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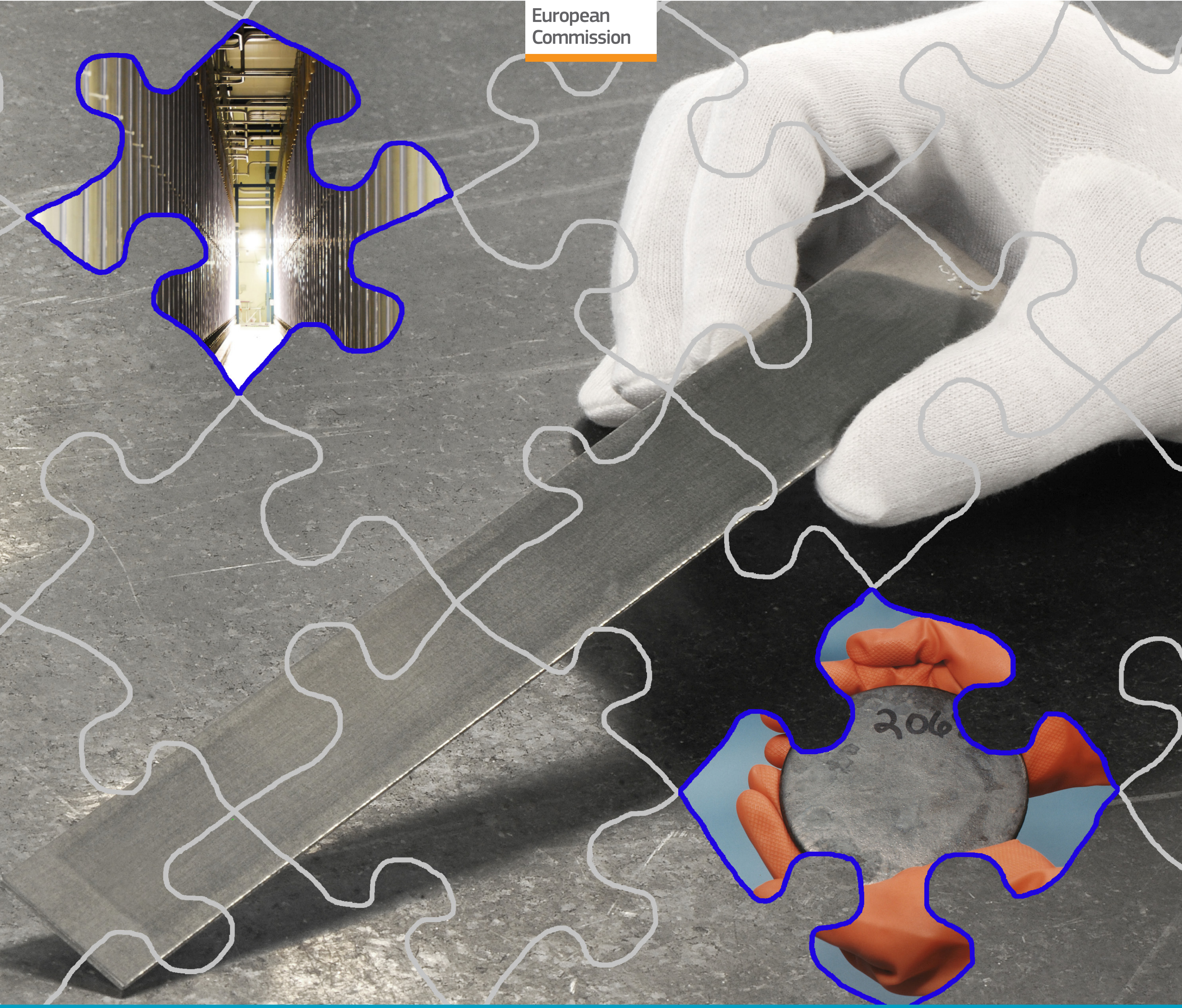

Securing the European Supply of 19.75% enriched Uranium Fuel

A REVISED ASSESSMENT

Euratom Supply Agency (ESA),
May 2019

Energy

Cover image : ©Framatome, Orano, US DoE

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This report reflects the collective views of the participating experts, though not necessarily those of the Austrian Member of the Advisory Committee.

