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# The Supply of Medical Radioisotopes

## 2019 Medical Isotope Demand and Capacity Projection for the 2019-2024 Period

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**NUCLEAR ENERGY AGENCY**
**STEERING COMMITTEE FOR NUCLEAR ENERGY**

# High-Level Group on the Security of Supply of Medical Radioisotopes

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## Acknowledgements

This report would not have been possible without the contributions of a large number of supply chain participants and stakeholders, including major research reactor operators and processors, generator manufacturers, nuclear pharmacies, governments and associations representing nuclear medicine professionals, nuclear pharmacies, hospitals and industry.

The OECD Nuclear Energy Agency (NEA) greatly appreciates the important information provided confidentially by supply chain participants to support the work of the NEA following on from the High-level Group on the Security of Supply of Medical Radioisotopes (HLG-MR), which ended its fourth and final mandate in December 2018.

The information on molybdenum-99 ($^{99}$Mo)/technetium-99m ($^{99m}$Tc) production capacity and facility utilisation supports the analysis of demand and the creation of capacity projections for the 2019-2024 period. These projections are intended to help policy makers, producers and other stakeholders take decisions that lead to appropriate actions to ensure the economically sustainable, long-term, secure supply of the key medical isotopes $^{99}$Mo and its decay product, $^{99m}$Tc.

The present report was written by Mr Kevin Charlton of the NEA Division of Nuclear Technology Development and Economics. Detailed review, comments and suggestions were provided by stakeholders.

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# List of abbreviations and acronyms

| | |
|---|---|
| ANM | ANSTO Nuclear Medicine (Australia) |
| ANSTO | Australian Nuclear Science and Technology Organisation |
| CNL | Canadian Nuclear Laboratories |
| EOP | End of processing |
| FCR | Full cost recovery |
| HEU | High-enriched uranium |
| HLG-MR | High-level Group on the Security of Supply of Medical Radioisotopes (NEA) |
| LEU | Low-enriched uranium |
| NEA | Nuclear Energy Agency |
| NRU | National Research Universal (CNL, Canada) |
| IRE | Institute for Radioelements (Belgium) |
| ORC | Outage reserve capacity |

# Chapter 1. Introduction

Medical diagnostic imaging techniques using technetium-99m ($^{99m}$Tc) account for approximately 80% of all nuclear medicine procedures, representing around 30 million examinations worldwide every year. Disruptions in the supply chain of these medical isotopes – which have half-lives of 66 hours for molybdenum-99 ($^{99}$Mo) and only 6 hours for $^{99m}$Tc, and thus must be produced continuously – can lead to cancellations or delays in important medical procedures, with consequent effects on patients, their treatment and their health.

Supply reliability has often been challenged over the past decade due to unexpected shutdowns and extended refurbishment periods at some of the $^{99}$Mo-producing research reactors and processing facilities, many of which are relatively old. These shutdowns have at times created conditions for extended global supply shortages (e.g. 2009-2010) and indeed periods of chronic shortages were again experienced in late 2017 and during 2018.

At the request of its member countries, the Nuclear Energy Agency (NEA) thus became involved in global efforts to ensure an economically sustainable, long-term secure supply of $^{99}$Mo/$^{99m}$Tc. From June 2009 until December 2018, the NEA and its High-level Group on the Security of Supply of Medical Radioisotopes (HLG-MR), over the course of four mandates, examined the causes of supply disruptions and developed a policy approach, including principles and supporting recommendations to address these causes.

Since the formal end of the HLG-MR in December 2018, the NEA has continued some of this work following on from the HLG-MR, including via this report. It was agreed at the final meeting of the HLG-MR that the NEA would continue to review the global $^{99}$Mo demand and supply situation periodically, to highlight future periods of potential supply weakness, underscoring the case for continuing to implement the HLG-MR policy approach in a timely and globally consistent manner.

In 2012, the NEA released an $^{99}$Mo supply and demand forecast up to 2030, identifying periods of potential low supply relative to anticipated demand. The 2012 forecast was updated with a report in 2014 that focused on the shorter period of 2015-2020, and this shorter report was updated annually. In 2018, the NEA published the report, "2018 Medical Isotope Supply Review: $^{99}$Mo/$^{99m}$Tc Market Demand and Production Capacity Projection 2018-2023" (NEA, 2018).

Every report since 2014 has underlined that a substantial delay can occur during the implementation of new projects, even when looking only at a six-year time window, which is confirmation that trying to project the likely production capacity for a period beyond the six-year window would have very little added value.

The present report[1] updates the 2018 analysis and focuses on the 2019-2024 period, an important period that follows the planned removal from service of a number of substantial production facilities. The OSIRIS reactor in France, in particular, permanently ended operations in late 2015, and the National Research Universal (NRU) reactor in Canada ceased routine production of $^{99}$Mo at the end of October 2016. The NRU reactor then permanently shut down all operations in late March 2018. The processing capacity associated with the NRU had moved to a "hot standby" mode for the period between

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[1] The scenarios presented by the NEA in this report should not be construed as a prediction or forecast on which projects will proceed and when. The scenarios are only meant to be illustrative of possible, future situations, regardless of whether planned new projects materialise or not.

October 2016 and March 2018, thereby retaining the capability to provide a contingency capacity during that period, if justified.

### $^{99}$Mo supply remained under pressure in 2018, with chronic shortages

Although the supply chain was put under substantial stress from mid-November 2017 due to the unplanned outage of the NTP Radioisotopes SOC Ltd facility in South Africa, the potential contingency capability was not called upon. The NTP facility returned to limited service in late February 2018 with a plan to move stepwise towards a return to full capacity during the first half of 2018. Unfortunately, further problems led to another period of outage from early June 2018 to late November 2018.

Since late November 2018, the NTP facility has been back in operation, but at a reduced operating capacity and with increased regulatory surveillance. It has been anticipated in the present report that the NTP facility would return to full operating capacity during the course of 2019, but there have been further intermittent supply interruptions reported in early 2019. The extent and duration of the NTP outages and the resulting reduced total irradiation and processing capacity drew the total short-term processing capacity below the key NEA demand of the + 35% outage reserve capacity (ORC) line during 2018, with the result of a chronic level of supply shortage being experienced in some markets at various periods during 2018.

The difficulties experienced at NTP were compounded at various times during 2018 with short-term operating problems at the BR2 reactor in Belgium)and the HFR reactor in the Netherlands. Additionally, some minor short-term reactor problems were experienced at the OPAL reactor in Australia, but, more importantly, an extended problem was experienced with overall generator production in Australia, leading to the need to ship bulk $^{99}$Mo from Australia to the US for generator production and then return the completed generators to Australia by ship. This "outsourcing" of generator production and the associated extensive transportation of bulk material and generators led to additional $^{99}$Mo decay losses during a period when bulk $^{99}$Mo was already in short supply.

### Some important progress has been made in recent years

The Curium processing facility in the Netherlands confirmed conversion to 100% use of low-enriched uranium (LEU) targets in mid-January 2018 and successfully produced bulk $^{99}$Mo using only LEU targets throughout the remainder of 2018. Through this action, around 70% of all worldwide $^{99}$Mo/$^{99m}$Tc production came from LEU sources. Some irradiation capacity reductions were identified, however, by reactor operators associated with conversion to LEU targets, confirming the anticipated effect of a reduction in irradiation efficiency with the use of LEU targets. The conversion by IRE to the use of LEU targets was further delayed during 2018, and conversion is now anticipated to begin in 2019.

The introduction of non-conventional reactor-based $^{99}$Mo/$^{99m}$Tc production was announced in early 2018, when approval was granted by the US Food and Drug Administration (FDA) for the NorthStar RadioGenix™ System. That decision allowed $^{99}$Mo/$^{99m}$Tc produced from from neutron-activated natural molybdenum targets produced in a conventional research reactor, to be supplied into the US market as the RadioGenix™ System.

The present report provides information on global irradiation and processing capacity under the same three main capacity scenarios as set out in previous reports since 2015. Former HLG-MR delegates emphasised the importance of continuing to produce report updates at least on an annual basis. The information in this report should be interpreted in terms of projected future trends and should not be interpreted as actual forecast production values and implementation dates.

# Chapter 2. Demand update and outage reserve capacity review

In 2011, the NEA released a study with the results of a global survey of future demand for $^{99}$Mo/$^{99m}$Tc (NEA, 2011), based on an assessment by an expert advisory group. The study anticipated $^{99}$Mo/$^{99m}$Tc demand growth up to 2030 in both mature and emerging markets, with stronger growth forecast in emerging markets.

