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Uranium: Sustainable Resource or Limit to Growth?

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Nuclear power has many advantages, among them at least two that directly flow from the uranium energy source itself - the low cost of the natural uranium as a proportion of overall generating costs, and the small amount of fuel necessary to provide very large amounts of energy. However, some recent publications have promoted the view that limited supplies of natural uranium are the Achilles heel of nuclear power as the sector contemplates a larger contribution to future clean energy [1], and even at this Symposium, authors have stated that finite resources will require the acceleration of fast breeder technology [2]. Is this true? If not, what gives the nuclear industry the confidence that new uranium supply will appear when needed? The answer involves taking a view of supply that goes well beyond the short term, and includes the entire economic system within which natural resources are discovered, developed, and produced.

Uranium supply news is usually framed within a short-term perspective. The concerns of short-term supply thinking are well known: who is producing with what resources, who might produce or sell, and how does this balance with demand? However, long-term supply analysis enters the realm of resource economics. This discipline has as a central concern the understanding of not just supply/demand/price dynamics for known resources, but also the mechanisms for replacing resources with new ones presently unknown. Such a focus on sustainability of supply is unique to the long view. This paper summarizes some of the perspectives and analysis that support the following conclusion: uranium supply, like that for other metals, is *economically sustainable*. This means that normally functioning metals markets and technology change provide the drivers to ensure that supply at costs affordable to consumers is continuously replenished, both through the discovery of new resources and the re-definition (in economic terms) of known ones.

Resources and scarcity

Civilizations have been using metals since earliest recorded history. Gold and silver played important roles as vehicles for wealth and currency, and iron and base metals gained gradual usage as smelting and metallurgical knowledge allowed access to more complex metal structures. Industrialization clearly caused a rapid increase in human society's intensity of metals use, and required new supply sources and technologies to keep up with demand growth. Compared

with the more than thousand years of base and precious metals usage, the world's demand for uranium is a very recent arrival.

Concerns about limitations from finite earth resources also go back in history, at least to the works of Malthus (1888), and more recently in the Club of Rome writings on limits to growth. This history has been well summarized by Hore-Lacy [3]. In virtually every respect, these concerns have not been realized, with one possible exception that will be mentioned later in this paper. Where have these dire predictions, which seem so intuitive and logical, gone wrong?

There are two principal areas where resource predictions have faltered:

- predictions have not accounted for new knowledge gains, both in geological understanding of mineral deposits and also related to the technologies utilized to discover and process them;
- economic principles have not been taken into account, which means that resources are thought of only in present terms, not in terms of what will be economic through time, nor with concepts of substitution in mind.

None of this is to make the claim that specific mineral resources, once mined and their metals put to use, are not physically non-renewable (at least on human time scales). But if this were the only dynamic at play, minerals would long ago have become scarcer and their costs much higher. Numerous economists have studied resource trends to determine which measures should best reflect resource scarcity [4]. Their consensus is that costs and prices, properly adjusted for inflation, provide a better early warning system for long-run resource scarcity than do physical measures such as resource quantities.

These historic data show that the most commonly used metals have declined in both their costs and real commodity prices [*Figure 1*] over the past century. Such price trends are the most telling evidence of lack of scarcity. However, resource quantities tell a similar and consistent story. To cite one example, world copper reserves in the 1970s represented only 30 years of then-current production (6.4 Mt/yr). Many analysts questioned whether this resource base could satisfy the large expected requirements of the telecommunications industry by 2000. But by 1994, world production of copper had doubled (12 Mt/yr) and the available reserves were still enough for another 30 years. The reserve multiple of current production remained the same.

Another way to understand resource sustainability is in terms of economics and capital conservation. Under this perspective, mineral resources are not so much rare or scarce as they are simply too expensive to discover if you cannot realise the profits from your discovery fairly soon. The economic system therefore discourages companies from discovering enormously more than society needs by sending messages of reduced commodity prices during times of oversupply. Economically rational players will only invest in finding these new reserves when they are most confident of gaining a return from them, which usually requires positive price messages caused by undersupply trends. If the economic system is working correctly and maximizing capital efficiency, there should never be more

than a few decades of any resource commodity in reserves at any point in time [Figure 2].