Foreword

This report was produced by a dedicated working group, which was initially set up in 2012 by decision of the Advisory Committee of the Euratom Supply Agency (ESA) and reinstated by the Advisory Committee in its April 2018 session. The reinstated group, which convened three times, has revised the previous report issued in 2013. This revised report was endorsed and approved by the Agency's Advisory Committee in its session of 21 March 2019.

The report provides an updated view of high-assay low-enriched uranium (HALEU) needs, including potential global demand. It also takes account of developments in recent years, specifically realistic scenarios for the conversion of high enriched uranium (HEU) fueled high-performance research reactors, new concepts for power reactors and fuel design, the current geopolitical situation, and issues relating to the shipping and transport of HALEU. It also addresses the pressing issue of US stocks of HEU available for downblending to HALEU, since these are only sufficient to cover needs until 2030-2040.

HALEU is not currently produced in any western country. The material used in research reactors is obtained either by downblending US HEU stocks or from Russia. If no action is taken, there is a risk that the supply of this critically important material cannot be guaranteed after 2030-2040. This could jeopardise European research technological applications and the production of the most vital medical radioisotopes. It is now recognised that HALEU production could be of major importance for the future of: i) nuclear technology, ii) science using nuclear technology and iii) nuclear medicine.

Readers of this report will find an overview of the demand for HALEU in the coming decades, a discussion on the potential future needs of small and medium-sized reactors using advanced HALEU fuel, and a description of issues related to the metallisation, deconversion and transport of HALEU.

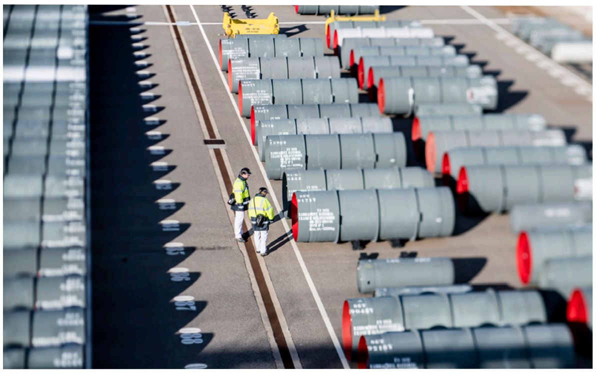
The core part of the report presents a business model to build European capacity for the production of metallic HALEU, based on three different market demand scenarios. The report concludes that building such a facility in the EU is feasible but that its economic viability would depend on certain conditions, in particular production volumes, price and financing.

By providing an overview of the current situation while looking ahead to the future, this report contributes to European and international discussion on the future secure supply of HALEU and provides policy-makers with a basis for making informed decisions on related initiatives.

Euratom Supply Agency

1. Introduction

In May 2012, a dedicated working group was set up by the Advisory Committee of the European Supply Agency (ESA) to evaluate the feasibility and opportunity of building a facility in Europe to produce metallic low-enriched uranium enriched to 19.75±0.2% (HALEU). This was to cover the needs of research reactors and ensure the production of Mo-99 for medical applications.



UF6 cylinders at GBII ©C. Crespeau - Orano

A report[1] issued in 2013 and published in May 2016 concluded that building such a facility on European soil would be economically viable only under certain conditions, such as a guarantee by customers to purchase the annual production of 1,300 kg at €20 k/kg (the current market price is around €12k/kg[2]). The report also concluded that from a legal perspective, there would be no need to amend international agreements (the Treaties of Almelo and Cardiff). Finally, it recommended that 'the Euratom Community invites the US and Russia to discuss the opportunity to commit to a long-term contract which would cover a supply period of ten years'.

The market has shifted since the report was issued. Sources from the US Department of Energy (DOE) have indicated that the stock of highly enriched uranium (HEU) available to supply domestic and foreign research reactors with either HEU or HALEU (obtained by downblending) will be exhausted at some point between 2030 and 2040[3]. In addition, new concepts of advanced fuel for (power) reactors may require higher enrichment than the conventional 5% fuel.

