ^{233}U started up in 1996 near Kalpakkam. The ^{233}U was recovered from ThO_2 fuel irradiated in another reactor. The Kamini reactor was built adjacent to the 40 MWt Fast Breeder Test Reactor, in which the ThO_2 is irradiated.

Hence, the development and introduction of the thorium fuel cycle with reprocessing offers another potential to meet the high demand for fissile material as specified in the hypothetical rapid growth scenario of this report.

Conclusion

Identified conventional uranium resources (NEA, 2008b) would not be sufficient to fuel lifetime reactor requirements for a rapid ten-time expansion of nuclear generating capacity in the 21st century. The uranium resource base would, however undoubtedly increase and unconventional resources could be brought into production should market prices increase, as would be expected by demand created by such a rapid expansion of nuclear generating capacity.

However, it will be a significant challenge to increase and sustain production of over 680 000 tU/yr, as required by fuel requirements arising from the hypothesized increase in nuclear generating capacity using a once-through fuel cycle exclusively. In addition, dealing with spent fuel produced by such a sizeable build-up of nuclear reactors exclusively employing a once-through fuel cycle (Figure 13) would also pose significant challenges. Public attitudes toward nuclear power and uranium mining would have to improve to accommodate such a rapid rate of growth in nuclear power and the associated fuel cycle facilities.

Implementing reactor operational efficiencies combined with more widespread adoption of reprocessing and recycling practices as well as the use of thorium as fuel could significantly ease fuel and waste disposal requirements of the expanded nuclear fleet considered in this study. Existing stocks of recyclable fissile materials could also contribute to meeting fuel requirements. However, significant investment would be required to facilitate such efforts, in particular to develop new fuel cycle facilities needed to use thorium as nuclear fuel.

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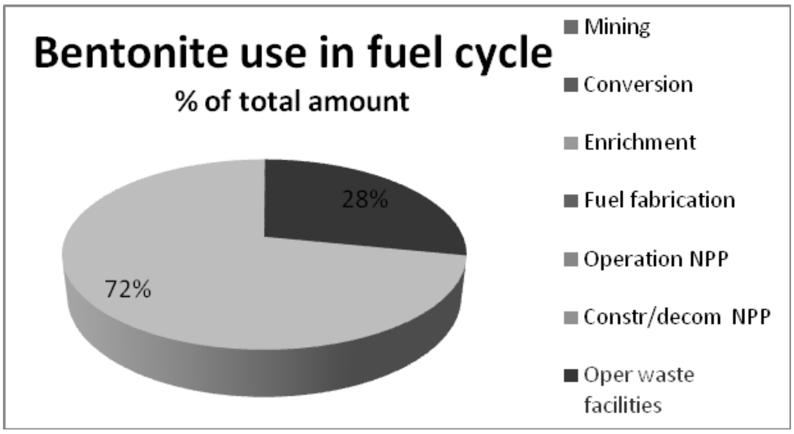
OTHER RAW MATERIALS OF CONCERN

In addition to uranium, other raw materials identified in the EPD®-based list of material requirements, although not in short supply, would take a significant share of the current global production capability under a rapid ten-time expansion of global nuclear generating capacity. Materials falling in this category (Table 4) are bentonite (86.2% of current production), fluorite (24.8%), indium (22.7%), fluorspar (11%), manganese (8.3%) and gadolinium (4.5%). It is important note that the material requirements for a ten-time expansion of nuclear energy would accumulate over several decades and the percentages cited above are based on current rates of production. Resources tend to grow with increased demand, as does production. It is nonetheless important to consider the uses of these materials in the nuclear fuel cycle, current resource estimates, production rates, and possible competing uses outside of the nuclear fuel cycle. Like uranium, the production of all of these materials is market based and with appropriate signals, exploration and production would likely be increased should the rapid build-up in nuclear generating capacity take place over the coming decades as outlined by the development scenarios discussed above.

Bentonite

Under the EPD® based requirement scenario for an overnight ten-time expansion of global nuclear generating capacity, bentonite requirements would amount to over 85% of the current rate of production, although resources are so large that even this level of demand would not significantly impact currently defined global resources. As noted in Figure 18, bentonite requirements, as documented in the Vattenfall AB (2007) EPD®, arise entirely at the back end of the fuel cycle (during the construction, decommissioning and operation of the waste facilities). Hence, these requirements would be spread out over several decades or longer, given the pace of development of these facilities and the ability to safely store spent fuel at reactor sites while spent fuel repositories are developed and commissioned. The complicating factor however is the requirement for bentonite with specific properties to be used in waste storage facilities.

Figure 18. Proportionate use of bentonite in the nuclear fuel cycle for the Ringhals NPS



Bentonite is a clay material that is typically generated by the alteration of volcanic ash. It consists predominantly of smectite minerals, usually montmorillonite. The special properties of bentonite (hydration, swelling, water absorption, viscosity, thixotropy) make it a valuable material for a wide range of uses and applications. These include cat litter, bonding material in the preparation of moulding sand for the production of iron, steel and non-ferrous casting, a binding agent in the production of iron ore pellets, a support and lubricant agent in diaphragm walls and foundations, in tunnelling, in horizontal directional drilling and as a component of Portland cement and mortars. It is also used for wastewater purification and as a sealing material in the construction and rehabilitation of landfills to ensure groundwater protection. Another conventional use of bentonite is as a mud constituent in drilling where it is used to seal borehole walls, remove drill cuttings and lubricate the cutting head. Bentonite is also used to remove impurities in oils and as a clarifying agent in beer, wine, mineral water and products such as sugar or honey.

Bentonite is also used in agricultural processes as an animal feed supplement and in the production of animal feed pellets. It is used to improve and condition soil and has pharmaceutical applications, where it is used as filler and to make pastes, an antidote in heavy metal poisoning and as a component of personal care products. It is a component of laundry detergents, liquid hand cleansers/soaps, as well as paints, dyes and polishes. It is also a crucial component in manufacturing and recycling paper and as a catalyst, for example in the production of fuel additives (Industrial Minerals Association of North America, http://www.ima-na.org/bentonite).

Since the volume of bentonite increases several times in contact with water, creating a gelatinous and viscous fluid, it is considered an important material in plans for deep geological disposal of nuclear waste, including high-level waste. Bentonite has been identified as the preferred material for the engineered barrier in a Japanese disposal system owing to its low permeability, high swelling capability and high adsorption capacity. These properties address aspects of the envisioned system, such as buffering chemical conditions, dissipating decay heat, supporting overpack and buffering external stress over a long period of time (Kurosawa and Ueta, 2001).

The high level waste disposal concept developed in Sweden involves deep burial in water-saturated granite, with spent fuel placed in copper canisters lined with titanium and deposited in a chamber surrounded by a bentonite buffer. The buffer protects the canister against small movements in the rock while holding it securely in place. Since the bentonite buffer absorbs water while swelling it further protects the canisters from contact with groundwater. The bentonite could also reduce radioactive releases, acting as a filter since radionuclides bind to the surface of the clay particles (Petterson and Widing, 2003).

A bentonite buffer helps ensure that groundwater movement is negligibly slow, fills gaps between the waste and the surrounding host rock, seals cracks in the host rock, controls temperature increases caused by radionuclide decay, maintains a proper pH and redox potential in pore water and controls the accumulation of corrosion products from the metal canisters.

Since bentonite also finds uses in many other applications and the disposal of spent fuel arising from a global nuclear generating capacity expansion considered in this report would account for a majority share of current production capacity, it would appear to represent a raw material constraint. However, since bentonite resources are considered to be “extremely large” (United States Geological Survey (USGS), 2000), no limitation to ramping up production is apparent, given appropriate market signals, provided that additional sources of bentonite with specific qualities required in waste facilities can be identified. This type of bentonite is currently restricted to one location, but other locations are being investigated for suitable supply sources (Swedish Nuclear Fuel Waste Management Company (SKB), 2006).

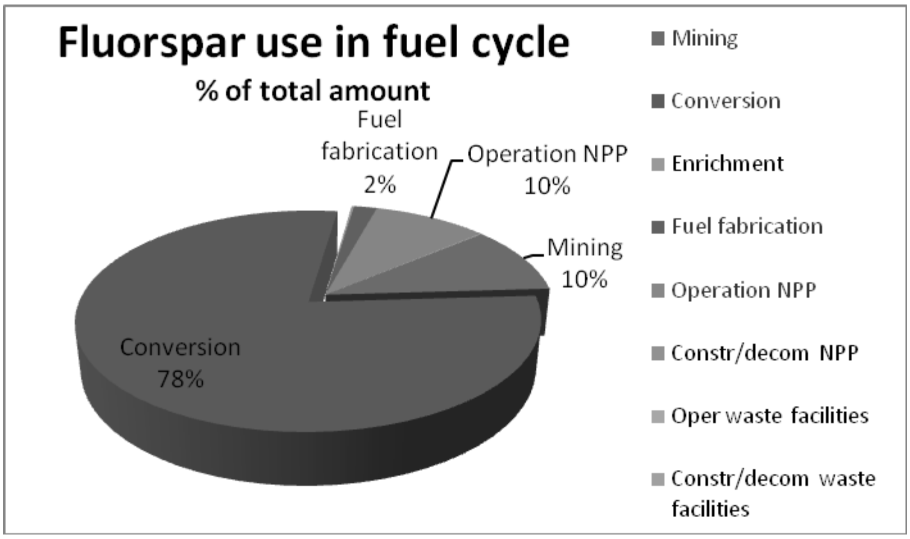
Flourite/Flourspar

The term fluorspar refers to crude or refined material that is mined and/or milled from the mineral fluorite (calcium fluoride). A ten-time expansion of global nuclear generating capacity would result in almost 25% of current fluorite production and 11% of current fluorspar production being consumed by the nuclear industry. Since these two raw materials are closely related, they are considered together in this section.

It is common to describe concentrates of fluorite sold as metallurgical grade (97% or less calcium fluoride) or acid grade (more than 97% calcium fluoride). Most acid-grade fluorspar goes toward making hydrofluoric acid and aluminium fluoride which together accounted for about 90% of acid-grade consumption in 2002 (Millar, 2003). The major use for hydrofluoric acid is manufacturing various fluorocarbon chemicals that are used as refrigerants, foam-blowing agents, solvents and producing high-performance plastics. Metallurgical-grade fluorspar is used primarily in steelmaking, but may also be consumed in cement, enamels, glass and fiberglass, iron and steel castings, and welding rod coatings.