The fact that many commodities have more resources available than efficient economic theory might suggest may be partly explained by two characteristics of mineral exploration cycles. First, the exploration sector tends to over-respond to the positive price signals through rapid increases in worldwide expenditures (which increases the rate of discoveries), in particular through the important role of more speculatively funded junior exploration companies. Exploration also tends to make discoveries in clusters that have more to do with new geological knowledge than with efficient capital allocation theory. As an example, once diamonds were known to exist in northern Canada, the small exploration boom that accompanied this resulted in several large discoveries, probably more than the market may have demanded at this time. These patterns are part of the dynamics that lead to commodity price cycles. New resource discoveries are very difficult to precisely match with far-off future demand, and the historic evidence would suggest that the exploration process over-compensates for every small hint of scarcity that the markets provide.

Another important element in resource economics is the possibility of substitution of commodities. Many commodity uses are not exclusive – should they become too expensive they can be substituted with other materials. Even if they become cheaper they may be replaced, as technology gains have the potential to change the style and cost of material usage. For example, copper, despite being less expensive in real terms than 30 years ago, is still being replaced by fibre optics in many communication applications. These changes to materials usage and commodity demand provide yet another dimension to the simple notion of depleting resources and higher prices.

In summary, historic metals price trends, when examined in the light of social and economic change through time, demonstrate that resource scarcity is a double-edged sword. The same societal trends that have increased metals consumption, tending to increase prices, have also increased the available wealth to invest in price-reducing knowledge and technology. These insights provide the basis for the economic sustainability of metals, to which we will next include uranium.

Uranium – rare or just a metal?

The preceding discussion summarizes arguments for economic sustainability of common metals. But what provides the confidence that uranium resources will behave like these metals? There are several lines of evidence.

1. Available crustal abundance

Simply put, metals which are more abundant in the Earth's crust are more likely to occur as the economic concentrations we call mineral deposits. They also need to be reasonably extractable from their host minerals. As an example, magnesium is a very abundant element, but its most common form of occurrence, bound in strong silicate minerals, means that only a portion of the Earth's magnesium is reasonably available to energy inputs that present economics can justify. By these measures, uranium compares very well to base and precious metals. Its average crustal abundance of 2.7 ppm is comparable to that of many other metals such as

tin, tungsten, and molybdenum, and many geologically common rocks such as granite and shales contain even higher uranium concentrations of 5 to 25 ppm. As well, uranium is predominantly bound in minerals which are not difficult to break down in processing.

2. Diversity of deposit types

As with crustal abundance, metals which occur in many different kinds of deposits are easier to replenish economically, since exploration discoveries are not constrained to only a few geological settings. Currently, at least 14 different types of uranium deposits are known, occurring in rocks of wide range of geological age and geographic distribution. There are several fundamental geological reasons why uranium deposits are not rare, but the principal reason is that uranium is relatively easy both to place into solution over geological time, and to precipitate out of solution in chemically reducing conditions. This chemical characteristic alone allows many geological settings to provide the required hosting conditions for uranium resources. Related to this diversity of settings is another supply advantage – that this wide range in the geological ages of host rocks ensures that many geopolitical regions are likely to host uranium resources of some quality.

3. Recent societal demand

Unlike the metals discussed above which have been in demand for centuries, society has barely begun to utilize uranium. As serious non-military demand did not materialize until significant nuclear generation was built by the late 1970s, there has been only one cycle of exploration-discovery-production, driven in large part by late 1970s price peaks [5]. This initial cycle has provided more than enough uranium for the last three decades and several more to come. Clearly, it is enormously premature to speak about long-term uranium scarcity when the entire nuclear industry is so young that only one cycle of resource replenishment has been required. It is instead a reassurance that this first cycle of exploration was capable of meeting the needs of more than half a century of nuclear energy demand.