In 2017, the DOE published a request for information for the supply of enriched uranium[4] for civilian and military purposes, to estimate the need of test reactor fuels as early as 2025. At the end of May 2019, DOE awarded a contract to American Centrifuge Operating, LLC, to demonstrate the production of high-assay low enriched uranium[5].

In June 2018, a group of European research reactor operators published a position paper stating that 'one or two new (at least partly) dedicated irradiation reactors will be necessary in the next decade to replace the reactors expected to shut down' to avoid shortages of radioisotopes in Europe. This is despite the fact that the Forschungsr-Neutronenquelle Heinz Maier-Leibnitz (FRM II) and Réacteur Jules Horowitz (RJH) reactors will begin producing radioisotopes in the near future, and the Belgian Nuclear Reactor 2 (BR-2) and High Flux Reactor (HFR) are investigating the possibility of continuing operations beyond 2026[6]. This means that the necessary supply of HALEU must be secured.

Due to the changes in the situation since 2012/2013, the security of supply of HALEU to meet European needs for at least the next three decades has to be reassessed.

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[1] Report on Securing the European Supply of 19.75% enriched Uranium Fuel, Euratom Supply Agency, Advisory Committee WG report, issued 2013 [http://ec.europa.eu/euratom/docs/ESA-MEP-rapport.pdf].

[2] This 'low' price is due to the existing HEU stock, which is downblended to HALEU and the artificial way of establishing the price. Because HEU will become a scarce material, the price of HALEU is expected to increase.

[3] The exact date will depend on the availability of appropriate fuel to convert the HEU research reactors. A HALEU core will need more fuel than the strict ratio of the enrichment HEU to HALEU.

[4] Request for information for supply of enriched uranium DE-SOL-0008552.

[5] https://www.fbo.gov/spg/DOE/PAM/HQ/Awards/89303519CNE000005.html

[6] European research reactor position paper by CEA, NCBJ, NRG, Pallas, RECR, SCK.CEN and TUM, 15/06/2018 [http://ec.europa.eu/euratom/docs/European%20Research%20Reactor%20Position%20Paper%20for%20DGE%20Energy%20%202018%20report_20180801.pdf]

2. Background

Traditionally, fuel for European research reactors and targets for use in radioisotope production have been manufactured using HEU, provided mainly by the US and Russia from military surplus under the Non-Proliferation Treaty. Over time, the supply and use of HEU has become subject to additional political and legislative constraints, and no new HEU has been produced. These factors make the future supplies of HEU uncertain.

FRMII © Astrid Eckert - TUM

In support of international non-proliferation, EU Member States are committed to the principle of HEU minimisation, with the objective of converting research reactors and radioisotope production targets to HALEU (19.75%)[7]. In line with this political commitment, European research reactors with low to medium power density cores have already successfully made this transition to HALEU. The remaining European High Performance Research Reactors (EU-HPRR) are actively working to achieve this conversion as soon as technically and economically feasible.

The long-term availability and accessibility of HALEU in metallic form is a key issue in guaranteeing the continued operation of research reactors and the production of fission radioisotopes using HALEU. Currently, no appropriate production facilities are in place in either the EU or the US. The only currently used alternative source is Russia. These circumstances create a potential risk to security of supply.

Political considerations similar to those for HEU supplies could also affect the future supply of 19.75% HALEU. Europe, therefore, must examine all alternatives to ensure the future availability of HALEU for its own needs. If no action is taken, there is a risk that the supply of this critically important material cannot be guaranteed some time after 2030.

A number of new concepts for power reactors and fuels are also emerging, almost all of which are considering using HALEU. The absence of a production facility may obstruct, or even fully prevent, these new developments, and reduce Europe's chances of playing a leading role in these important developments in support of the energy market.

3. Scope of this work

The study reported here focuses on the long-term supply of HALEU for European research reactors and the production of medical radioisotopes, but also considers other factors such as research reactors outside Europe and advanced power reactor and fuel concepts.

It concentrates on a process to produce metallic uranium, as ultimately needed for research reactor fuels, which combines enrichment[8] up to 19.75% and metallisation.

It also takes into account technical, political and market developments since the 2013 report, and discusses transport and metallisation, which were not examined in depth in the previous report.

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[7] One of the two major European producers of Mo-99 has already converted from HEU to HALEU. The second will have done so by the end of 2019.