Hydrofluoric acid (HF) is the primary feedstock for the manufacture of virtually all organic and inorganic fluorine-bearing chemicals and is a key ingredient in the processing of aluminum and uranium. A few thousand tonnes (t) per year of synthetic fluorspar are recovered primarily from uranium enrichment, but also from petroleum alkylation and stainless steel pickling in the United States. Primary aluminum producers recycle HF and fluorides from smelting operations. HF is recycled in the petroleum alkylation process (USGS, 2007). As noted in Figure 19, fluorspar is used in front end processes and the operation of the NPP.

Figure 19. Proportionate use of fluorspar in the nuclear fuel cycle for the Ringhals NPS



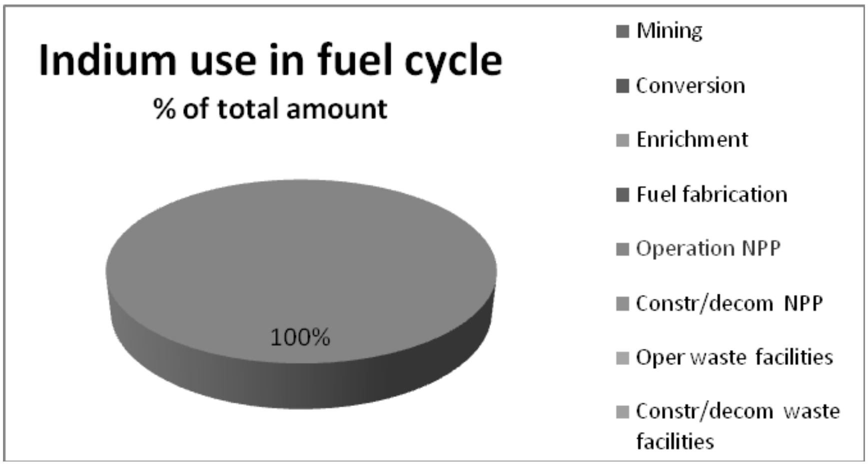
As is the case for bentonite, world resources of fluorspar are large (over 500 million t of contained fluorspar) and the amount of fluorine contained in phosphates is termed “enormous” (Millar, 2003). Production rates envisaged under this scenario of nuclear generating capacity growth would not impact the existing resource base, taking less than 1%. In addition, olivine and/or dolomitic limestone have been used as substitutes for fluorspar and by-product fluorosilicic acid derived from phosphoric acid production also has the potential to be used as a substitute in HF production, the principle material derived from fluorite that is used in the nuclear fuel cycle (Vattenfall AB, 2007). With increased demand and appropriate market signals, it would appear that production could be increased to meet increased nuclear fuel cycle demand.

Indium

The principle use of indium in the nuclear fuel cycle (Figure 20) is as an alloy component of control rods (e.g. 80% silver, 15% indium and 5% cadmium) owing to its high neutron capture cross section in thermal neutrons (http://en.wikipedia.org/wiki/Indium). However, the principle use of indium today, accounting for growing demand, is the production of thin-film coatings that are used in the manufacture of liquid crystal displays (LCDs) for flat-panel video screens. Indium semiconductor compounds are also used in infrared detectors, high-speed transistors, and high-efficiency photovoltaic devices.

Indium is a rare element that ranks 61st in abundance in the Earth's crust and the global resource base amounts to about 6 000 t (Tolcin, 2007). It occurs predominantly in the zinc-sulfide mineral, sphalerite and the average indium content of zinc deposits from which it can be recovered economically ranges from less than 1 part per million to 100 parts per million. Although indium occurs with other base metals—copper, lead and tin—and to a lesser extent with bismuth, cadmium and silver, in most of these types of deposits indium cannot be mined economically. A ten-time increase in nuclear generating capacity would require over 22% of the current global production of the element and consume almost 2% of the existing resource base. As documented in the Ringhals EPD® data, 100% of indium use in the fuel cycle is in the operation of the plant through the consumption of control rods.

Figure 20. Proportionate use of indium in the nuclear fuel cycle for the Ringhals NPS



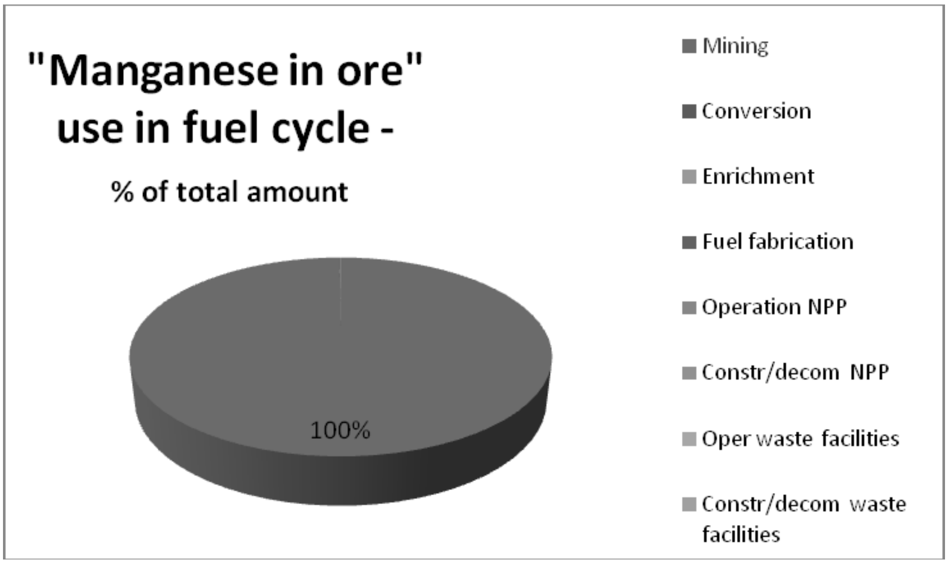
Given its relatively rarity and applications in sectors outside of nuclear fuel cycle that are principally responsible for rising demand, indium supply could be an issue with a rapid increase in nuclear generating capacity. However, hafnium can be used as a replacement for indium alloys in control rods and indium recycling opportunities are being pursued.

Manganese

Manganese is a brittle, grey-white metal that is used to make steel alloys, adding toughness, hardness and resistance to abrasion. It is also used in the manufacture of iron and aluminium alloys, alkaline batteries and as a treatment for rust and corrosion prevention. There is no satisfactory substitute for manganese and demand for manganese is driven by aluminium and steel making. Manganese recycling is rarely practised (Corathers, 2006).

As documented in the Ringhals EPD® data (Vattenfall AB, 2007), 100% of the manganese in ore is used in the mining phase of the fuel cycle (Figure 21). Under a ten-time expansion of nuclear generating capacity, use in the nuclear fuel cycle would require over 8% of current manganese production. In mining, manganese is used in a variety of applications, from specialised mill equipment like ore crushers and conveyer belts to heavy equipment components such as drag lines, caterpillars and trucks. Here, manganese offers a longer lifespan and improved performance when incorporated in equipment manufacture. Moreover, manganese dioxide is used as an oxidant in processing uranium ore, depending on the mineralogical characteristics of the ore. In the two mines used to source uranium for the Ringhals NPP, Rössing in Namibia (Johnson, 1990) and Olympic Dam in Australia, manganese dioxide is used as an oxidant in the milling process in order to maximise production efficiency.

Figure 21. Proportionate use of manganese in the nuclear fuel cycle for the Ringhals NPS



The global manganese resource base is large, amounting to over 5 billion t (Corathers, 2006). South Africa accounts for about 80% of the world's identified resources, and Ukraine accounts for about 10%. With increased demand and appropriate market signals, it would appear that production could be increased to meet increased nuclear fuel cycle demand.

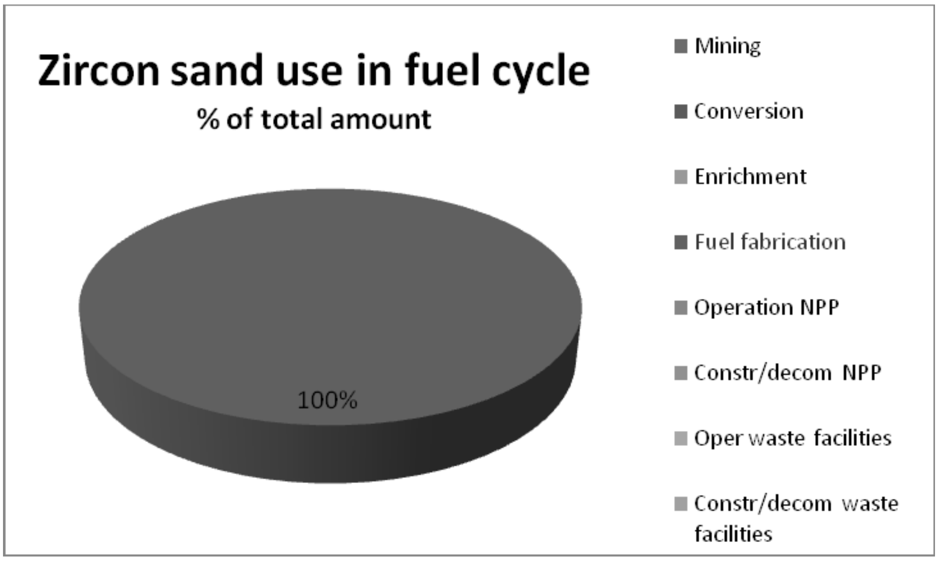
Zircon sand

Zircon sand is refractory mineral composed mainly of zirconium silicate ($ZrSiO_4$) that exhibits properties of low thermal expansion and high thermal conductivity. It is found throughout the world, normally being recovered as a co-product or by-product of the mining and processing of heavy-mineral sands by dredging and dry mineral processing (Gambogi, 2007).

Zircon sand is mainly used in the ceramics industry as an additive in glazes used on ceramic tiles, as a specialised refractory material, foundry sand, a component of the manufacture of faceplate panels for colour televisions and computer monitors to absorb x-rays generated from cathode tubes, as well as a number of smaller market uses, including the cladding for uranium oxide fuel (Kogel *et al.*, 2006).

In order to be used for nuclear fuel cladding (Figure 22), it must be purified to remove hafnium, which absorbs neutrons much more effectively.

Figure 22. Proportionate use of zircon sand in the nuclear fuel cycle for the Ringhals NPS.



Since all zircon sand is produced as a by-product of titanium production, zircon supply is heavily dependent on titanium demand, even though recent applications have increased demand for zircon sand considerably. Supply is tight and oriented toward applications in the ceramics industry, since this sector consumes over 50% of production. Recycling of zirconium is practised, but only on a limited scale. Columbium (niobium), tantalum and stainless steel can be used as substitutes in nuclear applications on a limited scale. Given its widespread distribution and the fact that an overnight ten-time expansion of nuclear energy would require less than 7% of current production and much less than 1% of the existing resource base, with appropriate market signals it would appear that sufficient quantities of zirconium could be produced to meet the requirements of an expanded nuclear power plant fleet.