In a subsequent report, “A Supply and Demand Update of the Molybdenum-99 Market” (NEA, 2012a), the NEA estimated global $^{99}$Mo demand at 10 000 6-day curies $^{99}$Mo per week[1] at end of processing (EOP). This demand was lower than the previous estimate of 12 000 6-day curies $^{99}$Mo per week EOP, and the difference primarily resulted from a number of market changes that occurred as a consequence of the 2009-2010 global supply crisis. Those changes included better use of available $^{99}$Mo/$^{99m}$Tc, more efficient elution of $^{99m}$Tc generators, adjustments to patient scheduling and some increased use of substitute diagnostic tests/isotopes. Some of the changes continued to be implemented in the market after the end of the 2009-2010 supply shortage period.

The April 2014 report, “Medical Isotope Supply in the Future: Production Capacity and Demand Forecast for the $^{99}$Mo/$^{99m}$Tc Market, 2015-2020” (NEA, 2014), used as a starting point the NEA 2012 estimate of 10 000 6-day curies $^{99}$Mo EOP per week from processors, but with modified annual demand growth rates of 0.5% for mature markets and 5% for developing markets. This change was based on information provided at that time by supply chain participants.

The 2015 NEA report, “The Supply of Medical Radioisotopes: 2015 Medical Isotope Supply Review: $^{99}$Mo/$^{99m}$Tc Market Demand and Production Capacity Projection 2015-2020” (NEA, 2015), introduced an adjusted world demand estimate of 9 000 6-day curies $^{99}$Mo EOP per week from processors. This estimate was based on a new set of data that was collected by the NEA from supply chain participants on capacity utilisation for each operating quarter of the period 2012 to 2014. The data, along with the actual operational periods for each facility (e.g. the actual number of operational days), provided useful information as it included known periods when the supply chain had been under stress because of unplanned facility outages.

The reasons behind the August 2015 market demand estimate being lower than in earlier reports were not clear. The continuation of some of the measures mentioned previously to increase efficiency of use of $^{99m}$Tc at the nuclear pharmacy and the clinic levels, combined with a reduction in average injected patient dose as a result of some technical improvements in gamma camera technology, as well as some protocol changes, may have played a role. Furthermore, in a market where full cost recovery (FCR) pricing continued to be implemented at different steps along the supply chain, with the result of steadily and substantially increasing prices, it would be understandable that efficiency of use of materials would be a priority for all supply chain participants whose objective was minimising costs.

This report builds upon the same approach as the August 2018 report; it is based upon an analysis of the same supply chain data set for the period from 2012 to 2018. Estimated market growth rates in this report have been kept unchanged at 0.5% for mature markets

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[1] A 6-day curie is the measurement of the remaining radioactivity of $^{99}$Mo six days after it leaves the processing facility (i.e. at the end of processing – EOP). In International System (SI) Units, 1 Ci is equal to 37 Giga becquerels.

and 5% for developing markets during the entire projection period. On this basis, at the end of 2018, mature markets were estimated to account for 81.5% of the global demand for $^{99}$Mo/$^{99m}$Tc, while emerging markets accounted for 18.5%.

The latest available data have been analysed to determine the level of recent market demand as described above, with reported global utilisation capacity being taken as a surrogate for market demand. The data set is not 100% complete. In this report, one processor and one consolidated irradiator/processor did not provide the requested data. For the purposes of this report, the market demand for $^{99}$Mo activity has been held at 9 000 6-day curies $^{99}$Mo EOP per week EOP based upon a starting reference time point of the end of 2014. This means that with the growth rates used in the current report, the market demand at the beginning of 2019 has increased and is estimated to be approximately 9 500 6-day curies $^{99}$Mo per week, representing a total increase of approximately 5% since the end of 2014.

### Total $^{99}$Mo/$^{99m}$Tc demand increased following the end of NRU operations

The latest analysis does not fully confirm nor disprove this level of estimated market growth during the period. The latest data, however, reconfirm that recent global demand for $^{99}$Mo is close to a level of 9 500 6-day curies $^{99}$Mo EOP per week, with some demand fluctuations seen at a quarterly level. There is some evidence that the level of production needed to supply the market increased in the period following the end of routine NRU production in late 2016. The end of NRU production directly resulted in extended supply lines to service the large US market, with increased volumes of bulk material delivered from outside North America. The short half-life of $^{99}$Mo (66 hours) – the product form that is transported internationally to generator manufacturers – results in approximately 1% of the entire quantity of product being lost through decay for every additional hour of distribution time. This is equivalent to a total 22.3% decay loss during 24 hours of additional distribution.

Increased distribution time has directly added to the demand for product per week at the time point EOP. The decay loss resulting from extended transport distribution was evident again in 2018 during the period of generator production problems in Australia. As an example, the actual production level at the time point EOP must increase by 28.7% to offset a 24-hour decay loss sustained in distributing product for an extra day. This is an example of how overall bulk $^{99}$Mo production capacity may need to increase without an equivalent increase in the end-user demand for patient doses.

### What capacity level is required to ensure that patient demand is met?

The total capacity level required to ensure that patients always receive their scans must include a sufficient level of paid outage reserve capacity (ORC). In the HLG-MR policy principles, it was proposed that a processor should hold a level of paid ORC sufficient to replace the largest supplier of irradiated targets in their supply chain. Likewise, participants further down the supply chain should hold similar levels of ORC. This is the so-called (n-1) criterion, that is, the level of ORC required by a customer to ensure that no supply disruption occurs when their largest individual supplier has an unplanned problem.

There have been occasions over the last few years when, for some participants, the (n-2) criterion (e.g. the ability to replace their two largest suppliers) may have been a more appropriate measure for ensuring secure supply. The actual levels for (n-1) and (n-2) criterion vary for each supply chain participant depending upon the diversity of their own supply chain and the actual levels of ORC required change as part of a dynamic process, for example when suppliers in different geographic locations enter and exit the market and when distribution distances change.

The number of separate supply chain participants has decreased since 2012 and the market share of the remaining participants has mostly increased. As a direct result, the general level of risk associated with an (n-1) type supply problem has generally increased. Furthermore, with fewer total supply chain members available, when an (n-1) supply stress situation does occur (as happened in 2018), the ability of the limited number of remaining suppliers to reschedule and cover all possible supply weaknesses is likely to be lower, especially when supply stress occurs over an extended period.

In the present report, the minimum ORC level recommended to meet demand has been held at the same level as the preceding report, that is, at a level of market demand plus ORC of +35%. Analysis of historical data has shown that the security of supply comes under stress whenever the theoretical maximum available production capacity falls below the +35% ORC level of demand.

Projected potential production capacity in this report is compared to "demand +35% ORC", with the level of demand without ORC also being shown as a reference line. Changes to the market share of the various supply chain members has been reviewed and while the maximum individual market share projected in 2019 is now higher than it was in 2012, the level of change does not justify adjusting the measure "demand + 35% ORC" as being a safe guidance level for an (n-1) supply situation. It should be made clear, however, that this statement is being made based on the clear provision that all of the members of the supply chain are implementing paid ORC in a full and appropriate way.

### What have been the challenges and changes to overall reserve capacity?

All supply chain participants agree that the principle of holding paid ORC is essential to ensure reliable supply. The need for ORC was amply illustrated in 2013, 2014, 2015 and most recently in late 2017 and 2018. Unplanned outages occurred at major $^{99}$Mo producers during these periods. On each occasion, significant outages tested the supply chain's ability to ensure reliable supply. In earlier years, the challenge was largely met by the supply chain using available ORC or perhaps by sourcing non-contracted reserve capacity on a temporary basis. This solution resulted in only a small number of limited supply shortages in some countries.

The supply stress events that started in mid-November 2017 have been more challenging, mainly because the total level of capacity available above the demand +35% ORC level had decreased by late 2017 as a result of planned facility closures in Canada and France, as reported earlier. Additionally, the outage problems had a duration of many months. The result was that there was an extended chronic shortage of around 5% of market demand for $^{99}$Mo through much of 2018, with some shorter periods of higher levels of shortage and some short duration supply problems with other isotopes (e.g. Iodine-131).