4. World exploration at primitive stages

Related to the youthfulness of nuclear energy demand is the early stage that global exploration had reached before declining uranium prices stifled exploration in the mid 1980s. The significant investment in uranium exploration during the 1970-82 exploration cycle would be expected to be fairly efficient in discovering exposed uranium deposits, due to the ease of detecting radioactivity. Still, very few prospective regions in the world have seen the kind of intensive knowledge and technology driven exploration that the Athabasca Basin of Canada has seen since 1975. This fact has huge positive implications for future uranium discoveries, because the Athabasca Basin history suggests that the largest proportion of future resources will be as deposits discovered in the more advanced phases of exploration. Specifically, only 25% of the 1.4 billion lbs U_3O_8 discovered so far in the Athabasca Basin could be discovered during the first phase of surface-based exploration [5]. A sustained second phase, based on advances in deep penetrating geophysics and geological models, was required to discover the remaining 75%. Another dimension to the immaturity of uranium exploration is that it is by no

means certain that all possible deposit types have even been identified. Any estimate of world uranium potential made only 30 years ago would have missed the entire deposit class of unconformity deposits that have driven production since then, simply because geologists did not know this class existed.

Market trends

Perhaps the best evidence that uranium is indeed like any other metal is that its price has also declined in real dollars since the late 1970s spike to \$40/lb U_3O_8 .

Uranium replacement costs

The preceding arguments show that normal market forces in an economic system will “automatically” replenish uranium resources as they are needed. But this abstract economic process does not seem to speak about the real costs involved in replacing resources, except to imply that they are large enough to discourage rational companies from expanding resources during times of price weakness. How much does it cost to replace uranium resources, and is this cost a concern?

A characteristic of metals resource replacement is that the mineral discovery process itself adds a small cost relative to the value of the discovered metals. As an example, the huge uranium reserves of the Athabasca Basin were discovered for about US\$0.70/kg (current dollars, including unsuccessful exploration). Similar estimates for world uranium resources, based on published IAEA exploration expenditure data and assuming that these expenditures yielded only the past uranium produced plus the present RAR and EAR-I categories of published resources at <US\$80/kg [6], yields slightly higher costs of about US\$1.80/kg. This may reflect the higher component of State-driven exploration globally, some of which had national self-sufficiency objectives that may not have aligned with industry economic standards.

From an economic perspective, these exploration costs are essentially equivalent to capital investment costs, albeit spread over a longer time period. It is, however, this time lag between the exploration expense and the start of production that confounds attempts to analyse exploration economics using strict discounted cash flow methods. The positive cash flows from production occur at least 10-15 years into the future, so that their present values are obviously greatly reduced, especially if one treats the present as the start of exploration. This creates a paradox, since large resource companies must place a real value on simply surviving and being profitable for many decades into the future; and, without exploration discoveries, all mining companies must expire with their reserves. Recent advances in the use of real options and similar methods are providing new ways to understand this apparent paradox. A key insight is that time, rather than destroying value through discounting, actually adds to the option value, as does the potential of price volatility. Under this perspective, resource companies create value by obtaining future resources which can be exploited optimally at a range of possible economic conditions. Techniques such as these are beginning to add analytical support to what have always been intuitive understandings by resource company leaders – that successful exploration creates profitable mines.

Since uranium is part of the energy sector, another way to look at exploration costs is on the basis of energy value. This allows comparisons with the energy

investment cost for other energy fuels, especially fossil fuels which will have analogous costs related to the discovery of the resources. From numerous published sources, the finding costs of crude oil have averaged around US\$6/bbl over at least the past three decades. Converted into metric units as for the historic world uranium discovery costs quoted above (US\$1.80/kg), oil finding costs are clearly less expensive per unit of weight at US\$0.045/kg of oil. However, when finding costs of the two fuels are expressed in terms of their contained energy value, oil, at US\$1.05/GJ of energy, is about 300 times more expensive to find than uranium, at US\$0.0034/GJ. Similarly, the proportion of current market prices that finding costs comprise are lower for uranium. Its finding costs make up only 6% of the recent spot price of US\$11/lb, while the oil finding costs are 24% of a recent spot price of US\$25/bbl.