Gadolinium

Gadolinium is a silvery-white, malleable and ductile metal, part of the lanthanide series of rare-earth elements (Hedrick, 2006). The rare-earths are a moderately abundant group of elements that typically occur as carbonate, oxide, phosphate, and silicate compounds. Gadolinium occurs in nature in salts and especially as the oxide gadolinia or the mineral gladolinite. It is one of the more abundant rare-earth elements and is contained in many rare minerals. It is mined mainly in China, USA, Brazil, Sri Lanka, India and Australia.

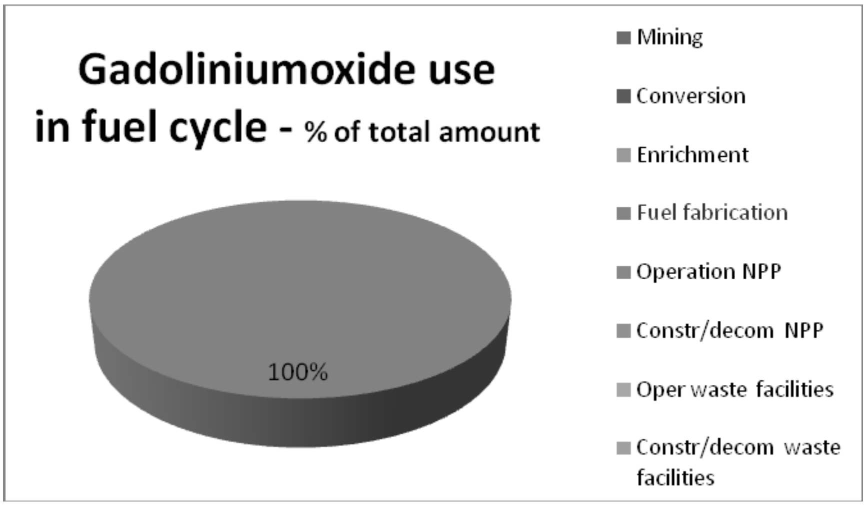
Gadolinium is rarely used in its metallic form, but its alloys are used to make magnets and electronic components such as heads for video recorders. It is also used for manufacturing compact disks and computer memory, in microwave applications and as phosphors in colour television sets. It also has medical uses, such as an injectable contrasting agent in magnetic resonance imaging.

Because gadolinium absorbs neutrons more effectively than any element, caused by two isotopes that are present only to a limited extent in natural gadolinium (The Columbia Encyclopedia, 2008), it is used in nuclear reactor control rods (Figure 23). It has also been used as a “poison” in nuclear fuels in some reactor designs to control the initial rapid reaction and “burning out” as the reaction proceeds.

The annual amount of gadolinium used in the reactors of the French nuclear fleet amounts to about 1 tonne, 200 kg of which are loaded in fuel assemblies for the CP0 reactors. At 2006 electricity production of 428.7 TWh, this amounts to about 4.67E-07 g/KWh, slightly less than the amount consumed at the Ringhals NPS (6.07E-06). Each REP 900 CP0 fuel assembly contains between 1.4 kg and 1.8 kg of gadolinium. Each reload contains 28 assemblies. Each REP 1 300 fuel assembly contains between 1.6 kg and 2 kg of gadolinium and each reload contains 24 assemblies (Loaëc, 2008).

Given its relative abundance and the fact that it consumption would require less than 5% of current production capability under a ten-time expansion of nuclear generating capacity, gadolinium is not considered raw material in short supply under the hypothetical expansion of nuclear energy considered in this report.

Figure 23. Proportionate use of gadolinium in the nuclear fuel cycle for a Ringhals PWR reactor



Resource information on aluminium, clay, calcite, carbon, sodium hypochlorite, soil, sulphur, volcanic rock, lignite and peat was not available, presumably because these substances are abundant and that for some no market exists. Production information was not available for clay, calcite, gravel and sand, gypsum, kieserite, olivine, quartzite, rock, salt, shale, sodium hypochlorite, sodium sulphate, sulphur, talc, volcanic rock, lignite and peat. Most of these substances are however relatively common.

No production and resource information was available for boron carbide. This is produced fusing boric oxide and carbon. Production of boron oxide is included in Table 4 and since requirements for a ten-time expansion of nuclear generating capacity would consume <2% of current production capacity it is not considered to be a raw material of concern. Boron carbide is however an important component of the nuclear fuel industry as it is used for shielding and is a component of control rods.

Conclusion

In all cases of raw materials of concern, resources are large and with appropriate market signals there is little available evidence at present to suggest that production could not be increased to meet rising requirements for use in the nuclear fuel cycle under a scenario of rapid expansion. There are also opportunities to increase re-cycling above what is practised today.

In addition, indium and zirconium have possible substitutes and even though bentonite with specifications required for use in spent nuclear fuel repositories is not particularly abundant today, the resource base is considered so vast that it is likely other sources of the bentonite with the required properties can be identified. And although gadolinium is a rare earth, it is one of the more common elements of this group and sources are widespread, although competition for use in computer applications may become more important.

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LAND AND WATER

In addition to raw materials required for the full life cycle of a NPP, two additional natural resources, land and water, must also be considered in nuclear energy lifecycle (cradle-to-grave) material requirement analyses. Comparisons with land and water requirements for other competing sources of electricity production (e.g. fossil fuels and renewable energy) provide a useful starting point as they help place nuclear technology requirements for these resources in perspective.

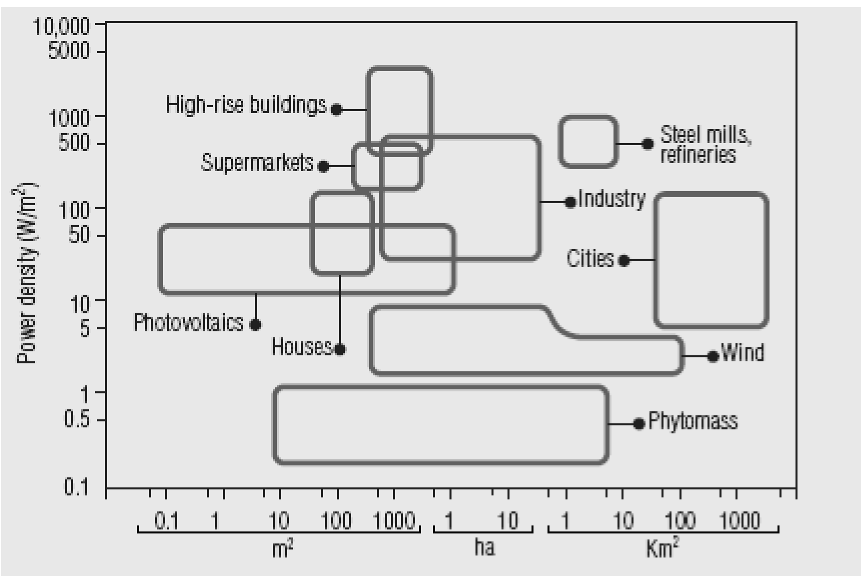
Land Requirements

The extent of land covered by the power plant and the infrastructure necessary to sustain its operation across its lifecycle are important indicators of the environmental impact of any energy technology. In contrast to pre-industrial agricultural societies, critical natural resources such as land requirements have been largely ignored as factors of production for some time in the energy intensive societies of the mid and late 20th century.

Power Densities in Generation

A revealing illustration of land requirements for modern energy generation and use is a comparison of power densities for renewable energy sources with those that rely on fossil fuels. As can be seen from Figure 24, in no case does the average power generation density of renewable energy sources (for example, photovoltaics, phytomass and wind) surpass $10W/m^2$, although solar heat collectors come close to this value in sunny locations.

Figure 24. Comparison of power densities of energy consumption and energy generation by renewable (Smil, 2006)



In contrast, thanks to the lengthy periods involved in their formation, fossil fuel deposits are an extraordinarily concentrated source of energy. Extraction of fossil fuels such as coal, crude oil and natural gas allows power generation with power densities ranging mostly between 10^3-10^4 W/m^2. Thus, comparatively small land areas are needed to supply huge energy flows.

Nuclear is even several orders of magnitude more "compact" in its power density: enriched uranium undergoing nuclear fission in PWR reactor cores achieves power densities of ~100 MW/m^2 (10^8 W/m^2).

Power Densities in Consumption

With today's conversion and efficiency technologies, the electricity supply chain works by producing (fossil fired) power with densities that are 1-3 orders of magnitude higher than the common power densities with which houses, industrial installations, energy intensive industries and entire cities use energy. Typical consumption power densities range mostly between 20 and 100 W/m^2 for houses and low energy intensity manufacturing industries (Figure 24).

In a fully solar-based society using today's civil and industrial infrastructures, various renewable energies would be harnessed with at best the same power densities with which they would be used in our buildings and factories. Consequently, in order to supply a house with electricity, PV cells would have to cover the entire roof. A supermarket would require a PV field roughly ten-times larger than its own roof, or 1 000 times larger in the case of a high-rise building. In other words, a transition to renewable energy would greatly increase the fixed land requirements of energy production and would also necessitate more extensive right-of-ways for transmission.

Land Requirements for Different Generation Technologies

The high power densities of fossil and nuclear fuels mentioned above enable relatively small power plant areas of some several km^2. In contrast, the low energy densities of renewables, measured by land requirements per unit of electricity produced, is demonstrated by the resulting large land areas required for a 1 000 MWe generation technology with values determined by local requirements and climate conditions (solar and wind availability factors ranging from 20-40%) (Smil, 2006):

- Fossil and nuclear sites: 1-4 km^2 (corresponding to: 250-1 000 W/m^2).
- Solar thermal or PV parks: 20-50 km^2 (about the size of a small city; corresponding to: 20-50 W/m^2).
- Wind fields: 50-150 km^2 (corresponding to: 7-20 W/m^2).
- Biomass plantations: 4 000-6 000 km^2 (corresponding to: 0.2-0.25 W/m^2).

For solar, wind and biomass, the corresponding power density values as estimated by the IAEA (1997) in brackets in the bullet list above correspond to the 2006 OECD values (Smil, 2006) in Figure 24.

For nuclear, the power density value of ~10^8 W/m^2 mentioned above would – for a 1 000 MWe NPP – translate into an area of 10 m^2 for "the core". Together with nuclear and civil islands, on-site storage of spent fuel and radioactive wastes, and the entire fenced plant sites, this could typically add up to the 1-4 km^2 mentioned by the IAEA (1997).