Long-term analysis, at a quarterly level, of the theoretical total reserve capacity available to the market (total available capacity minus actual utilised capacity) shows an overall long-term positive trend. This was the case for both irradiation capacity and processing capacity during the period from 2012 until 2016. Both then had a sustained, anticipated trough period starting from 4Q 2016 because of the planned withdrawal of the NRU reactor and the associated processing capacity. While the overall reserve capacity trends are positive, the actual capacity utilisation data show some periods of quite significant peaks and troughs. The lowest trough period since 2012 for reserve irradiation capacity was 1Q 2018, while the lowest trough for reserve processing capacity was 3Q 2018, both of which were primarily driven by the NTP outage problems. The shortages in 2017 and 2018 were driven by extended periods of reduced capacity, during which time there was essentially no reserve capacity available for many weeks.

In early 2019, the overall reserve capacity still remains in a trough period that began in 4Q 2016, but reserve capacity is projected to improve during 2019. Future reserve capacity levels for both irradiation and processing capacity from existing market players, based on planned operating regimes, are projected to increase progressively to reach levels above long-term trend lines by 2020. It should be noted that these projected increases are largely dependent upon additional capacity entering the market from Australia and upon the level of capacity from South Africa returning to historic levels.

### Insufficient paid ORC is being held

It is important to specify that the level of theoretical reserve capacity is not the same as contracted paid ORC. As mentioned in previous reports, the NEA has no direct way to measure the actual amount of paid ORC that is held in the supply chain. The actual level of paid ORC is the subject of many commercial agreements, each held between two or more supply chain participants.

It is also worth recalling that contracted ORC itself can be provided in a number of ways; these include the holding of additional supply contracts with supply chain members higher up the chain, and/or additional supply contracts held horizontally between supply chain members at the same level within the supply network. Demand-side ORC can also be provided by supply agreements held with individual customers. For example, a customer could accept that their supplier activate demand-side ORC measures during supply stress periods and accept to receive less material, perhaps for a financial compensation. There is some evidence to suggest that some demand-side measures were taken in the period November 2017 to November 2018.

Whichever ORC mechanism is used, the key principles must include an agreement to keep the ORC level constantly available and immediately dispatchable to the full extent covered. The provider of the ORC service must also be fully reimbursed for all the costs involved in providing the services, even if those services are not actually used. Any reserve capacity available in the market that is not contracted, or that cannot be immediately and fully dispatched, or that is not fully paid for, is not “true” ORC.

The NEA report entitled “Results from the Third Self-Assessment of the Global $^{99}$Mo/$^{99m}$Tc Supply Chain” (NEA, 2017b) pointed to progress towards implementing ORC since a similar analysis performed in 2014. However, the report also indicated that a major irradiator still remained only in the low category of “some progress made” and that two irradiators had still made “no progress” in implementing ORC at all. The fact that paid ORC has only been fully implemented for around 60% of the total theoretical supply capacity in the market is important. This indicates that while clear targets for the level of ORC are identified (e.g. the +35% ORC in this report), it is likely that the market itself has not fully implemented the recommended levels throughout the entire supply chain.

As paid ORC is not fully implemented in the supply chain, some supply chain members are either choosing to ignore the need for contracted ORC, or are only contracting it at a level somewhat below the recommended level. The under-contracting of ORC by the supply chain gives customers and stakeholders a false sense of security. Supply chains with insufficient levels of paid ORC carry a higher risk of supply disruption and an increased chance that the reserve capacity, which is theoretically available to the market is actually not usable during a supply stress event.

The 2017 NEA report mentioned above also indicated that many generator manufacturers had a low level of confidence in their suppliers actually holding sufficient paid ORC. The experience of generator manufacturers during the challenging 2017-2018 supply period, where almost all generator manufacturers experienced some level of shortage, reconfirms the concern that insufficient true “paid” ORC is held within the supply chain.

Given that the actual ORC level required for each supply chain participant will change over time, the ORC level recommended in this report should only be used with caution in providing advice or making decisions. The NEA believes that the demand curve with +35% ORC remains a good representation of the “safe” level of paid ORC capacity required to meet market demand under an (n-1) supply stress situation. However, this figure is fully dependent on the reserve capacity held by market players that can be considered true “paid” ORC, or in other words, which fully meets the key principles discussed above.

# Chapter 3. Scenarios and assumptions for $^{99}$Mo/$^{99m}$Tc production capacity

The NEA regularly updates the list of current and planned new $^{99}$Mo/$^{99m}$Tc irradiation and processing projects. The updates include revisions to production start/end dates and a review of the status of "qualified" potential projects. Appendix 1 provides various tables that list current and potential new $^{99}$Mo/$^{99m}$Tc producers, along with the status of "qualified" projects as of early 2019. Following the experience of extensive project delays over successive years, the configuration of the tables has been adjusted in the present report. It should also be noted that the tables are not exhaustive and do not include every potential project for $^{99}$Mo/$^{99m}$Tc production that exists around the world. Inclusion in any of the tables in this report does not translate into an expectation on the part of the NEA that potential new facilities may be operational by the indicated times shown, or even at all.

Supply chain participants acknowledge that, given the inability to store radioisotopes for later use, the actual weekly $^{99}$Mo/$^{99m}$Tc production levels will generally match the market demand. Therefore, the intent of this capacity projection is not to predict the actual level of $^{99}$Mo/$^{99m}$Tc produced in a specific period. It is rather intended to identify periods of increased risk of supply shortage in order to inform government policy makers, the industry and nuclear medicine professionals. Such higher-risk periods occur when the projected production capacity curve is close to or below the projected NEA demand curve of +35% ORC; that demand curve is shown as the green line in all graphs in the report.

The time horizon for $^{99}$Mo/$^{99m}$Tc production capacity used in this report is the six-year period 2019-2024. The report anticipates the commissioning of new reactor- and non-reactor-based projects around the world during this period. The capacity scenarios presented in the report are based on the data in Appendix 1, with some caveats.[1] Appendix 1 provides the current, available, maximum weekly capacity for producing reactors and processors under normal operating conditions. It should be noted that this maximum capacity level may not always be available for every week of operation and may vary for some periods.

The report explains the results obtained from the three capacity scenarios presented in six-month intervals (January-June and July-December). In all scenarios, the six-month projection intervals are based upon a weighted split of planned operating capacity between the two six-month periods, adjusted for the anticipated operational patterns provided by existing operators where that is known:

- Scenario A: "Reference" scenario – a baseline case that includes only currently operational irradiation and processing capacity.
- Scenario B: "Technological challenges" scenario – this adds the capacity from anticipated projects to scenario A, but in most cases, not all their planned new $^{99}$Mo production capacity. Conventional reactor-based projects, given their proven technology and the direct access of their product to the existing supply chain, are assumed to start production on their announced commissioning dates and are included in the analysis from their first full year of production. Alternative non-

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[1] See the notes under each table in Appendix 1.

conventional technology projects (including reactor- and non-reactor-based projects) are assumed to have a 50% probability of starting full-scale production on their announced commissioning dates. Given the unproven nature of these alternative technologies therefore, and in some cases their more difficult access routes to the market, only 50% of their new anticipated capacity is included in the projection for their anticipated first full year of operation.

- Scenario C: "Project delayed" scenario – this builds on the scenario B by further assuming that all new projects, whether conventional or non-conventional technology, are delayed by one year further beyond their present anticipated first full year of production.

A so-called "all-in" scenario (e.g. where all the planned new/replacement projects are included at full projected capacity) is not reported. If all new potential projects were to proceed at the capacities and times presently announced, there would be significant overcapacity in the $^{99}$Mo/$^{99m}$Tc market by 2024, a capacity level unlikely to be sustainable by the market in the long term.

It should be noted that scenarios B and C in this report do not include all of the announced projects listed in Appendix 1. In the present report, the projects listed in Table 5 have not been included in the projections, and in many cases, their likely commissioning dates have been delayed beyond 2024. This is not to suggest that those projects will not become operational, but it simply recognises that the report does not anticipate them being operational in the forecast period.

The approach for this report concerning the effects of LEU conversion has changed since the August 2018 report, where a simple blanket effect of a 10% level of efficiency loss was applied in the case that LEU conversion was still to take place. The market has now converted to greater than 70% supply from LEU targets and the final conversion project is in a late stage of implementation. Guided by the latest information available, it is thus now believed that LEU conversion effects will have no further negative effect on reported capacity.

# Chapter 4. Reference scenario: A

The reference scenario includes only current approved $^{99}$Mo production capacity, that is, the irradiators and processors that are part of the current global supply chain, including those in Argentina, Russia and, since 2018, the first NorthStar project in the United States. It should be noted that the capacity identified in previous reports as "transitional" (i.e. anticipated to be introduced by 2019) and that has now been successfully added to the global supply chain, such as the NorthStar capacity, is included in the reference scenario.