By these measures, uranium is a very inexpensive energy source to replenish, as society has accepted far higher energy replacement costs to sustain oil resources. This low basic energy resource cost is one argument in favour of a nuclear-hydrogen solution to long-term replacement of oil as a transportation fuel.

Resource estimates and exploration

If resource prices are better indicators of long-term supply adequacy, then are resource quantities of any value? Yes, since short-term supply will still largely come from known resources, we still need to understand the size, grade, and cost characteristics of all resources known at the present. As long as it is accepted that studies based solely on known resources are essentially a rear-view mirror perspective on supply, such approaches can still provide useful guidance about the next 2-10 years. However, supply forecasting beyond ten years, if it is to meaningfully project future supply trends, needs to include the effects of exploration on new supply. This is particularly true if the shorter term analysis indicates a rise in prices, since exploration cycles are largely signalled by price.

Numerous articles and studies have examined the known uranium resources [e.g. 7,8]. However, none have provided such an estimate of exploration-based supply additions, despite ample historic evidence that the 1970-82 exploration cycle was very efficient in discovering large and low-cost primary supply. Supply forecasters are often reluctant to consider the additive impacts of exploration on new supply, arguing that assuming discoveries is as risky and speculative as the exploration business itself. Trying to predict any single discovery certainly is; however, as long as the goal is merely to account for the estimated total discovery rate at a global level, a proxy such as estimated exploration expenditures can be used. Since expenditures correlate with discovery rate, the historic (or adjusted) resources discovered per unit of expenditure will provide a reasonable estimate of resource gains to be expected. As long as the time lag between discovery and production is accounted for, this kind of dynamic forecasting is more likely to provide a basis for both price increases and decreases, which metals markets have historically demonstrated.

Without these estimates of uranium resource replenishment through exploration cycles, long-term supply-demand analyses will tend to have a built-in pessimistic

bias (i.e. towards scarcity and higher prices), that will not reflect reality. Not only will these forecasts tend to overestimate the price required to meet long-term demand, but they can play into the agendas of opponents of nuclear power, who can use such forecasts to bolster arguments that nuclear power is unsustainable even in the short term. In a similar fashion, these finite-resources analyses also lead observers of the industry to conclude that fast breeder reactor technology will soon be required [Figure 2]. Fast breeders may indeed make a gradual appearance, but if uranium follows the price trends we see in other metals as argued here, their development will be due to strategic policy decisions, not because uranium has become too expensive.

The resource economics perspective tells us that new exploration cycles should be expected to add uranium resources to the world inventory, and to the extent that some of these may be of higher quality and lower operating cost than resources previously identified, this will tend to mitigate price increases. This is precisely what has happened in uranium, as the low-cost discoveries in the Athabasca Basin have displaced higher-cost production from many other regions, lowering the cost curve and contributing to lower prices. Secondary uranium supplies, to the extent that they can be considered as a very low-cost mine, have simply extended this price trend.

The depletion/sustainability balance

Arguments for the economic sustainability of mineral resources such as this one, relying as it does on the discipline of resource economics, are often criticized for ignoring the effects of depletion. Such criticisms have led to polarizing debates that appear to pit gloomy pessimists against rosy optimists. At the heart of such debates is the concern that human use of natural resources is unsustainable because of resource depletion, but there are also elements of distrust of economic systems and the role of markets.

The exhaustion of mineral resources during mining is real, and resource economists do not deny the fact of depletion, nor its long-term impact that in the absence of other factors, depletion will tend to drive commodity prices up. But as we have seen, mineral commodities can become more available or less scarce over time if the cost-reducing effects of new technology and exploration are greater than the cost-increasing effects of depletion.

One development that would appear to argue against economic sustainability is the growing awareness of the global depletion of oil, and in some regions such as North America, natural gas. Although there are many industry observers who believe that higher prices will continue to drive expansion of oil and gas production, a growing consensus is emerging that production of at least conventional crude oil will peak within the next 10 to 20 years. How does this fit with the arguments for sustainability of metals?