However, it is also necessary to consider the requirement of low population zones around a NPP, (i.e. risk and emergency type of zones). Here, differences in national legislation can result in relevant differences in estimates of required land: a comparison between energy, material and requirements between a nuclear fission and fusion plant (Schleisner *et al*. 2001) results in a value of ~200 m^2/MW (or: 0.0002 km^2/MW) for a "typical" European fission plant. A fusion plant would have a land requirement of ~300 m^2/MW (as compared to the IAEA (1997) values of 1-4 km^2 per 1 000 MWe, or 1 000-4 000 m^2/MW).

Additional uncertainty is introduced with respect to the ultimate land area needed for long-term repositories for radioactive wastes. Although final repositories are likely to be located in uninhabited and difficult-to-access regions, even in such cases there may be land use conflicts. The World Nuclear Association (2002) estimated that the total land requirement for 1 000 MW nuclear capacity is 1-10 km^2 across the entire lifecycle, i.e. including mining and the fuel cycle; corresponding to 100-1000 W/m^2, i.e. in agreement with the IAEA values cited above (IAEA, 1997).

EPD®s conducted by Vattenfall and NOK discussed in preceding sections include determination of the land area required for the entire life cycle of their respective NPPs. For Vattenfall's Ringhals NPS, the total land utilisation the operation, construction and dismantling of facilities involved in electrical generation amounted to 2.12 (10^{-5}) m^2/KWh (Vattenfall AB, 2004). For NOK's Beznau NPP, the amount of land occupied during the operation, construction and dismantling of facilities involved in electrical generation totalled 3.7 (10^{-4}) m^2/KWh (Nordostschweizerische Kraftwerke AG (NOK, 2008). The dominant factor is the infrastructure of the Beznau NPP itself (56% of the total land use).

New infrastructures for power production should fit as much as possible within the footprint of the old infrastructures, in order to minimise further land disturbance. As an illustrative example, the replacement of a typical 1 000 MWe NPP with renewable energy systems would require more than 2 500 km^2 of prime land for the biomass option and ~770 km^2 for the wind farm option. The Czech Republic President Václav Klaus calculated in his book "Blue Planet in Green Shackles" (2007) that the replacement of the Temelín NPP alone would require 4 750 windmills, resulting in a 150 m high and 665 km long "wall" between Temelín and Brussels. However, it is recognised that these comparisons of land requirements apply to those arising during normal operations and do not include any land interdiction that might arise from an accident.

Although land requirements are relatively low compared to other sources of electricity production (barring accidents), there is at times significant public resistance to the siting of new nuclear, particularly greenfield sites for NPPs and siting for nuclear waste repositories and uranium mines. Even though land requirements are relatively small, this could be a significant factor in the scenario of rapidly increased nuclear generating capacity considered in this report. Siting repositories for the amount of spent nuclear fuel alone produced in the greatly expanded nuclear fleet with exclusive use of a once-through fuel cycle (Figure 13) could be a major impediment to the development of nuclear energy on the scale considered in this report.

Water Requirements

All thermal electricity generation plants, whether coal, nuclear or, to a lesser extent gas, require substantial volumes of water for cooling and as a result are typically located close to large and reliable water sources. A number of supply sources can be used (e.g. river, lake, dam or sea water) and either an open, once-through or a closed-loop system can be employed[3].

[3] "Closed cycle" – the steam is cooled in towers or ponds and the water that is not lost to evaporation is recycled through the plant again. "Once-through" – the steam is cooled by more water that is pumped from an outside source in pipes through a condenser. Of the two systems, the closed cycle withdraws about 2-3% of the water volumes used by the once-through system. However, of the two systems the closed cycle consumes more water.

The water is needed to turn the turbines that drive the generators. To do this, water is turned into high pressure steam by a boiler or nuclear reactor. This steam is then cooled so that the water can be pumped through the system again. The amount of water a power plant uses and consumes depends on the cooling technology.

Power plants using a once-through system withdraw large quantities of water, but most of this water is later returned to the source (albeit generally at a higher temperature) and can be used again for other purposes. Although all power plants consume some of the water used in the production cycle, the greatest consumption rates are in closed-loop systems, where water is lost through evaporation.

The US EPRI compared the water needs and consumption rates of existing power plants by type of fuel and cooling technology (Electrical Power Research Institute, 2002). The analysis indicated that existing NPPs in the United States used and consumed significantly more water per MWh than fossil fuelled electricity generators:

- Use: Nuclear "once-through" systems withdraw ~20-25% more water than fossil fuelled plants, and nuclear "closed systems" can take up to 83% more water.

- Consumption*:* Actual water consumption rates for nuclear plants are also higher; for once-through cooling systems nuclear consumes ~33% more than fossil plants and ~50% more than fossil fuelled power plants with a closed-loop system.

In summary, per MWe existing NPPs use and consume more water than power plants using fossil fuel. This is because the steam in NPPs is designed to operate at lower temperatures and pressures, which means that they are less efficient at using the heat from the reactor and thus require more water for cooling. Depending on the cooling technology used, the water requirements for a NPP can vary between 20% - 83% more than for fossil plants.

EPD®s conducted by Vattenfall and NOK discussed in preceding sections include a calculation of the water required for the entire life cycle of their respective NPPs. For Vattenfall's Ringhals NPS, water use amounted to 216 g/KWh in 2004 (Vattenfall AB, 2004) and 182 g/KWh in 2007 (Vattenfall AB, 2007). For NOK's Beznau NPS, water requirements amounted to 3.42 (10^4) g/KWh of freshwater and 3.14 g/KWh of saltwater (NOK, 2008).

Conclusion

Although the area of land required for the normal operation of NPPs and fuel cycle operations is relatively small compared to other sources of electricity generation, public resistance to the siting of facilities required to support the expanded nuclear fleet will undoubtedly be an issue, at least in some cases. Although water use for fossil fuel generators is also high, reports reviewed in this study indicate that water use for NPPs is the highest. Water use could become an issue of increasing concern should climate change impacts include more frequent heat waves, as currently expected. All large thermal generators, including NPPs, are susceptible to reduced production during extended periods of hot weather when return water temperatures to already warm water bodies approach or exceed regulatory requirements.

Concerns around the intake of organisms during withdrawal of large quantities of water in open, once-through cooling systems, in some cases involving threatened species, have been raised for existing NPPs. Closed system cooling towers offer solutions to intake and temperature release issues, but are more expensive and consume more water through evaporative loss. Hence, the high intake and use of water characteristic of NPPs, relative to other base-load generating technologies, could pose a barrier for development, particularly in regions with water shortages and in jurisdictions with strong water withdrawal regulatory requirements.

Careful site selection for new nuclear facilities combined with deployment of the most effective water management technologies and systems available in order to minimise the impact of water cooled facilities could help to alleviate some of these concerns. Dry cooling is a possible alternative, but currently these systems appear to be too expensive to be used frequently. Although most Gen II, Gen III and Gen III+ NPPs use water for cooling, most Gen IV designs under development employ alternative coolants that offer a longer-term solution.

Nuclear power can however be used for desalination, a process that alleviates fresh water shortages in areas with access to salt water supply. Nonetheless, if NPPs are developed on the scale envisaged in this report, water use issues will likely need to be resolved.

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RAW MATERIAL REQUIREMENTS FOR ADVANCED NUCLEAR TECHNOLOGIES

Technology Classification

Nuclear reactors have been informally classified into three different types of designs, reflecting the time of development and the evolution of design technology. In the Nuclear Energy Outlook (NEA, 2008), reactor technologies are classified as follows:

- Generation (Gen) II - PWR, BWR, CANDU.
- Gen III - CANDU 6, System 80+, AP600.
- Gen III+ - EPR, ABWR, ESBWR, AP1000, ACR 1000, APWR.

Others use variations on this theme. For example, Peterson et al. (2005) classifies advanced reactor technologies as follows:

- Gen III - EPR, ABWR.
- Gen III+ - ESBWR, AP1000.

The United States Department of Energy (DOE) NP2010 programme considers the ESBWR, ABWR and AP1000 reactors to be Gen III+ designs (DOE, 2004). The EPR was not considered in this programme.

Gen IV reactors are advanced reactor designs under development (Section 7.3).

While the information contained in EPDs discussed in preceding sections provide data on raw material requirements arising from the operation, construction and dismantling of nuclear power plants, as well as the disposal of spent fuel, these data refer specifically to the Gen II reactor designs built in the 1970s. Nuclear technology has continued to develop and reactors marketed by vendors today are considered either Gen III or Gen III+ designs, in acknowledgment of the evolution of the technology and the development of new design concepts, such as passive safety systems.

Development is also underway for revolutionary new reactor designs, termed Gen IV, that are currently anticipated to be brought into commercial service in the 2030 time range. These include fast neutron reactors that are designed to produce more fuel than they consume during operation. Research fast reactors have been built and operated in the past but have proven technically challenging and are today generally considered uneconomic, given relatively low prices of uranium.

Since the Gen III, III+ and IV designs are either currently available or expected to be commercially available in the time frame envisioned for the development of the nuclear fleet considered in this study, material requirements of these designs compared to Gen II designs are outlined in this section, to the extent possible. Since much of this information is either commercially confidential or, in the case of Gen IV designs and FRs, unknown to some extent, this section is necessarily based on subjective expert evaluation of what little published information is available in terms of the requirements for these designs, as opposed to direct quantitative comparisons.

In nuclear power plants the major construction inputs are concrete and steel. An evaluation of the concrete and steel requirements for newer reactor designs, based on analysis of scaled drawings (Peterson *et al*., 2005), concludes that evolutionary new reactor designs (in this case EPR and ABWR) use more steel and concrete than the Gen II designs of the 1970s. In contrast, the new designs employing passive features (e.g. ESBWR, AP1000) achieve substantial reductions of steel and concrete requirements. In addition to this analysis, NPP component requirements for Gen III designs are compared to component requirements of the older Gen II designs in the following sections.

GEN III and GEN III+ Primary and Secondary Equipment Requirements

Reactor Pressure Vessels and Primary Circuit Components (DOE, 2004; 2005)

Reactor pressure vessels (RPVs) can range in size to a maximum of 7 m inside diameter by 27 m in height and can weigh up to 1 090 t (tonnes). Each GEN III+ unit has one RPV and one RPV head.