The existing supply chain successfully implemented additional capacity to progressively raise the level of the reference scenario in small steps during the period 2016 to 2017. However, in the 2018 report, some irradiation capacity reductions were reported as being linked to the conversion to LEU targets used at the Curium processing facility in the Netherlands. In 2018, there was also a reduction reported in the general capacity available in Russia. Additional capacity in Australia, which uses existing facilities, is included within the reference scenario, but the additional capacity that is planned from the new ANM processing facility is still excluded.

The supply chain was disrupted in late 2017 and during 2018 primarily as a result of unplanned outages of the NTP facility in South Africa. The NTP facility returned to operation, but at temporarily reduced capacity levels and with some intermittent supply interruption in early 2019. The effects of the NTP outages and resulting reduced capacity are visible in reference scenario A. The six-month periods starting from July-December 2017 and in 2018 have been retained in all scenario graphs in the present report to identify the capacity that existed prior to the period affected by the problems experienced at NTP.

It should be noted that the NRU reactor in Canada ended routine $^{99}$Mo production in October 2016 and finally ended all operations in March 2018. All potential contingency capacity from that source has thus been removed from the report.

## Reference scenario: A – Irradiation and processing capacity

Figure 4.1 shows the projected 2019-2024 global NEA demand estimate for $^{99}$Mo, the NEA demand estimate +35% ORC, and the projected current irradiation capacity and current processing capacity based on reference scenario A. This is the capacity of the present fleet of irradiators and processors, inclusive of any planned additional capacity adjustments to those existing facilities.

## Reference scenario: A – Irradiation capacity

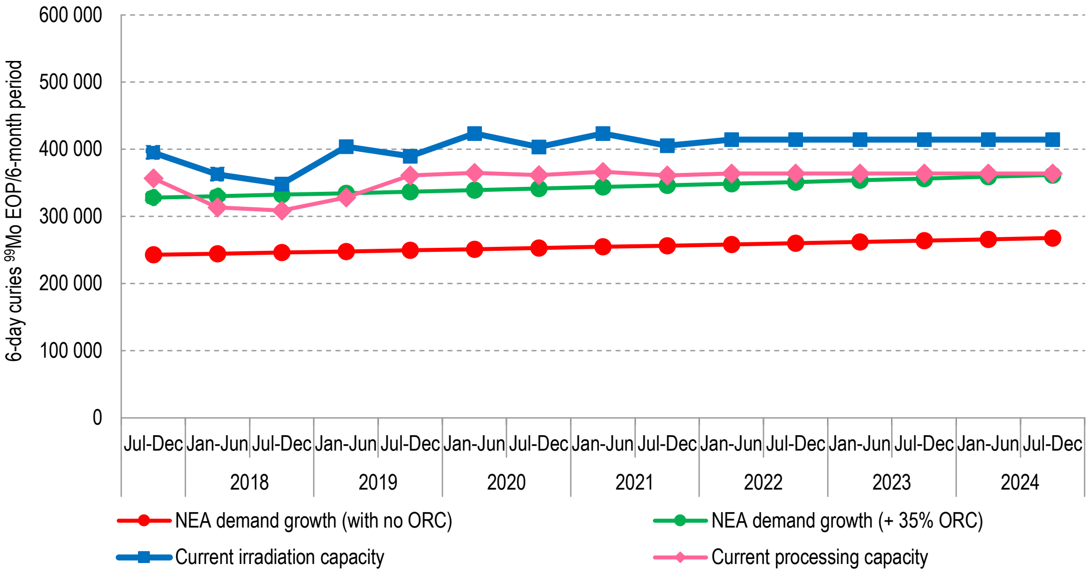
In the reference scenario A Figure 4.1, the irradiation capacity during 2018 reflects the unplanned loss of NTP capacity. The year 2019 began with the NTP facility having recently returned from an unplanned shutdown, but with temporarily reduced capacity. As a result, a proportion of the normal anticipated capacity from NTP has also been lost in the January-June 2019 period. Nonetheless, overall irradiation capacity recovers in 2019 with the minor reduction in irradiation capacity noted in the July-December 2019 period being due to scheduling and planned irradiator maintenance periods at BR-2 in Belgium, LVR-15 in the Czech Republic, MARIA in Poland and OPAL in Australia.

Irradiation capacity is then projected to remain relatively flat through the period to 2024, with minor capacity fluctuation in 2020 and 2021 due to reactor scheduling.

Irradiation capacity remains above the NEA demand of the +35% ORC line through to 2024. Overall, the irradiation capacity appears to be sufficient to ensure supply throughout the projection period.

In Europe, a network of four reactors supply two processing facilities, while $^{99}$Mo-irradiating reactors outside Europe each have individual associated processing facilities. In recent years, the total European irradiating capacity under normal operating conditions has been greater than the total European processing capacity. The level of that additional irradiation capacity can be seen by comparing the irradiation and processing capacity curves in Figure 4.1. The additional irradiation capacity in Europe is projected to be at its lowest in the July-December 2019 period due to scheduling and planned maintenance at some reactors.

**Figure 4.1: Demand (9 500 6-day Ci $^{99}$Mo/week EOP) and demand +35% ORC vs. current irradiation and current processing capacity, 2019-2024: Scenario A**



## Reference scenario: A – Processing capacity

In the reference scenario A shown in Figure 4.1, the processing capacity during 2018 reflects the unplanned loss of NTP capacity, with total processing capacity in 2018 being structurally below the important NEA demand +35% ORC line. During much of 2018, a chronic level of supply shortage was experienced at the generator level of the supply chain, with supply shortages in some markets throughout the period. At times during 2018, these shortages affected nuclear pharmacies and some clinical services.

The year 2019 began with the NTP facility having recently returned from an unplanned shutdown, but at reduced processing capacity and vulnerable to further disruption. A proportion of the normal anticipated capacity from NTP has also been lost in the January-June 2019 period, with the result of holding the total processing capacity level below the NEA demand of +35% ORC. Some limited shortages have been reported in early 2019, and the level of reserve processing capacity remains uncomfortably low.

Total processing capacity is projected to return to above the NEA demand +35% ORC line for the July-December 2019 period, but this is entirely dependent upon the NTP facility returning to full capacity. Overall existing processing capacity in 2019 is held slightly lower due to planned maintenance work at the IRE processing facility in Belgium. Processing capacity from existing supply chain members is projected to remain relatively stable with minor variations due to scheduling and to remain a little above the key NEA demand +35% ORC line, until finally reaching that line in 2024. The level of projected global processing capacity from existing facilities will be uncomfortably close to the NEA demand +35% ORC line throughout the period.

Overall, the current irradiators and processors, if well maintained, planned and scheduled should be able to manage limited periods of unplanned outage of a reactor during the projection period. The capability to manage any longer-term adverse events, in particular for processing capacity, is very low, and this capability reduces throughout the reference period. If no additional capacity is added above the reference scenario A (representing only existing suppliers), the security of supply risks being compromised if unplanned outages occur, especially if they are of extended duration. That risk slowly increases in the latter years of the projection, and supply risk is further increased if the full supply chain does not hold the recommended level of paid ORC.

# Chapter 5. Technological challenges scenario: B

The technological challenges scenario presented in this report has carried over the principles from previous reports. The scenario is a direct extension of reference scenario A presented in the previous section, and includes the addition of "qualified" new reactors and processors, as well as alternative technology projects, although the number of projects categorised in this group (as listed in Tables A1.3 and A1.4) has reduced in this report.

In the preparation of this report, Tables A1.1 to A1.4 shown in Appendix 1 were thoroughly reviewed and revised in consultation with potential supply chain participants using a standard format of project timeline reporting. Because of an increasing number of projects previously reported in Tables A1.3 and A1.4 having slipped out of the projection period (2019 to 2024) as a result of further delays or no progress being reported on the projects, an additional Table A1.5 has been developed to include projects that are now considered out of scope for the scenario B projection. In other words, not all of the projects announced around the world have been included in this technological challenges scenario B.

More specifically, the NEA has decided to consider only new projects that are likely to be commissioned and operational for at least one year before the end of 2024. Projects that are excluded are those that have unspecified construction start, licensing and/or commissioning dates, or where there is inconclusive information about likely operational or licensing dates. By making such a determination, the NEA is not suggesting that there is no possibility of the projects in Table A1.5, or other projects, never materialising, but rather that they may not be commissioned within the forecast period or have their products licenced. Projects are not included or excluded on the basis of their proposed technology.