[8] Using technology which is currently commercially available in Europe

4. Assessment of European demand for HALEU

The estimate of European needs is based on assumptions about the fate of current research reactors and the development of new facilities. It includes the future conversion to HALEU by EU-HPRRs which still use HEU.

Although the quantity involved is relatively small, the study also explicitly takes into account the uranium needed for medical targets used to produce Mo-99. This is due to the societal importance of ensuring a sustainable supply of Mo-99 (the most-used radioisotope) for European nuclear medicine.

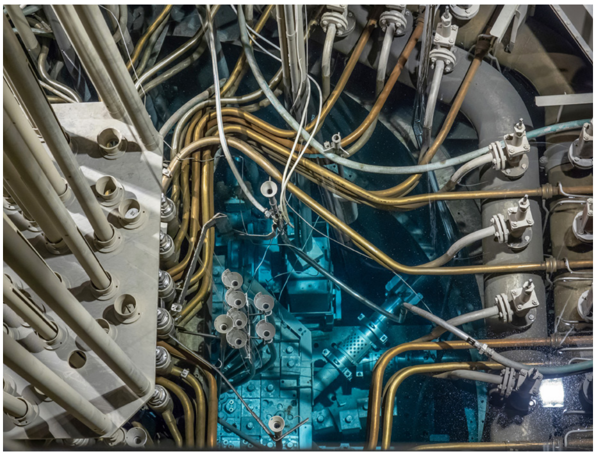
Cylindrical targets ©Framatome - Cyrille Dupont

The following table shows current demand and projected demand to 2030 for three scenarios (high, medium and low).

In the high scenario, full conversion of the remaining EU-HPRRs has occurred by 2030. This is probably a rather optimistic assumption. The medium scenario assumes that conversion is ongoing. In the low scenario, there are further delays in conversion and shutdown of reactors.

The 2013 figures are also reported for comparison.

While the expected quantities needed in Europe are limited , they are crucial if Europe is to maintain world-leading research and its leading role in the radioisotope industry.



MARIA research reactor in Poland ©NCBJ

The fragility of this niche market should be made clear. There are fewer customers, since in the medium term (>2030), only four large reactors (BR-2, FRM II, JHR, PALLAS/HFR) may still be operating. This emphasises the difficulty of making reliable projections.

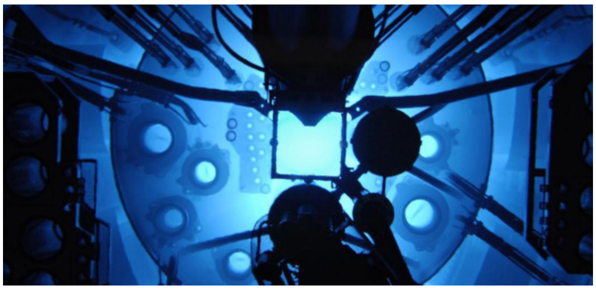
Table 1: Annual demand from European research reactors for uranium fuel

REACTORS			ANNUAL DEMAND IN KG OF URANIUM ENRICHED TO 19.75%				
			Current demand	2013 report	2030 projections		
Country	Designation	Power (MW)			high	medium	low
Belgium	BR2	60	HEU	180	1476	861	241
Bulgaria	IRT SOFIA		7	-			
Czechia	LVR15	10	25	30			
France	RJH	100	-	300			
	RHF	58	HEU	280			
	Orphée	14	HEU	65			
Germany	BER-2	10	30	30			
	FRM-II	20	HEU	280			
Greece	DEMOCRITOS	5	-	15			
Hungary*)	VVR-M2	10	10	0			
Italy	TRIGA	1	-	-			
The Netherlands	HOR Delft	2.3	6	0			
	HFR	50	130	-			
	PALLAS	25-30	-	130			
Poland	MARIA	30	44	70			
Romania	PITESTI	14	20	?			
Targets			25	10			
Total			**282**	**1380**	**1476**	**861**	**241**

*) 60 kgU for the whole period until 2023 (licence validity)

5. Assessment of demand from HALEU research reactors outside Europe

The estimation of the need for research reactors outside of Europe is restricted to the five major US research reactors – all still operating with HEU but with the clear objective to be converted to HALEU within the years 2026-2032 – with the addition of major research reactors outside of Europe and the USA which could potentially be interested in a European supply. It is considered that the research reactors in Russia and China are domestically supplied.