Steam Generators/Moisture Separator Reheaters: Steam generators can range in size to a maximum of 24 m tall with a 5.5 m diameter upper section and a 4.3 m diameter lower section. Each steam generator can weigh as much as 665 t. Moisture separator reheaters can range in size up to a maximum of 30 m long and 4 m in diameter. Each moisture separator reheater can weigh as much as 400 t. Each GEN III+ unit (in this case ESBWR, ABWR and AP1000 designs are considered Gen III+) uses between two to four steam generators or two to four moisture separator reheaters.

The piping materials predominately used in the construction of the GEN III+ units are 304 and 316 stainless steel, and Inconel 690 alloy piping. Each alloy contains a significant quantity of nickel. Nickel shortages in 2005 made these high-nickel alloys difficult to purchase.

Control Rod Drives and Fuel Elements

Up to 200 fine-motion control rod drives and up to 1 000 fuel elements are used per reactor.

Steam Turbine Generators and Condensers

Steam turbine generators (STGs) range in size up to 1 540 MVA and have low pressure (LP) turbine with last-stage blades that are 1.3 m long. The high pressure steam turbine can weigh as much as 500 t. Up to three LP rotors would each weigh as much as 225 t. The generator stator would weigh up to 455 t and the generator rotor would weigh up to 225 t. The STG condenser lower sections each weigh up to 600 t with dimensions of 17.4 m by 9.5 m by 10.4 m. Each STG would have up to three condensers.

Pumps

Up to ten (usually 4) reactor coolant pumps are used for each reactor. Up to two turbine-driven feed-water pumps and two motor-driven feed-water pumps are used in each reactor. Each unit has up to nine large (>400 HP) safety-related pumps, 24 other large pumps, ten small (<400 HP) safety related pumps and 82 other small pumps. The AP1000 and ESBWR designs have “passive safety” features and do not require any safety-related pumps.

Valves

GEN III+ units are expected to use up to 2 100 valves for the reactor systems. Approximately 1 000 motor operated valves (MOVs) and air operated valves (AOVs) are used in each unit with up to

700 of these valves are 7.6 cm or larger. Each unit would have a total of 3 000 to 6 000 valves that are 7.6 cm and larger and 6 000 to 12 000 valves that are 6.4 cm or smaller. The total number of valves used in a GEN III+ unit can range between 9 000 and 18 000 with up to 2 100 used in the plant's reactor systems.

Approximately 70% of the MOVs and AOVs are 7.6 cm or larger and 30% of the motor and air operated valves are 6.4 cm or smaller.

Class 1E Switchgear and Equipment

GEN III+ units are expected to have the following Class 1E equipment: up to three medium voltage switchgear panels, three 5 MW emergency diesel generators, nine 480 V motor control centers, four 125 VDC uninterruptible power supply systems, and three 120 VAC uninterruptible power supply systems. The AP1000 and ESBWR designs have "passive safety" features and do not require back-up emergency diesel generators.

Control Equipment

GEN III+ units are expected to have 2 000 to 3 500 instruments, digital plant control systems, main control panels, reactor protection panels, local panels, and a plant simulator.

Table 7. Estimated component requirement comparison of Gen III+ to Gen II

Gen III+ Component	Comparison to Gen II
Valve	40% fewer
Pump	30% fewer
Pipe	70%-80% less
Seismic Building Volume	40% less
Cable	70%-80%

Table 8. Gen II (600MW) component requirements (DOE, 2004)

Component	Value	Unit
Safety Valves	2 800	no.
Pumps	280	no.
NSSS Piping	33 528	m
Cable	2 743 200	m
Combined quantity of power and control cable in a single-unit PWR or BWR	1 981 200	m
Combined quantity of power and control cable in reactor building	762 000	m
Seismic Building Volume	56 634	m^3

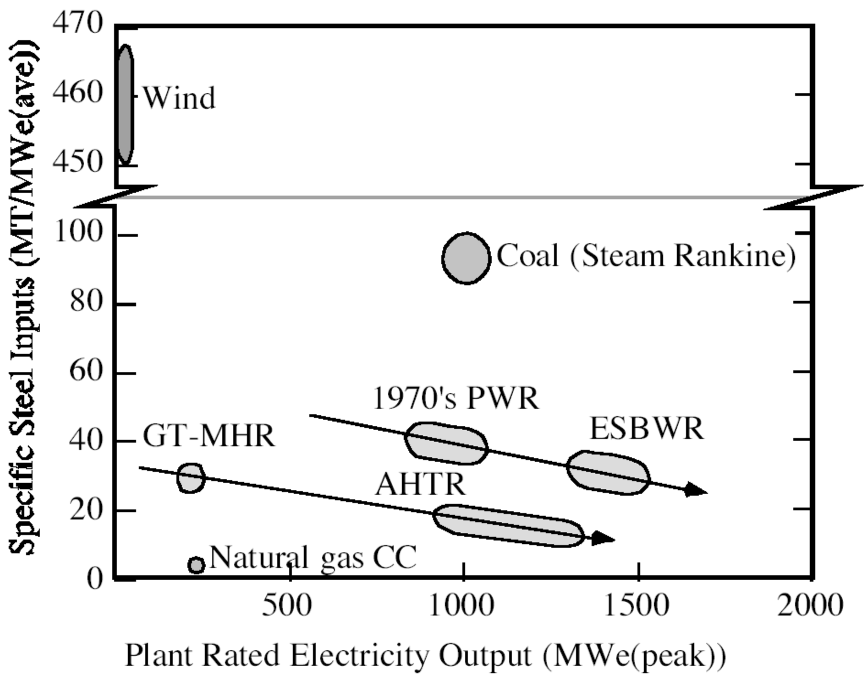
Construction Materials

An analysis of approximate steel and concrete input estimates for Generation III, and III+ systems, based on available arrangement drawings and scaling laws, concludes that "evolutionary" Generation III plants (EPR and ABWR) use approximately 25% more steel and 70% more concrete than 1970 Gen II designs (Peterson *et al.*, 2005). In contrast, passive Gen III+ designs (ESBWR and

AP1000) require 73% less steel and 50% less concrete than construction of an ABWR. The construction of existing 1970-vintage U.S. nuclear power plants required 40 metric tonnes (t) of steel and 90 m^3 of concrete per average megawatt of electricity (MW(ave)) generating capacity, when operated at a capacity factor of 0.9 (Figure 25).

Westinghouse (2007) states that the AP1000 design reduces the amount of safety-grade equipment required through the use of passive safety systems. Consequently, less Seismic Category I building volume is required to house the safety equipment (approximately 45 percent less than a typical reactor). The reactor also has a smaller footprint than an existing nuclear power plant with the same generating capacity.

Figure 25. Metal inputs for 1970's Gen II designs, Gen III+ (ESBWR) and Gen IV designs (GT-MHR and AHTR), combined cycle natural gas, coal and wind generating facilities (Peterson et al., 2005)



The Gen III+ design that is estimated to have the lowest inputs, the 1 380 MW General Electric ESBWR, requires 80 m^3/MW(ave) of concrete and 32 MT/MW(ave) of steel.

Russian nuclear reactor manufacturer Rosatom states that the new WWER design AES-2006 (http://atomcon.ru/public/_doc_forum/sek_1/(7).ppt) would use 17.4% less construction materials (per MWe) than the previous design (WWER-1000). Since the power of the new AES-2006 power plants increased by 14.7% compared to WWER-1000 (from 1 020 to 1 170 MWe), the total amount of construction materials needed for one unit would decrease by 5.2%.

Table 9. Estimated bulk material requirements for the construction of a single GEN III+ unit (DOE, 2005)

Bulk Material	Unit	Quantity	Unit	Quantity
Concrete	cubic yards	460 000 (not including concrete for site preparation).	m^3	351 695 (not including concrete for site preparation).
Reinforcing Steel and Embedded Parts	tonnes	46 000	t	41 730
Structural Steel, Miscellaneous Steel, and Decking	tonnes	25 000	t	22 680
Large Bore Pipe (> 2½ inch)	ft	260 000	m	79 248
Small Bore Pipe	ft	430 000	m	131 064
Cable Tray	ft	220 000	m	67 056
Conduit	ft	1 200 000	m	365 760
Power Cable	ft	1 400 000	m	426 720
Control Wire	ft	5 400 000	m	1 645 920
Process and Instrument Tubing	Ft	740 000	m	225 552

1 cubic yard = 0,764 554 857 984 $m^{3;}$ 1 ft = 0,3048 m

Table 10. Estimated material requirements for the construction of a single Gen III+ unit (DOE, 2004)

MATERIALS	
Length of piping (≥ 6.4 cm. diam.) required for two-unit nuclear power plant of size range 840-1 300 MWe	51 800 to 83 8200 m
Piping quantity (≥ 6.4 cm. diam.) in new plant designs as a percentage of past	Maximum: 90% Minimum: 50%
Piping quantity in reactor building relative to total	20-30 %
REACTOR BUILDING CHARACTERISTICS	
Shape Diameter Height	Cylinder 40 m 30 m
Inputs for Steel-Plate Reinforced Concrete Structures	
Amount of materials used to construct concrete walls Concrete Rebar Embedments Formwork	 9 360 m^3 2 820 t 171 070 kg 19 590 m^2
Inputs for Advanced Cable Splicing	
Combined quantity of power and control cable in a single-unit PWR or BWR	1 981 200 m
Combined quantity of power and control cable in reactor building	762 000 m

Gen IV

The Generation IV International Forum (GIF) was initiated in 2000 and formally chartered in mid 2001. Its ten active members (Canada, China, the European Union, France, Japan, Korea, the Russian

Federation, South Africa, Switzerland and the United States) collaborate on the development of the six systems deemed most promising for the future of nuclear energy: gas-cooled fast reactors (GFR), lead-cooled fast reactors (LFR), molten-salt reactors (MSR), supercritical water-cooled reactors (SCWR), sodium-cooled fast reactors (SFR) and very high temperature reactors (VHTR). These systems were selected owing to their ability to best fulfil the GIF objectives set for future nuclear power plants, compared to current reactors and projects (Gen II, Gen III and III+), in terms of enhanced safety, waste minimisation and better use of natural resources, as well as improved economics, proliferation resistance and physical protection.

These six system designs were selected from some one hundred reactor concepts. They were chosen to better respond to the social, environmental and economic requirements of the 21st century and to enhance the future contribution and benefits of nuclear energy. These systems employ advanced technologies and designs to improve the performance of reactors and fuel cycles, compared to current systems. They would allow meeting increased energy demand on a sustainable basis, at the same time being resistant to diversion of materials for weapons proliferation and secure from terrorist attack. Large commercial deployment of the first GEN IV nuclear systems is foreseen in 2030 and beyond. However, not all six systems are at the same level of development at this time.