Furthermore, all new technology projects, whether reactor-based or non-conventional reactor-based are assumed to have a 50% probability of being commissioned within their announced timelines, as noted in Tables A1.3 and A1.4. This assumption is to account for the fact that most alternative and non-conventional technologies have yet to be proven at a large scale in the $^{99}$Mo/$^{99m}$Tc market. It has been translated by applying only 50% of the expected maximum capacity to the forward projection for each of these projects.

Appendix 1 (Tables A1.3 and A1.4) now contains only some of the planned, "qualified" projects that were in previous NEA reports, and these tables contain no new projects that have been announced since the 2018 report. Scenarios B and C (see also Chapter 6) include only the projects that remain in Tables A1.3 and A1.4.

Five projects previously included in those tables have been transferred to Table A1.5, those being:-

- The proposed Korean reactor and processing facility put on hold due to an earthquake.
- The Polish processing facility associated with the MARIA reactor, which is still subject to budget approval.
- The Brazil MR reactor and processing facility project, which is now scheduled for completion later than 2024.

- The China Advanced Research Reactor and associated $^{99}$Mo processing facility, where no firm project planning could be ascertained.
- The SHINE (Subcritical Hybrid Intense Neutron Emitter) project, where the company did not provide the requested data.

All of these projects have been the subject of multi-year project delays. A review of all of the projects over sequential NEA reports (see Chapter 7) has identified many, multi-year delays involving both conventional and alternative technologies. Multi-year delays are often linked to budget problems, although some delays are also due to technical and licensing delays. It should be assumed that timeline slippage will continue to be a feature affecting many projects that have yet to secure full funding and/or all relevant licence approvals.

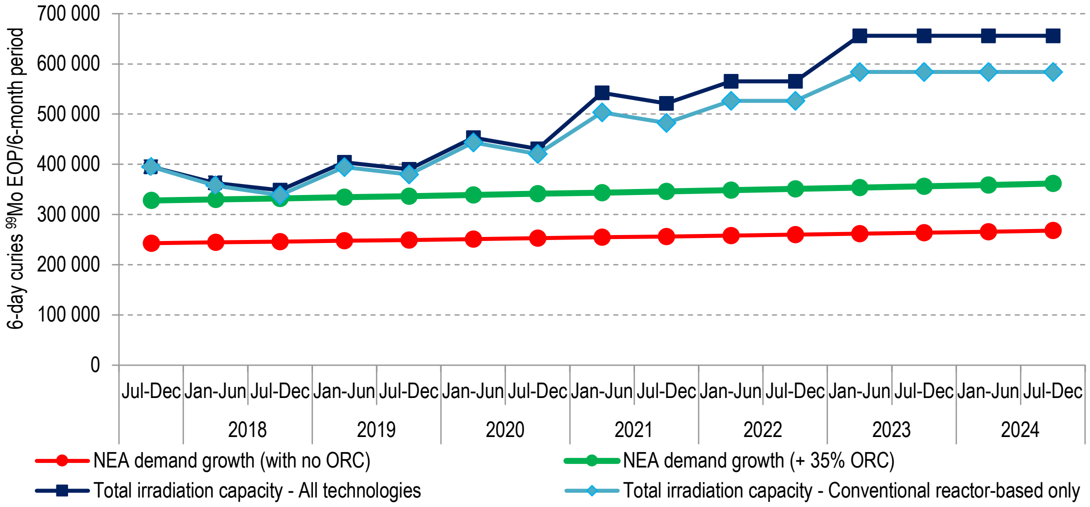
The number of projects remaining within the 2019 to 2024 projection period is a concern. In this 2019 report, no new projects with the potential to become operational by 2024 have been added to this analysis. The remaining two projects that support increased supply capacity to the recently licenced NorthStar RadioGenix™ equipment remain in this section of the analysis. It should be noted that the successful licensing of the RadioGenix™ System could provide a potential route to market for material from other "non-uranium fission" based $^{99}$Mo technology.

In the period beyond 2024, the proposed projects for $^{99}$Mo/$^{99m}$Tc irradiation and associated processing capacity, if all are completed, would significantly exceed the projected market demand. However, this apparent future excess capacity should not imply that long-term security of supply is ensured. It does not take into account any current capacity being retired early, or the potential for continued multi-year delays of projects; nor does it consider any commercial sustainability effects that future potential "overcapacity" may have on the market.

### Technological challenges scenario: B – Irradiation capacity

Figure 5.1 presents the NEA projected demand, projected demand +35% ORC and the irradiation capacity under the technological challenges scenario B. This shows both the total capacity for "all technologies" and the capacity for "conventional reactor-based only". It can be seen that following the recovery of irradiation capacity in the January-June 2019 period, even without all planned new projects being fully included, the global capacity of both lines looks to be sufficient to meet projected demand throughout the six-year projection period.

**Figure 5.1: Current demand (9 500 6-day Ci $^{99}$Mo/week EOP) and demand +35% ORC vs. irradiation capacity – total and conventional reactor-based only, 2019-2024: Scenario B**



To compare the contribution that alternative $^{99}$Mo/$^{99m}$Tc production technologies may have upon irradiation capacity, Figure 5.1 separates out conventional (reactor-based) irradiation capacity from total irradiation capacity. These lines started to diverge in 2018 when the first capacity from the NorthStar RadioGenix™ project became available to the market.

Irradiation capacity dips in the July-December 2019 period due to the scheduling of existing capacity described in scenario A, and is then projected to increase in 2020 with full capacity being available from the ANM (Australia) project. As in the reference scenario A, the irradiation capacity is anticipated to fluctuate lightly in 2020 and 2021 due to reactor scheduling.

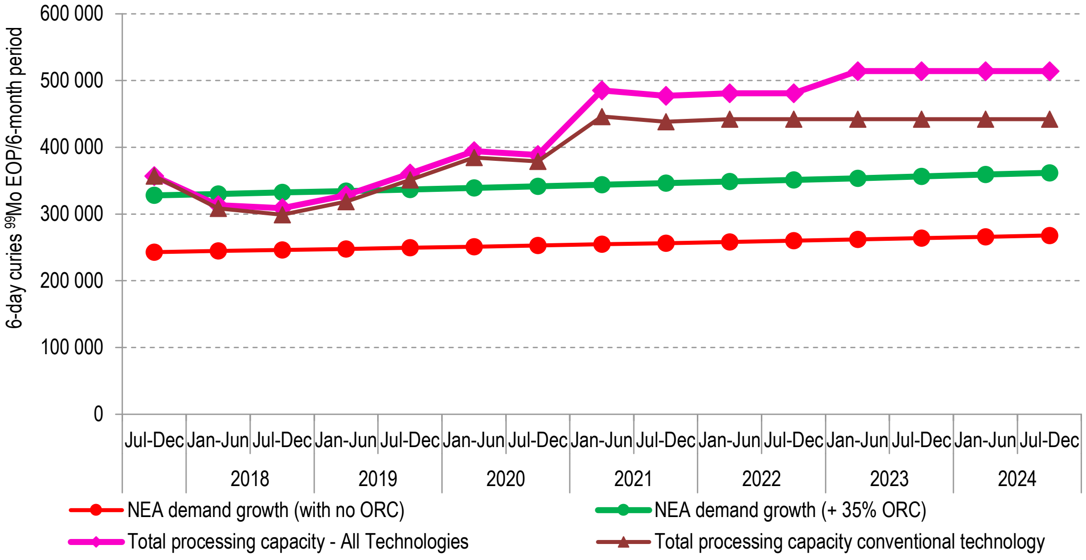
Substantial, additional conventional irradiation capacity is projected to be added from the RA-10 reactor (Argentina) in 2021, while additional capacity to the European network from the FRMII reactor (Germany) has been delayed until 2022, and further capacity from the JHR reactor (France) remains scheduled for 2023. Additional irradiation capacity from "alternative technology" will only substantially add to security of supply from 2021, with that capacity coming from the United States.

The total irradiation capacity projected by 2024 is now around 13% lower than the equivalent projection made to 2023 in the previous report; this reduction in projected longer-term capacity is primarily due to delays in projects now listed in Table A1.5.

## Technological challenges scenario: B – Processing capacity

Figure 5.2 presents the NEA projected demand, projected demand +35% ORC and the processing capacity under the technological challenges scenario B. It shows both total processing capacity for "all technologies" and processing capacity for "conventional technology only". It appears evident that following the anticipated recovery of capacity in the July-December 2019 period, even without all planned new irradiation projects being fully included, the global capacity of both lines looks to be sufficient to meet the projected NEA demand +35% ORC throughout the six-year projection period.