Part of the answer is that oil is a fundamentally different material. This starts with geology, where key differences include the fact that oil and gas were formed by only one process: the breakdown of plant life on Earth. Compared to the immense volumes of rock-forming minerals in the Earth's crust, living organisms on top of it have always been a very tiny proportion. But a more important fact is that the

world has consumed oil, and recently natural gas as well, in a trajectory of rapid growth virtually unmatched by any other commodity. Consumption growth rates of up to 10% annually over the past 50 years are much higher than we see for other commodities, and support the contention that oil is a special depletion case for several reasons: it has been inexpensive to extract, its energy utility has been impossible to duplicate for the price, and its resulting depletion rates have been incredibly high.

This focus on rates of depletion suggests that one of the dimensions of economic sustainability of metals has to do with their relative rates of depletion. Specifically, it suggests that economic sustainability will hold indefinitely as long as the rate of depletion of mineral resources is slower than the rate at which society is capable of offsetting the impact of depletion. This offsetting force will be the sum of individual factors that work against depletion, and include cost-reducing technology and knowledge, lower cost resources through exploration advances, and demand shifting through substitution of materials. An economic sustainability balance of this type also contemplates that, at some future point, the offsetting factors may not be sufficient to prevent irreversible depletion-induced price increases, and it is at this point that substituting materials and technologies must come into play to take away demand. In the case of the special case of rapid oil depletion mentioned above, that substitute appears to be hydrogen as a transport fuel.

Markets and timing

All of the resource replacement discussed above can only happen, however, if there is, in fact, a new exploration cycle. This must be initiated by clear economic and market changes. The timing of these market signals is therefore critical if the economic system is to incentivise exploration to discover new resources in time to replace those exhausted. In highly liquid markets such as copper or nickel, where inventories are not large compared to annual demand, these market signals have high credibility as indications of supply-demand dynamics.

In the case of uranium, it is an open question whether the current spot market provides sufficient liquidity and diversity to accurately signal future supply constraints. Significant here is the role of secondary supplies in deferring market evidence of impending primary supply tightness. It can be argued that secondary uranium should simply be treated as if it were primary. Since it has exceedingly low discovery costs (presumably its owners knew where it was), and very low production costs, the fact that it has displaced significant primary production fits well with economic theory. This is true up to a point, however, what is missed with this approach is that since secondary supply represents a “one-time” finite supply, its depleting inventory will not be replaced by resources with similar timing characteristics. Secondary uranium was and is available essentially instantly – new primary production will not be. While the uranium spot market has correctly responded to the availability of cheaper supply, it may not adequately signal the need for new primary supply which has very different timing from that being depleted. The final result of any such inefficiency in the spot market is difficult to predict, however the general trend should be towards

more volatility, not less, as the market finds out in real time when secondary sources reach depletion.

There has been only one significant exploration cycle in uranium's young history. While the mining industry has many talented firms that could undertake successful uranium exploration, few companies will be willing to make the necessary investments in uranium exploration until they see that the second cycle has begun. The support for this new exploration cycle will be the combined incentives of higher spot prices and renewed prospects for the growth of nuclear generation. The long-run story for uranium prices can be stated simply: prices must go up before they can come down again.

Conclusions

1. Evidence from centuries of metals use in society argues that metals are economically sustainable, and that cost-reducing impacts from new technology, exploration, and substitution have resulted in metals which are cheaper in real currency than before.
2. Despite being an energy commodity, uranium has the geological attributes of metals, and is expected to display the same economic sustainability into the long term as new exploration cycles, incentivized by market indications of supply tightness, and to generate new resources to replace those depleted.
3. Low-cost secondary supplies of uranium have displaced primary sources as they should in an efficient market; however, the instant availability of secondary sources will not be duplicated, given the lead times needed for both development of known primary resources and discovery of new ones.
4. The wide geological availability of uranium, its low cost of resource replenishment, and its low cost to the customer as a component of final generating costs – all of these combine to make the natural uranium source a significant advantage for the future of nuclear power.

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