Gas-cooled Fast Reactor (GFR)

The GFRs are high-temperature helium-cooled reactors designed to operate at temperatures of about 850°C. They are suitable for power generation, thermochemical hydrogen production or other process heat applications. The reference GFR unit is 1 200 MWe, with a thick steel reactor pressure vessel and three 800 MWt loops. Nitride or carbide fuels would incorporate depleted uranium and any other fissile or fertile materials in the form of ceramic pins or plates, with plutonium content of 15% to 20%. The main characteristics of the GFR are a fast neutron spectrum, robust refractory fuel, high operating temperatures, high efficiency electricity production, energy conversion with a gas turbine and full actinide recycling, possibly conducted at an integrated on-site reprocessing facility. Research is focussed on fuels and materials, as well as approaches to system safety. Although no GFR has ever been built, this type of reactor shares several technologies with VHTR, especially regarding the energy conversion system.

Lead-cooled Fast Reactor (LFR)

The LFR is a flexible fast neutron reactor that is designed to use depleted uranium or thorium fuel matrices and to burn LWR actinides. It is characterised by a fast-neutron spectrum and a closed fuel cycle with full actinide recycling. The coolant could be either lead (the preferred option), or a lead/bismuth eutectic, both of which offer a high degree of safety since the coolant is less chemically reactive than sodium. Two reactor size options are under consideration: a small transportable system of 50 to 150 MWe with a very long-lived core and a medium sized system of 300 to 600 MWe. An operating temperature of 550°C is readily achievable, but 800°C is envisaged in the longer term with advanced materials required to provide lead corrosion resistance at high temperatures. High operating temperatures would also enable thermochemical hydrogen production. Research is focussed on fuels and materials, as well as innovations in design and safety. This technology has been used for propulsion of Alpha class submarines (Pb-Bi) in the Russian Federation.

Molten Salt Reactor (MSR)

The MSR system embodies the very special feature of liquid fuel dissolved in the coolant. Specifically, liquid fluorides of uranium and plutonium are dissolved in fluorides of lithium, beryllium, sodium or other elements. MSR concepts, which include systems that can be used as efficient burners of transuranics from spent LWR fuel, also have a breeding capability in any kind of neutron spectrum ranging from thermal (with a thorium based fuel cycle) to fast (with the U-Pu fuel cycle). The reference plant is up to 1 000 MWe. Fission products are removed continuously and the actinides are fully recycled, while plutonium and other actinides can be added along with ^{238}U, without the need for fuel fabrication. Coolant temperature is 700°C at very low pressure, with 800°C envisaged. A secondary coolant system is used for electricity generation. Thermochemical hydrogen production is also feasible. Research is focussed on the fuel chemistry, structural materials and core design.

Supercritical Water-cooled Reactor (SCWR)

SCWRs are a class of high-temperature, high-pressure water-cooled reactors operating with a direct energy conversion cycle and above the thermodynamic critical point of water (374°C, 22.1 MPa). The higher thermodynamic efficiency and plant simplification opportunities afforded by a high-temperature, single-phase coolant translate into improved economics. A wide variety of design options are being considered, such as thermal-neutron and fast-neutron spectra as well as pressure vessel and pressure tube configurations.

The supercritical water (25 MPa and 510-550°C) is planned to directly drive the turbine, without any secondary steam system, simplifying the plant. Passive safety features are similar to those of simplified boiling water reactors. Fuel is uranium oxide, enriched in the case of the open fuel cycle option. However, it can also be built as a fast reactor with full actinide recycling based on conventional reprocessing. Due to the higher temperature and pressure in the primary circuit the reactor will be more compact, with reduced component sizes compared to current water cooled reactors.

Sodium-cooled Fast Reactor (SFR)

The SFR uses liquid sodium as the reactor coolant, allowing high power density and low coolant volume. It builds on more than 300 reactor-years experience with SFRs over five decades in eight countries. The SFR utilises depleted uranium as the fuel matrix and the coolant temperature of 500-550°C enables electricity generation via a secondary sodium circuit, the primary one being near atmospheric pressure. The reactor can either be arranged in a pool layout or a compact loop layout.

Reactor size options under consideration range from small (50 to 300 MWe) modular reactors to larger (up to 1 500 MWe) units. The SFR features a closed fuel cycle for fuel breeding and/or actinide management. The associated fuel cycle technology options are advanced aqueous and pyro-metallurgical processing. Progress in developing the SFR is well under way and advances have been made in various fields, such as fuel technology and compact heat exchangers.

Very High-Temperature Gas Reactor (VHTR)

The VHTR is the next step in the evolutionary development of high-temperature reactors. It is a helium gas-cooled, graphite-moderated, thermal neutron spectrum reactor that can achieve a temperature of 900°C or higher. The ceramic fuel and the foreseen thermal power offer a high degree of passive safety and an efficiency approaching 50%. The high temperatures make the cogeneration of electricity and process heat applications possible. Initially a once-through LEU (<20% ^{235}U) fuel cycle is intended. Closed fuel cycles will also be assessed, as well as potential symbiotic fuel cycles with other types of reactors (especially LWRs) for waste reduction.

VHTR outlet temperatures of over 900°C enable thermochemical hydrogen production via an intermediate heat exchanger, with electricity cogeneration or direct high-efficiency electricity generation. Modules of 600 MW thermal are envisaged. The VHTR has potential for high burn-up (150-200 GWd/t), completely passive safety systems, low operational and maintenance costs and modular construction.

Gen IV Material Requirement Estimates

Implementation of these systems would address aspects of raw material issues in terms of fuel, coolant and structural materials. Regarding fuel, reference designs typically use uranium or plutonium, whether as a metal, oxide or nitride, depending on the concept. The MSR is usually considered as one of the best concepts for utilising thorium as its main fuel cycle.

While most of current commercial nuclear power plants use water (light or heavy) or CO_2 as the primary coolant, this is not the case for the Gen IV systems, with the exception of the SCWR design. Other systems use helium, sodium or lead as the primary coolant. The MSR is unique in the sense that the primary fluid combines coolant and fuel. Despite the lack of near-term prospects for commercial designs, it is possible to evaluate some aspects of material requirements for these fluids based on previously operating facilities and preliminary designs.

For example, the Pebble Bed Modular Reactor (PBMR), the former South African project for commercial VHTR, requested an initial inventory of 7 290 kg of helium (He) in its 400 MWth design, plus an additional 7.92 kg of He/day to compensate for losses, amounting to a total of to 123.6 t He for 40 years of reactor operation for each PBMR.

Such high helium requirements in VHTRs could pose a supply challenge. Although helium is the second most common element in the universe, it is not easily captured or recovered. Produced through the decay of uranium and thorium, quantities are trapped in natural gas fields and extracted by fractional distillation of the recovered natural gas. Known helium reserves amount to a little over 30 billion m^3 (a little over 5 million t), and major competing uses of helium include cryogenics, in particular magnetic resonance imaging, pressurising and purging, welding and controlled atmospheres (Pacheco, 2009). However, new natural gas discoveries combined with improved He recovery and management could alleviate this potential supply challenge.

In another example, the French SUPERPHENIX SFR (1 200 MWe; closed in 1997) required 3 500 t of nuclear quality sodium for the primary coolant, plus an additional 1 500 t for the secondary circuit. However, since sodium reserves are large, the production of nuclear-grade sodium should be able to meet rising demand if these types of reactors are to be built in numbers.

The selection of new fluids as coolant, in some cases much more corrosive than current fluids, particularly when combined with the higher temperatures foreseen in these designs, raises issues concerning structural materials and fuel cladding. Since design activities are ongoing, and many options regarding secondary fluid and/or associated components remain under consideration, specific material requirements cannot however be addressed at present.

In addition to materials needed for civil engineering, materials for three main families of design elements - metal alloys, ceramics and graphite - remain to be determined. Metal alloys used for previous generations of reactor designs are still needed for the Gen IV systems, such as the ferritic-martensitic steels. These well known materials are often considered as reference materials, at least for near and medium-term prototype units, while new materials will be developed and qualified over the longer term. Examples of potential new metallic alloys are the oxide dispersion strengthened steels

(ODS) and the high temperature Ni-based alloys. Both may be better known outside the nuclear industry, but qualities of these alloys will need to be tested before they can be deemed suitable for use in Gen IV NPPs. Standard steel requirements for one PBMR (a small sized VHTR reactor according to IAEA standards, with a helium outlet temperature of 900°C) were evaluated to amount to about 12 500 t. In addition, over 1 500 t of high temperature metallic materials were expected to be required.

Ceramics and composite material requirements are also foreseen, especially for high temperature applications, where metallic alloys would be difficult to use in components such as control rods for the VHTR, fuel cladding for the GFR, thermal insulation for the VHTR and GFR, heat exchangers between coolant and chemically active process fluids for the VHTR or GFR, etc. These materials are still under development and may well be of interest to other industries using materials in extreme conditions. In addition, the final design of components is ongoing (e.g. pin fuel vs. plate fuel in the GFR), making it impossible to anticipate the quantity of material needed for any concept at this time.

Graphite is very important for the VHTR, as it is the main element of the core structure, but it is also important in the thermal design of the MSR. The required graphite must also have specific properties to meet nuclear grade standards, with constraints on density and purity, together with mechanical and thermal properties. These may not always be readily available. For example, the graphite used in the 1970s in the HTR in the United States (Fort Saint Vrain, Peach Bottom) is no longer available because of the scarcity of one of its base constituents. New grades are however being developed and the accompanying R&D is taking required standards into account in order to ease development and qualification of those new grades.

Concerning the amount of graphite needed for different VHTR concepts, the GT-MHR design developed by ROSATOM and General Atomics (a small sized reactor according to IAEA standards) anticipates using around 870 t of graphite, part of which will need to be replaced periodically in fuel blocks and replaceable reflectors, amounting to a total of about 6 000 t of graphite needed over the course of the expected 60 year life of one reactor. The possibility of recycling graphite is being investigated in order to both reduce the overall amounts needed and minimise the associated graphite waste, including processes to re-establish critical graphite properties after degradation through irradiation.

According to preliminary design by the *Karlsruher Institut für Technologie* (Koehly, 2010), the High Performance Light Water reactor (HPLWR), part of the SCWR design family, would use about:

- 69 kg of gadolinium/1 000 MWe/yr,
- 403 kg of molybdenum/1 000 MWe/yr,
- 153 kg of titanium/1 000 MWe/yr,
- 34.7 t of the stainless steel 1.4970/1 000 MWe/yr, and
- 378 kg of boron carbide/1 000 MWe/yr.

This represents a slight increase in gadolinium, molybdenum and boron carbide requirements, but a decline in titanium requirements, compared to those of Gen II reactors documented in Chapter 3. Stainless steel requirements also decline from Gen II design requirements under this design scenario.