**Figure 5.2: Current demand (9 500 6-day Ci $^{99}$Mo/week EOP) and demand +35% ORC vs. processing capacity – total and processing capacity – conventional only, 2019-2024: Scenario B**



As in scenario A, global processing capacity was reduced during 2018 and early 2019 as a result of the NTP problems and resulted in overall processing capacity being below the important NEA demand +35% ORC line. Processing capacity in scenario B is projected to recover in late 2019 and into 2020 with full capacity becoming available from the ANM (Australia) project. Substantial, additional conventional processing capacity is projected to be added from the Argentinian project in 2021 and some light fluctuation can be perceived in both 2020 and 2021 due to scheduling.

Processing capacity has been supported since 2018 with capacity from the NorthStar project, and additional processing capacity from the NorthStar enriched Mo targets project is now anticipated to be added in 2021, with further contributions from alternative technology in 2023.

The total processing capacity in scenario B projected by 2024 is around 8% lower than the equivalent projection made to 2023 in the previous report; this reduction in projected longer-term processing capacity is due to some reported capacity reductions and project delays.

It should be noted that when new processing capacity is linked one-to-one with new irradiation capacity, then both the processing and irradiation components of the projects must be successfully deployed for these technologies to provide additional capacity to the supply chain.

# Chapter 6. Project delays scenario: C

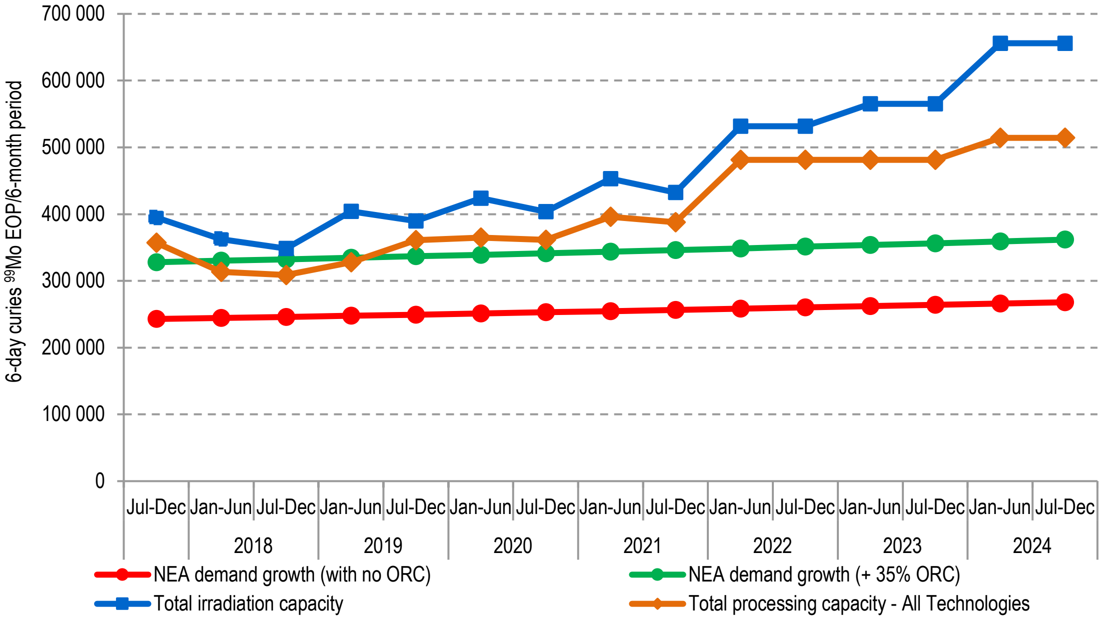
The project delays scenario C has been developed from the technological challenges scenario B by modelling a delay of one year for all new projects. This scenario considers the theoretical impact on future capacity when examining the technical complexity of new reactor-based projects and the often ground-breaking efforts undertaken for alternative technologies to reach large-scale, commercial production.

Review of past performance shows that large projects often take much longer to complete and license than originally envisaged, with multi-year delays being common. This conclusion has already been clearly demonstrated in previous NEA reports and in the analysis of scenario B in the present report. As further project delays can be anticipated, the project delays scenario C is probably the scenario most likely to reflect future events.

## Project delays scenario: C – Irradiation and processing capacity

Figure 6.1 shows the projected global irradiation and processing capacity under the project delays scenario C. Under this scenario, delayed projects will have a negative effect on both irradiation and processing capacity, with processing capacity remaining close to the reference scenario A level and the demand +35% ORC line until 2021.

**Figure 6.1: Current demand (9 500 6-day Ci $^{99}$Mo/week EOP) and demand +35% ORC vs. total irradiation capacity and total processing capacity – projects delayed, 2019 – 2024: Scenario C**



After recovering from lower levels of irradiation and processing capacity in 2018, and after the January-June 2019 period resulting from NTP problems, the projected capacities for both total irradiation capacity and total processing capacity in the projects delayed scenario C are projected to remain above the NEA demand +35% ORC line throughout the period to 2024.

Both the projected total irradiation capacity and total processing capacity remain relatively flat through 2020 and 2021, with irradiation capacity and to a lesser extent processing capacity showing the same half-yearly fluctuations described earlier in the report due to scheduling and planned maintenance periods. The projected levels of increase in capacity in 2021 in scenario C are much lower than in scenario B, and more substantial increases in total irradiation and processing capacities are delayed until 2022.

As in the 2018 report, the effects of project delays modelled in scenario C in this report are less pronounced than the equivalent scenario that was anticipated in the 2016 report. This is because a substantial amount of additional irradiation and processing capacity from the transition project in Australia are already locked into the reference scenario A. The total level of the capacities projected to be available by 2024 in scenario C are the same as those projected in scenario B.

The potential impact of project delays that are more extended is relevant; history confirms that most projects experience some delays and often suffer multi-year delays. Figure 6.2 looks at the potential impact of even longer delays and concentrates only on processing capacity, because it has a lower level of reserve capacity in all scenarios.

**Figure 6.2: Current demand (9 500 6-day Ci 99Mo/week EOP) and demand +35% ORC vs. processing capacity – current, total, total conventional only and total two-year delay, 2019-2024: Scenarios A + B + C (two-year delay)**

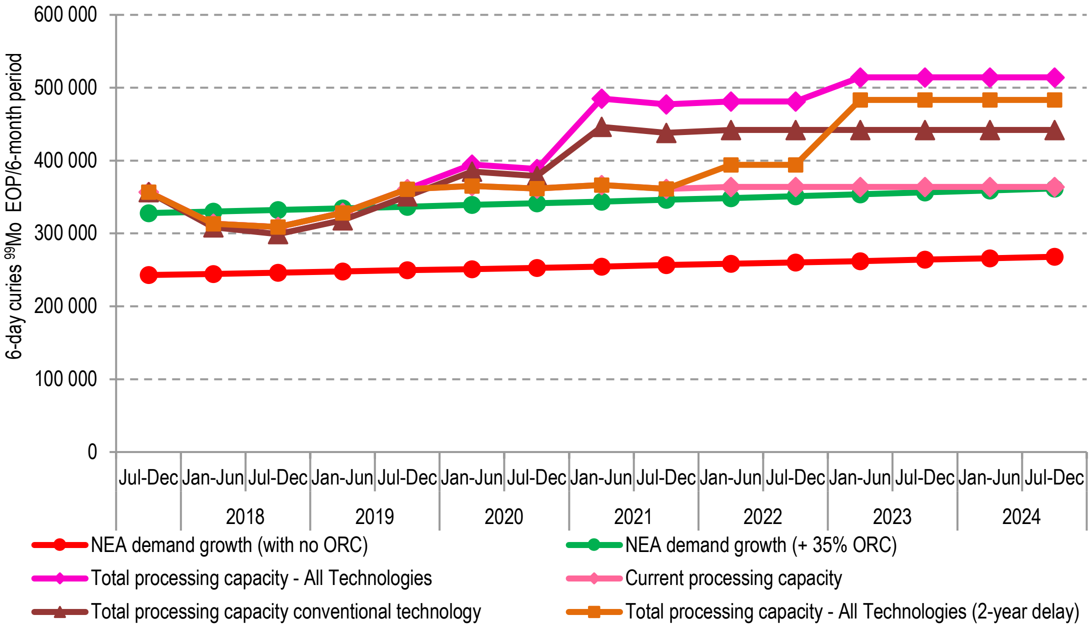


Figure 6.2 shows projected demand and projected demand +35% ORC lines compared to the current processing capacity (from scenario A), the projected total processing capacity and the projected capacity for conventional technologies only (both from scenario B), all of which have no project delay included. Figure 6.2 also projects a total processing capacity line with a two-year total project delay. The graph lines therefore represent the minimum,

the maximum and two potential intermediate lines representing different challenges for processing capacity through the period to 2024.