OPAL reactor ©ANSTO

The following table shows current demand and projected demand to 2030. It is assumed that the five high-performance US research reactors have been converted to HALEU, again under three scenarios (high, medium and low).

It is probably optimistic to assume that the full conversion of the US reactors has occurred by 2030. The medium and low scenarios anticipate delays in conversion. It should also be noted that while it is possible that non-European needs could be met by European suppliers, the inclusion of this information does not necessarily imply that this market would be accessible to European suppliers.

In light of the data collected in the two tables, the expert group recommends exploring in more detail the economical business model for enriching to 19.75% in three cases: 800 kg/year, 1,500 kg/year and 3,000 kg/year.

Table 2: Estimated future annual demand for HALEU from selected non-European research reactors

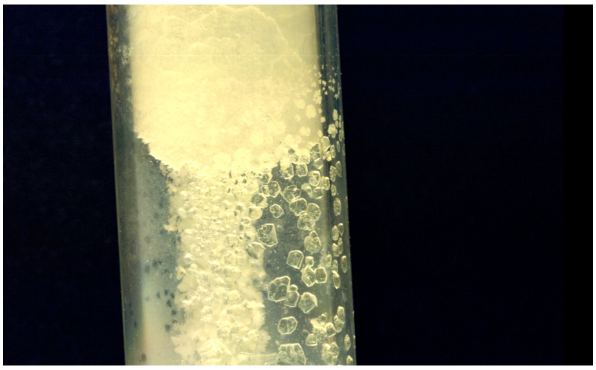
REACTORS			ANNUAL DEMAND IN KG OF URANIUM ENRICHED TO 19.75%			
			Current demand	Projections by 2030		
Country	Designation	Power (MW)		high	medium	low
Argentina	RA-3	10	HALEU	1885	675	639
	RA-10	30	HALEU			
Australia	OPAL	20	HALEU			
Brazil	IEA-R1	5	HALEU			
	RMB	30	HALEU			
Japan	JRR-3M	20	HALEU			
S. Africa	SAFARI-1	20	HALEU			
S. Korea	HANARO	30	HALEU			
	KJRR	15	HALEU			
USA	ATR	250	HEU			
	HFIR	85	HEU			
	MITR-II	6	HEU			
	MURR	10	HEU			
	NBSR	20	HEU			
Rest of world**)			HALEU			
Total			**384**	**1885**	**675**	**639**
Total including European reactors			**666**	**3361**	**1536**	**880**

**) Algeria (NUUR), Chile (RECH-1), Egypt (ETRR-2), Indonesia (RSG-GAS), Jordan (JRTR), Kazakhstan (VVR-K), Morocco (MA-R1), Peru (RP-10), Tashkent (VVR-SM)

6. Potential future needs for small and medium reactors using advanced HALEU fuel

How the nuclear industry will fuel the next generation of commercial advanced nuclear reactors and technologies is an important topic of discussion among industry experts.

Many of the new (and existing) advanced non-research reactors will require HALEU enriched to 5-20% U-235, and HALEU availability will allow and/or facilitate their deployment.



UF6 ©Orano

In order to ensure a secure supply of HALEU, the current nuclear fuel cycle infrastructure consisting of enrichment, de-conversion and fuel fabrication will need to be further developed and made more robust. Depending on the future fuel cycle infrastructure, associated transport means will also need to be developed.

In the same way as for research reactors, the supply of HALEU for commercial reactors is dependent on a well-established infrastructure consisting of enrichment, deconversion/metallisation, fuel fabrication and associated transport systems. The existing commercial nuclear fuel cycle is limited to 6% U-235 enrichment.

Unlike the material needed for research reactors and targets, however, the necessary (and substantial) industrial investment in infrastructure for HALEU for commercial reactors is realistically achievable only if there are prospects of sufficient customer demand and if the prices are acceptable to these customers.