The current design of HPLWR would also use significantly less concrete, but more rebar for the reactor building and the containment, compared to generic Generation II designs. However, since the nuclear power plant layout of HPLWR may differ significantly from the current development design schemes, comparisons made at present are preliminary and subject to change.

Table 11 summarises materials information on the 6 systems as they were identified by GIF members in the Technology Roadmap. This document, as well as more information about Generation IV International Forum, is available on the GIF Website (http://www.gen-4.org).

Table 11. Material requirements foreseen in Gen IV systems under development

				Structural Materials	
System	Spectrum, T_{outlet}	Fuel	Cladding	In-core	Out-of-core
GFR	Fast, 850°C	MC/SiC	Ceramic	Refractory metals and alloys, Ceramics, ODSVessel: F-M	Primary Circuit: Ni-based superalloys 32Ni-25Cr-20 Fe-12.5W-0.05C Ni-23Cr-18W-0.2 CF-M w/ thermal barriersTurbine: Ni-based alloys or ODS
LFR	Fast, 550°C and Fast, 800°C	MN	High-Si F-M, Ceramics, or refractory alloys		High-Si austenitics, ceramics, or refractory alloys
MSR	Thermal, 700–800°C	Salt	Not Applicable	Ceramics, refractory metals, High-Mo Ni-base alloys (e.g., INOR-8), Graphite, Hastelloy N	High-Mo Ni-base alloys (e.g., INOR-8)
SFR (Metal)	Fast, 520°C	U-Pu-Zr	F-M (HT9 or ODS)	F-M ducts 316SS grid plate	Ferritics, austenitics
SFR (MOX)	Fast, 550°C	MOX	ODS	F-M ducts 316SS grid plate	Ferritics, austenitics
SCWR-Thermal	Thermal, 550°C	UO_2	F-M(12Cr, 9Cr, etc.) (Fe-35Ni-25Cr-0.3Ti) Incoloy 800, ODS Inconel 690, 625, & 718	Same as cladding options	F-M
SCWR -Fast	Fast, 550°C	MOX, Dispersion	F-M (12Cr, 9Cr, etc.) (Fe-35Ni-25Cr-0.3Ti) Incoloy 800, ODS Inconel 690 & 625	Same as cladding options	F-M
VHTR	Thermal, 1000°C	TRISO UOC in Graphite Compacts; ZrC coating	ZrC coating and surrounding graphite	Graphites PyC, SiC, ZrC Vessel: F-M	Primary Circuit: Ni-based superalloys 32Ni-25Cr-20Fe-12.5 W-0.05CNi-23Cr-18 W-0.2CF-M w/ thermal barriers Turbine: Ni-based alloys or ODS

Abbreviations:
- F-M: Ferritic-martensitic stainless steels (typically 9 to 12 wt% Cr)
- ODS: Oxide dispersion-strengthened steels (typically ferritic-martensitic)
- MN: (U,Pu)
- MC: (U,Pu)C
- MOX: $(U,Pu)O_2$

In summary, all design concepts aim at higher efficiencies, higher burn up or more compact components than current reactors, which should considerably reduce their material requirements. Deployment of fast breeder reactors, reprocessing of the nuclear fuel and closing of the fuel cycle will help avoid any potential shortcomings in the availability of fissile fuel and make nuclear power a long term option, even under the aggressive hypothetical scenario considered in this report. Several of the Gen IV designs under consideration would be capable of producing hydrogen for use as carrier of energy should its use, for example in transportation, become more common. Moreover, some Gen IV designs offer potential for process heat applications.

Most of the six Gen IV systems employ a closed fuel cycle, including the reprocessing and recycling of plutonium, uranium and minor actinides in fast reactors, in order to maximise the fuel resource base and minimise high-level wastes destined for a repository. Three of the six are fast neutron reactors, one is described as epithermal, and only two can operate both with thermal neutrons like most of today's operating nuclear power plants, or with fast neutrons.

The fast neutron reactors were originally conceived to burn uranium more efficiently and breed new fissile fuel in form of plutonium (i.e. fast breeder reactors). This could extend the time horizon of global uranium resources by a factor up to about 60.

The conventional fast reactors built to date are mostly sodium-cooled fast breeder reactors implying a net increase in ^{239}Pu from breeding. They have a "fertile blanket" of depleted uranium (^{238}U) around the core, and this is where much of the ^{239}Pu is produced.

Fast reactor concepts being developed for the Generation IV program will have fertile material in the core, where plutonium will both be produced and consumed. Due to the high neutron flux in the core the production of plutonium isotopes heavier than ^{239}Pu will be facilitated.

The most advanced Gen IV reactors are in the conceptual design status. Because all detailed specifications for their components are not yet available, detailed calculations and analyses of their material requirements is impossible.

Conclusion

Precise raw material requirements for Gen III and Gen III+ reactors are not available as they are considered commercially confidential. Subjective assessment of Gen III and Gen III+ designs, based on scaled design diagrams and generic component lists, suggest that some variation in raw material requirements exists within these new designs. For example, scaled design diagrams indicate that the EPR and ABWR use approximately 25% more steel and 70% more concrete than Gen II reactors. In contrast, Gen III+ designs that incorporate passive safety features, such as the ESBWR and the AP1000, are expected to require substantially less of these materials (73% less steel and 50% less concrete) than the ABWR.

Component requirement lists indicate that the ABWR, ESBWR and AP1000 use substantially fewer valves, pumps, piping and less cable than Gen II designs. This, combined with an estimated 40% reduction in seismic building volume, also suggest reduced raw material requirements for these types of advanced reactor designs. However, even though the number of components is reduced overall, suggesting that overall raw material requirements will be reduced, it is not possible to say categorically that raw material requirement supplies will not be limited since raw material inputs to these components are unknown.

Despite this variation between advanced reactor types, it can be concluded that with few exceptions, Gen III and Gen III+ designs would appear to require less raw material inputs than Gen II designs. The exceptions, such as increased concrete and steel requirements for the EPR and possibly the ABWR, are not considered to be limits to nuclear development on the scale envisioned in this report, since raw material inputs to steel and concrete were not identified as being materials of concern in the analysis of requirements for a greatly expanded fleet of Gen II reactors.

In the case of Gen IV reactors currently under design, raw material requirements are not well known given the early stages of development. This greatly limits the ability to compare raw material requirements for these advanced designs (Gen III, Gen III+) being marketed today with the Gen II designs built in the 1970s, such as the PWRs and BWR currently in operation at the Ringhals NPS. However, preliminary analysis suggests that helium supply could pose a challenge if Gen IV gas cooled designs are commercialised and built in large numbers.

Given that all Gen IV design concepts aim at higher efficiencies, higher burn up or more compact components than current reactors, a considerable reduction in material requirements can be anticipated. Successful development and deployment of FRs and closure of the fuel cycle could also help avoid any shortcomings in the availability of fissile fuel, making nuclear power a longer term option under the scenario considered in this report. Moreover, rather than simply consuming materials, some Gen IV designs are expected to be suitable for the production of hydrogen.

What is not included in the above assessment, owing to a lack of available information, are materials that may be used in more advanced designs, in particular in new forms of fuel and fuel bundles not used in Gen II reactors. This was considered by the expert group as one of the greater sources of uncertainty in this analysis.

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FINDINGS AND CONCLUSIONS

Life cycle raw material requirements for Gen II reactors and the associated fuel cycle are documented in Environmental Product Declarations. Data in these reports provide a comprehensive starting point for assessing raw material requirements arising from a hypothetical rapid expansion of global nuclear generating capacity. Owing to the dominance of PWRs in the existing fleet and their expected dominance, at least during the initial build-up of capacity considered in this report, the focus of this project, to the extent possible, was directed toward material requirements arising from the operation of PWRs. Hence, a detailed dataset from the Ringhals NPS (75% PWR and 25% BWR) provided by Vattenfall was selected as the basis for this study.

A number of institutions have produced simulations of growth in nuclear generating capacity that see the possible development of nuclear generating capacity and electricity generation to ten-time the scale of operation today, although the timing of development varies. Review and analysis of these development scenarios suggest that the most realistic timing of the ten-time development of nuclear electricity generation is the IIASA/WEC projection that sees target capacity reached in 2085. Examination of the evolution of fuel cycle requirements for development of a global reactor fleet of this scale shows the need for extensive fuel resources and spent fuel storage and disposal facilities, should the fleet exclusively employ a once-through fuel cycle.

Scaling-up material requirements outlined in the Environmental Product Declaration for the Gen II Ringhals NPP to simulate requirements for a ten-time expansion of nuclear generating capacity indicate that the only raw material limited in availability is uranium. This is not surprising, given that freshly mined uranium has met only about 60% to 70% of annual reactor requirements in the past several years, the remainder being derived from sources of previously mined uranium (so-called “secondary sources”).The amount of uranium required to fuel a fleet with a combined capacity of 3 720 GWe, exclusively using a once-through cycle, is estimated to amount to some 683 000 tU/yr. Meeting this level of demand would require increasing uranium production by more than 15 times the 2006 level of production.

Identified conventional uranium resources would not be sufficient to fuel lifetime reactor requirements for such an expansion of nuclear generating capacity in the 21st century. The uranium resource base would, however undoubtedly increase and unconventional resources could be brought into production over the next several decades should market prices increase, as would be expected by demand created by such a rapid expansion of nuclear generating capacity. Nonetheless, it would be a significant challenge to increase and sustain production of over 680 000 tU/yr, as required by fuel requirements arising from a once-through fuel cycle. Public attitudes toward uranium mining would have to improve considerably to accommodate such a rapid rate of growth in mines.

Implementing reactor operational efficiencies combined with more widespread adoption of reprocessing and recycling practices as well as the use of thorium as fuel could significantly ease fuel and waste disposal requirements for the expanded nuclear fleet. Existing stocks of recyclable fissile materials could also contribute to meeting fuel requirements. However, significant investment would be required to facilitate such efforts, in particular to develop new fuel cycle facilities needed to use thorium as nuclear fuel.

In addition to uranium, six other raw materials (bentonite, fluorite and fluorspar, indium, manganese, zircon sand and gadolinium) were identified as materials of concern since requirements arising from a ten-time expansion would exceed 4% of current total global production capability (86%, 25%, 11%, 23%, 9%, 7% and 4%, respectively). In all cases of raw materials of concern however, resources are large and with appropriate market signals there is little available evidence at present to suggest that production could not be increased to meet rising requirements for use in the nuclear fuel cycle under this scenario of rapid expansion. There are also opportunities for substitution and to increase recycling above what is practised today.