In all cases other than reference scenario A, after recovering from the period of reduced capacity resulting from the NTP outage in the 2018 and January-June 2019 period, the projected processing capacity stays above the NEA demand +35% ORC line throughout the period to 2024. However, in Figure 6.2, the 2019 projection for the maximum total processing capacity (from scenario B) is lower by the end of the reference period than in the equivalent 2018 projection.

The impact of assuming a further two-year delay in all processing projects results in a similar pattern to that of no additional processing capacity above the base line reference scenario A until 2022, leaving the total processing capacity uncomfortably close to the important NEA demand +35% ORC line for three years. Only a modest increase in processing capacity is projected in 2022, and any substantial increase is delayed until at least 2023.

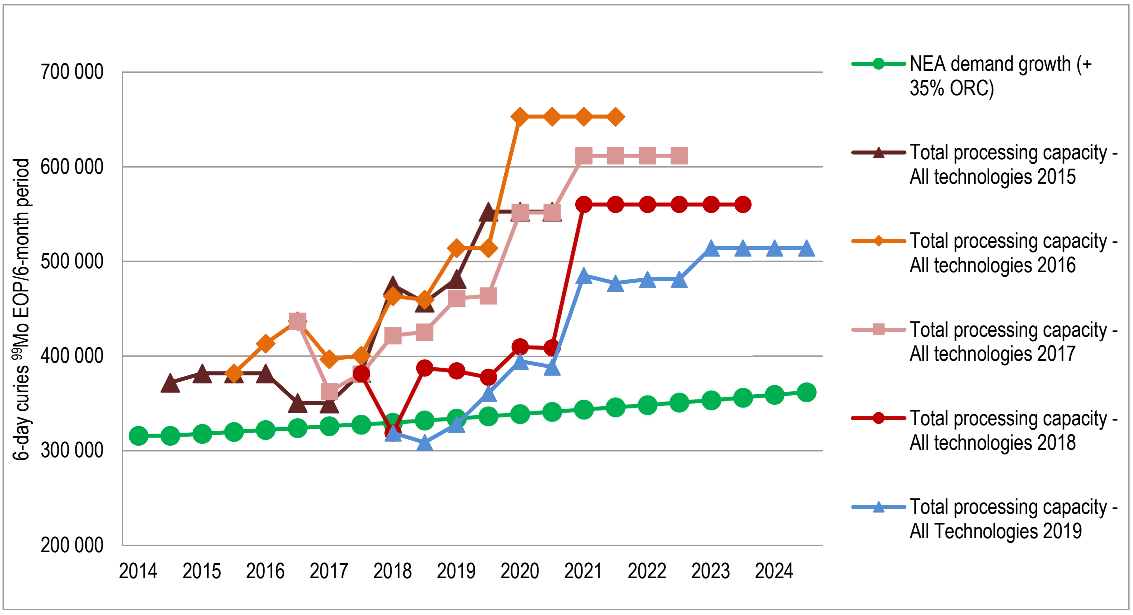
When only conventional technologies are considered, the projection (from scenario B) shows increased processing capacity beginning in 2021. This projection is unchanged from the equivalent projection in the 2018 report. The situation has been maintained because the Argentinian project schedule has remained on track.

The latest analysis reconfirms the importance of the availability of full capacity from the Australian project from late 2019 for total processing capacity. It also underlines the importance of maintaining the projected schedule of 2021 for the addition of capacity from conventional facilities in Argentina and from alternative technologies.

# Chapter 7. The cumulative effect of project delays

Since the report series began in 2014, it has been determined that multi-year delays can occur during the development of potential new projects. The NEA added some analysis of the effects of extended project delays in the 2018 report. That analysis has been continued in this report and Figure 7.1 shows the cumulative effect of project delays by comparing the "Technological challenges scenario B" projection line for total processing capacity each year for the period starting in 2015.

**Figure 7.1. Scenario B – "Technical Challenges": Effect of multi-year delays**



In Figure 7.1, the sequential projections for scenario B starting from 2015 are shown against the NEA demand + 35% ORC reference line. The first projection for total processing capacity for scenario B in 2015 (dark brown line) anticipated a reduction of processing capacity by 2017 (e.g. in the period after the end of NRU routine production), followed by a recovery in capacity by 2018, which then continued to mostly increase in a number of steps until 2020.

By 2016, the equivalent scenario B projection (orange line) showed that substantial actions had been planned by the existing supply chain members, either through increasing capacity from existing facilities, or by adding additional capacity and making transition plans. Those actions anticipated adding capacity in 2016 ahead of the end of NRU routine production, but still anticipated some reduction in capacity in 2017 when the NRU stopped. The projection then stabilised before increasing stepwise from 2018 onwards. The 2016 projection anticipated that the total capacity by 2020 would be higher than anticipated in the 2015 report as other new projects had been added.

Unfortunately, the 2017 scenario B projection (pink line) showed that not all of the additional capacity anticipated in the 2016 report had been achieved and that the capacity reduction anticipated at the end of NRU routine production would be larger than originally forecasted. The 2017 projection also anticipated some minor delays in some projects from 2018 onwards (the pink line moves a little to the right of the orange line). It also projected a decrease in the total anticipated capacity by 2021 as some capacity estimates for new projects were scaled back.

The 2018 scenario B projection (red line) showed the initial negative effects of the NTP unplanned outage on the short-term outlook and identified more extended delays to planned additional capacity (the red line has substantially shifted to the right of the pink line). The 2018 projection also identified a further decrease in the total anticipated capacity that would be achieved by 2021, partly as a result of project withdrawal.

The new 2019 scenario B projection (blue line), when superimposed onto the previous projections, reinforces the depth of the negative effects experienced following the NTP unplanned outage in 2018. The actual market effects that were experienced were more severe, because some planned projects had not yet fully materialised (note the difference between the actual capacity available in late 2018 [blue line] compared with the anticipated capacity by 2018, shown in the earlier projections). The total capacity now anticipated by 2021 has been further reduced compared to earlier projections, and the total capacity anticipated by 2024 is a further step lower.

When compared with the 2016 projection (orange line), the 2019 projection (blue line) shows that the main bulk of potential projects that were anticipated to have been introduced by 2018 were progressively delayed to later years, or they were cancelled. The total capacity projected to be available by 2018, as stated in the 2016 report, is not yet available. In 2019, that capacity is not projected to be achieved before 2021 now, effectively a total delay of at least 3 years. The cumulative effect of delays can be seen in the sequential projection lines that move in progressive steps (from 2015 to 2019) to lower levels and later time points. The anticipated total processing capacity in the 2019 scenario B projection for the 2019-2020 period is now at its lowest level since the start of this NEA series of capacity projections.

The cumulative effect of unplanned outages, multi-year project delays and project cancellations suggest that total processing capacity will now remain under pressure until at least 2021. It should be noted with caution that the projections shown in Figure 7.1 are from scenario B and are therefore relatively optimistic projections. Figure 6.2 shows the more likely projections for the total processing capacity that will be available during the 2019 to 2021 period, with some projections discussed in Chapter 6 showing that processing capacity could remain under pressure until 2023.

# Chapter 8. Conclusions

As in previous reports, the global estimate of demand growth has been maintained, using the same levels of annual increase since 2014. As a result, the projected demand level in 2019 has increased to approximately 9 500 6-day Ci $^{99}$Mo per week at end of processing (EOP). The level of production required at EOP at the processor point in the supply chain has likely increased since routine production in Canada ended because of the lengthening of supply lines, which has led to increased decay loss during transportation. This increase in the level of production required is unlikely to represent an actual increase in product demand at the final end-user level in the supply chain, and so the increased demand should primarily be seen as an extra stress and an extra cost to the system.

Some positive developments occurred in 2018, with conversion to 100% production using low-enriched uranium (LEU) targets at the Curium processing facility in the Netherlands and the licensing of the first alternative technology in the United States (Northstar). However, some irradiation capacity reductions resulted from LEU conversion, confirming decreased efficiency in LEU target irradiations.