Although the area of land required for the normal operation of NPPs and fuel cycle operations is relatively small, compared to other sources of electricity generation, public resistance to the siting of NPPs and facilities required to support the expanded nuclear fleet will undoubtedly be an issue, at least in some cases. Water use could also become an issue of increasing concern should projected climate change impacts of more frequent heat waves come to fruition. All large thermal generators, including NPPs, are susceptible to reduced production during extended periods of hot weather when return water temperatures to already warm water bodies approach or exceed regulatory requirements. Concerns around the intake of organisms during withdrawal of large quantities of water in open, once-through cooling systems have been raised for existing NPPs. Closed system cooling towers offer solutions to intake and temperature release issues, but are more expensive and consume more water through evaporative loss.

Careful site selection for new nuclear facilities combined with deployment of the most effective water management technologies and systems available in order to minimise the impact of water use could help to alleviate some of these concerns. Dry cooling is a possible alternative, but currently these systems appear to be too expensive to be used frequently. Most Gen IV designs under development employ alternative coolants, offering a longer-term solution.

Precise raw material requirements for Gen III and Gen III+ reactors are not available as they are considered commercially confidential. Despite some apparent variation between advanced reactor designs, it is concluded that with few exceptions, Gen III and Gen III+ designs appear to require less raw material inputs than Gen II designs. The exceptions, such as increased concrete and steel requirements for the EPR and possibly the ABWR, are not considered to be limits to nuclear development on the scale envisioned in this report, since raw material inputs to steel and concrete were not identified as materials of concern.

In the case of Gen IV reactors currently being designed, raw material requirements are not well known given the early stages of development. Given that all Gen IV design concepts aim at higher efficiencies, higher burn up or more compact components than current reactors, a considerable reduction in material requirements can be anticipated. Deployment of FRs and closure of the fuel cycle would also help avoid any shortcomings in the availability of fissile fuel, making nuclear power a longer term option under the scenario considered in this report. Preliminary analysis suggests that helium supply could pose a challenge if VHTR helium cooled designs are commercialised and built in large numbers.

Also of note is potential growing demand for non-conventional applications of nuclear energy such as water purification and desalination, district and process heat generation and hydrogen production. As opposed to simply consuming raw material inputs, it should be recognised that NPPs are currently capable of producing hydrogen and heat. Advanced designs promise to do so more efficiently and FRs offer the prospect producing more nuclear fuel than they consume. As a result, when considering the consumption of raw materials to build, operate and decommission NPPs to produce electricity, recognition should be given to potential applications to produce potable water, heat, and hydrogen as an energy carrier.

One remaining area of uncertainty is associated with new nuclear fuel designs. Efforts to improve fuel efficiencies may well incorporate materials not used in fuel design today. In some cases, these materials may be in short supply. This is a cautionary note only as it is not possible to assess at this time the likelihood of the usage of these materials.

APPENDIX A
EXPERT GROUP MEMBERS

Czech Republic

Mr Lubor ŽEŽULA	Nuclear Research Institute Řež plc

France

Mrs Christine LOAËC	CEA Saclay DEN/SAC/DM2S/SERMA

Germany

Mr. Jürgen KUPITZ	System Analysis Group in the Research Center Juelich

Hungary

Dr Tamás J. KATONA	Nuclear Power Plant Paks Ltd.

Republic of Korea

Mr KIM, SEUNG-SU	Korea Atomic Energy Research Institute (KAERI)

United States

Mr. Abdellatif YACOUT	Argonne National Laboratory

European Commission

Mr. Christian KIRCHSTEIGER	DG for Energy & Transport

International Atomic Energy Agency

Mr Rayman SOLLYCHIN	Division of Nuclear Power and INPRO

OECD Nuclear Energy Agency

Mr. Robert VANCE
Mr. Torsten ENG
Mr Alexey LOKHOV
Mr Jean-Charles ROBIN

Vattenfall AB

Ms. Caroline SETTERWALL

APPENDIX B
RAW MATERIAL REQUIREMENTS, GLOBAL PRODUCTION AND RESOURCES (LINKS ONLY)

Raw Material	Link
Aluminium in ore	http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/mcs-2008-alumi.pdf
Bauxite	http://en.wikipedia.org/wiki/Bauxite#World_bauxite_mine_production.2C_reserves.2C_and_reserve_base
Bentonite	http://minerals.usgs.gov/minerals/pubs/commodity/clays/190302.pdf
Borax	http://minerals.usgs.gov/minerals/pubs/commodity/boron/boronmcs04.pdf
Boron Carbide	http://minerals.usgs.gov/minerals/pubs/commodity/boron/myb1-2007-boron.pdf - B2O3 production
Cadmium	http://minerals.usgs.gov/minerals/pubs/commodity/cadmium/140497.pdf - recycling possibilities (e.g. batteries)
Carbon	http://minerals.usgs.gov/minerals/pubs/commodity/graphite/myb1-2006-graph.pdf: graphite production only
Chromium in ore[1]	http://www.indexmundi.com/en/commodities/minerals/chromium/chromium_t7.html
Coal[3]	http://www.worldcoal.org/pages/content/index.asp?PageID=104
Copper in ore	http://www.indexmundi.com/en/commodities/minerals/copper/copper_t20.html
Crude oil[3]	http://www.eia.doe.gov/emeu/aer/txt/ptb1105.html
Chrysotile	http://www.google.com/search?sourceid=navclient&ie=UTF-8&rlz=1T4GGLJ_enFR246FR258&q=world+chrysotile+production
Cinnabar	http://minerals.usgs.gov/minerals/pubs/commodity/mercury/mcs-2008-mercu.pdf
Cobalt	http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2008-cobal.pdf
Colemanite	http://minerals.er.usgs.gov/minerals/pubs/commodity/boron/120397.pdf
Diatomite	http://minerals.usgs.gov/minerals/pubs/commodity/diatomite/mcs-2008-diato.pdf

Raw Material	Link
Feldspar	http://www.indexmundi.com/en/commodities/minerals/feldspar_ and_nepheline_syenite/feldspar_and_nepheline_syenite_t8.html
Ferromanganese	http://minerals.usgs.gov/minerals/pubs/commodity/manganese/mangamcs06.pdf
Fluorite	http://www.agiweb.org/geotimes/dec03/resources.html
Fluorspar	http://minerals.er.usgs.gov/minerals/pubs/commodity/fluorspar/fluormcs06.pdf
Gadoliniumoxide GdO3	http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/rareemyb05.pdf
Gypsum	http://minerals.usgs.gov/minerals/pubs/commodity/gypsum/gypsumcs06.pdf
Hafnium	http://minerals.usgs.gov/minerals/pubs/commodity/zirconium/zircomcs07.pdf
Helium	http://minerals.usgs.gov/minerals/pubs/commodity/helium/myb1-2006-heliu.pdf
Indium	http://minerals.usgs.gov/minerals/pubs/commodity/indium/indiumcs07.pdf
Iron in ore	http://minerals.usgs.gov/minerals/pubs/commodity/iron_ore/340302.pdf
Kieserite	http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mgcommcs06.pdf
Lead in ore	http://minerals.usgs.gov/minerals/pubs/commodity/lead/lead_mcs06.pdf
Magnesium in ore or water	http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mgcommcs06.pdf
Manganese in ore	http://minerals.usgs.gov/minerals/pubs/commodity/manganese/mangamcs07.pdf
Molybden	http://minerals.usgs.gov/minerals/pubs/commodity/molybdenum/molybmcs07.pdf
Natural gas[3]	http://www.eia.doe.gov/oil_gas/natural_gas/info_glance/natural_gas.html
Nickel in ore	http://minerals.usgs.gov/minerals/pubs/commodity/nickel/nickemcs07.pdf
Niobium	http://minerals.usgs.gov/minerals/pubs/commodity/niobium/mcs-2008-niobi.pdf
Palladium in ore	http://minerals.usgs.gov/minerals/pubs/commodity/platinum/platimcs05.pdf
Phosphorous in ore	http://minerals.er.usgs.gov/minerals/pubs/commodity/phosphate_rock/phospmcs07.pdf
Platinum in ore	http://minerals.usgs.gov/minerals/pubs/commodity/platinum/platimcs07.pdf
Potassium chloride	http://minerals.usgs.gov/minerals/pubs/commodity/potash/potasmcs06.pdf
Quartzite	http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/
Rhenium in ore	http://minerals.usgs.gov/minerals/pubs/commodity/rhenium/rhenimcs05.pdf
Rhodium in ore	http://minerals.usgs.gov/minerals/pubs/commodity/platinum/mcs-2008-plati.pdf
Rock (blasted masses)	http://minerals.usgs.gov/minerals/pubs/commodity/stone_dimension/
Salt	http://minerals.usgs.gov/minerals/pubs/commodity/salt/salt_mcs07.pdf
Selenium[1]	http://minerals.usgs.gov/minerals/pubs/commodity/selenium/selenmcs07.pdf

Raw Material	Link
Silver in ore	http://minerals.usgs.gov/minerals/pubs/commodity/silver/silvemcs07.pdf
Soda (Sodium carbonate)	http://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/mcs-2008-sodaa.pdf
Sodium sulphate	http://minerals.usgs.gov/minerals/pubs/commodity/sodium_sulfate/nasulmcs07.pdf
Stibnite (antimon)	http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2008-antim.pdf
Sulphur	http://minerals.usgs.gov/minerals/pubs/commodity/sulfur/640499.pdf
Talc	http://minerals.usgs.gov/minerals/pubs/commodity/talc/mcs-2008-talc.pdf
Tin in ore	http://minerals.usgs.gov/minerals/pubs/commodity/silver/silvemcs07.pdf
Titanium in ore	http://minerals.usgs.gov/minerals/pubs/commodity/titanium/timinmcs07.pdf
Titanium dioxide	http://minerals.usgs.gov/minerals/pubs/commodity/titanium/tidiomcs07.pdf
Ulexite	http://minerals.usgs.gov/minerals/pubs/commodity/boron/boronmcs06.pdf
Zinc in ore	http://minerals.usgs.gov/minerals/pubs/commodity/zinc/mcs-2008-zinc.pdf
Zircon sand[1]	http://minerals.usgs.gov/minerals/pubs/commodity/zirconium/zircomcs07.pdf; http://www.melbourneminingclub.com/pdfs/M%20Folwell%2011%20August%2005.pdf
Non-renewable energyware	
Natural gas	http://www.eia.doe.gov/oil_gas/natural_gas/info_glance/natural_gas.html
Uranium in ore[2]	Uranium 2005: Resource, Production and Demand