Extended unplanned outages at the NTP facility decreased irradiation capacity and pushed processing capacity below the NEA demand +35% outage reserve capacity (ORC) guideline in 2018. Although the NTP facility had returned to service by late 2018, its operation at reduced capacity and vulnerability will continue to affect both irradiation and processing capacity during 2019. The recovery of total processing capacity to above the NEA demand +35% ORC guideline in the short term is dependent upon the NTP facility returning to full capacity.

The addition of further processing capacity from the new ANM facility was delayed again into 2019. The latest news confirms, however, that this new facility is now licensed and online, and full capacity is anticipated to become available in the second half of 2019. Further delays have been experienced in the introduction of some alternative irradiation and processing technologies. Delays to large, conventional technology projects have continued and have pushed back many projects beyond 2024. The multi-year delay of many projects remains a concern, and the effects can be seen in the Chapter 7 analysis.

When existing facilities are well maintained and well scheduled, and when unplanned outages are avoided, total irradiator capacity should be sufficient. That said, the supply chain must fully implement the recommended levels of paid ORC in order to be able to manage unplanned processor outages. However, when no additional processing capacity is added above the present level, the capability to manage adverse events will remain low and will be further reduced with time.

The supply situation will continue to require careful and well considered planning to minimise security of supply risks. A high degree of co-operation between all supply chain participants will continue to be essential for the foreseeable future, and the supply chain must complete the short-term planned increases to processing capacity, diversify further and implement sufficient “true” paid ORC to ensure against the risks of supply disruptions. The market situation continues to require regular monitoring and review.

## References/further reading

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All of the above reports are available at www.oecd-nea.org/med-radio

# Appendix 1

## Table 1. Current irradiators

| Reactor (Fuel) | Current targets[6] | Normal operating days/year | Anticipated $^{99}$Mo production weeks/year | Expected available capacity per week (6-day Ci $^{99}$Mo) | Expected first full year of $^{99}$Mo production[7] | Expected available capacity per year (6-day Ci $^{99}$Mo) by 2024 | Estimated end of operation |
|---|---|---|---|---|---|---|---|
| BR-2 (HEU) | HEU/LEU | 147 | 21 | 6 500 | NA | 136 500 | At least until 2026 |
| HFR[1] (LEU) | HEU/LEU | 275 | 39 | 6 200 | NA | 241 800 | 2026 |
| LVR-15 (LEU) | HEU/LEU | 210 | 30 | 3 000 | NA | 90 000 | 2028 |
| MARIA (LEU) | LEU | 200 | 36 | 2 200 | NA | 79 200 | 2040 |
| OPAL (LEU)[2] | LEU | 300 | 43 | 2 150 | NA | 92 450 | 2057 |
| RA-3 (LEU) | LEU | 230 | 46 | 500 | NA | 23 000 | 2027 or earlier based on RA 10 introduction |
| SAFARI-1 (LEU) | LEU | 305 | 44 | 3 000 | NA | 130 700 | 2030 |
| RIAR[3] (HEU) | HEU | 350 | 50 | 540 | NA | 27 000 | At least until 2025 |
| KARPOV[3] (HEU) | HEU | 336 | 48 | 350 | NA | 16 800 | At least until 2025 |
| MURR[4] (HEU) | Natural Mo in CRR | 339 | 52 | 750 | 2019 | 39 000 | 2037 |
| OPAL[5] (LEU) | LEU | 300 | 43 | +1 350 | 2020 | 58 050 | 2057 |

Notes: 1). HFR capacity increased to 6 200 per week from 2017, 2). OPAL extra irradiation capacity now operating at 12 plates, 3). RIAR and KARPOV material needs to comply with specific requirements to be available in some markets; the KARPOV facility will be relicensed in 2020 to continue its operation; RIAR weekly production varies depending on RBT-6/RBT-10 availability, 4). MURR irradiations for the NorthStar system started in 2018, 5). OPAL extra irradiation capacity at 12 plates in the new ANM $^{99}$Mo facility started 2019, first full year 2020, 6). HEU >20% enriched Uranium, LEU <20% enriched Uranium, 7). NA = Not Applicable

### Table 2. Current processors

| Processor | Targets[5] | Anticipated $^{99}$Mo production weeks/year | Available capacity per week (6-d Ci $^{99}$Mo) | Expected available capacity per year (6-d Ci $^{99}$Mo) by 2024 | Expected first full year of $^{99}$Mo production[6] | Expected year of conversion to LEU targets | Estimated end of production |
|---|---|---|---|---|---|---|---|
| ANSTO Health | LEU | 43 | 2 150 | 92 450 | NA | LEU | 2057 |
| CNEA | LEU | 46 | 500 | 23 000 | NA | LEU | 2027 or earlier based on RA 10 introduction |
| IRE | HEU | 49 | 3 500 | 171 500 | NA | 4Q 2019 | At least until 2028 |
| Curium[1] | LEU | 52 | 5 000 | 260 000 | NA | LEU | Not Known |
| NTP | LEU | 44 | 3 000 | 130 700 | NA | LEU | At least until 2030 |
| RIAR[2] | HEU | 50 | 540 | 27 000 | NA | 2019 | At least until 2025 |
| KARPOV Institute[2] | HEU | 48 | 350 | 16 800 | NA | 2019 | At least until 2025 |
| MURR/NorthStar[3] | Natural Mo target | 52 | 750 | 39 000 | 2019 | NA | At least until 2037 |
| ANSTO Nuclear Medicine (ANM)[4] | LEU | 43 | +1 350 | 58 050 | 2020 | LEU | 2057 |

Notes: 1).Curium converted to LEU in early 2018, 2). RIAR and KARPOV material needs to comply with specific requirements to be available in some markets; the KARPOV facility will be relicensed in 2020 to continue its operation, 3). NorthStar RadioGenix$^{TM}$ System production started in 2018, 4). ANM extra processing capacity is due to the additional; facility fully licenced from May 2019, 5). HEU >20% enriched Uranium, LEU <20% enriched Uranium, 6). NA = Not Applicable

## Table 3. Potential irradiators entering in period 2019 to 2024

| Irradiation source (Fuel) | Targets/technology[3] | Expected operating days/year | Anticipated Mo-99 production weeks/year | Expected available capacity per week (6-d Ci $^{99}$Mo) by 2024 | Potential annual production (6-day Ci $^{99}$Mo) by 2024 | Expected first full year of production | Project status (January 2019) |
|---|---|---|---|---|---|---|---|
| MURR/NorthStar[1] (HEU) | Enriched Mo in CRR | 339 | 52 | +2 250 | +117 000 | 2021 | In production scale up |
| RA-10 (LEU) | LEU in CRR | 315 | 48 | 2 500 | 120 000 | 2021 | Finish Building during 2019 |
| FRM-II (HEU) | LEU | 240 | 32 | 2 100 | 67 200 | 2022 | Project still in licencing phase |
| NorthStar (non U) | Non-fissile from Electron Accelerators | 339 | 52 | 2 540 | 132 080 | 2023 | In production scale up |
| Jules Horowitz Reactor[2] (LEU) | LEU in CRR | 220 | 24 | 4 800 | 115 200 | 2023 | Under construction |

Notes: 1). MURR/NorthStar Enriched Mo capacity is additional to the Natural Mo capacity when introduced, 2). JHR reactor begins active commissioning in 2022, but $^{99}$Mo capacity is not expected to be available until 2023, 3). CRR = Conventional Research Reactor, LEU <20% enriched Uranium, Mo = inactive Molybdenum, either natural or enriched

**Table 4. Potential processors entering the global supply chain in period 2019 to 2024**

| Processor | Targets[2] | Anticipated Mo-99 production weeks/year | Expected available capacity per week (6-day C $^{99}$Moi) by 2024 | Potential available capacity per year (6-day Ci $^{99}$Mo) by 2024 | Estimated first full year of production | Project status (January 2019) |
|---|---|---|---|---|---|---|
| MURR/NorthStar[1] | Enriched Mo target | 52 | +2 250 | +117 000 | 2021 | In production scale up |
| CNEA | LEU | 48 | 2 500 | 120 000 | 2021 | Building start by end 2019 |
| NorthStar | Non-fissile | 52 | 2 540 | 132 080 | 2023 | In production scale up |

Notes: 1). MURR/NorthStar Enriched Mo capacity is additional to the Natural Mo capacity when introduced, 2). LEU <20% enriched Uranium, Mo = inactive Molybdenum, either natural or enriched