It is very difficult to make reliable forecasts of HALEU demand for future commercial reactors based on the information currently available. A number of advanced reactor designs involving the use of a 19.75% enrichment level are currently being discussed. One factor affecting whether or not these projects come to fruition will be a new infrastructure for securing the HALEU supply. There is currently no consolidated European or global assessment of HALEU needs, but many projects point to a future involving increased demand from commercial reactors for HALEU.

The development of smaller nuclear power stations has been of particular interest in recent years. These reactor types – small modular reactors (SMR) –typically have an electrical output of 3–100 MWe, but some designs have higher outputs up to 300 MWe. SMRs offer benefits in terms of flexibility due to their lower electrical power output, and are attractive because capital costs per power station are smaller. Many of the designs entail very long refuelling cycles or lifetime cores, requiring higher enrichment of the fissile material in the core.

According to a 2016 assessment[9] by the Organisation of Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA), up to 21 GWe of SMRs could be added by 2035 in a high case scenario. This represents 3% of total global installed nuclear capacity. This assessment does not take into account the potential for further development of SMR technologies, as currently known and with realistic realisation potential.

SMR designs can be based on 'traditional' light water technology (LWR) or on advanced (GenIV) reactor technology, such as high temperature reactors (HTR) or molten salt reactors (MSR). Fast reactor designs, based on sodium or lead cooling, exist as well. In addition to the SMRs, advanced reactors with a high electrical output > 500 MWe are being developed. In some cases, these use HALEU.

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[9] 'Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment', OECD-NEA, 2016, [www.oecd-nea.org/ndd/pubs/2016/7213-smrs.pdf].

Looking at the fuel demand, we can distinguish, roughly, the following:

- Small modular reactors, LWR-based → mostly use UO2 with enrichment < 5%
- Small modular reactors, HTR-based → mostly use HALEU
- Small modular reactors, MSR-based → mostly use HALEU
- Small modular reactors, sodium- or lead-cooled → mostly use HALEU or mixed oxides (MOX)
- Advanced reactors > 300 MWe. These are mostly fast reactors, sodium or lead-cooled and use MOX fuel or, in some cases HALEU.

The demand for HALEU for use in advanced nuclear technologies is becoming an interesting aspect of the international fuel cycle. It might also be of interest for current light-water reactors, especially to develop safer fuels. The US Nuclear Regulatory Commission and DOE are encouraging the development of these 'accident tolerant fuels' (ATF)[10] for use in light water reactors.

It will still probably take some time before these developments result in a significant demand for HALEU. Prototype fuel, or 'lead test assemblies' (LTA), however, will require smaller volumes in the near future. If these LTA programs are successful, the volume of HALEU required to support reload quantities for a large LWR in the long term will be enormous – about 40tU/reload at 16% U-235 enrichment.

The US nuclear industry Nuclear Energy Institute (NEI) assessed their national HALEU demand in 2018. The NEI surveyed advanced reactor developers and fuel designers that use HALEU, in order to identify their annual needs to 2030. Based on this industry estimate, initial annual demand of less than 1 tonne of HALEU in 2018 will increase to an annual demand of some 185 tonnes of HALEU by 2030 in various assay bands ranging from 13–19.75%.

These figures must, of course, be treated with caution, but they show that the nuclear industry may need HALEU in the short term for new development. The expected volumes could rapidly exceed current established needs for research reactors and other purposes.

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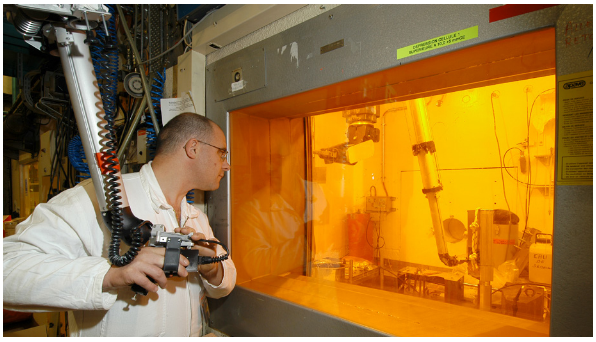
[10] Fuel that allows for significantly more time to prevent core meltdown under accident conditions.

7. Metallisation and deconversion



Hot cell of Osiris research reactor ©L Godart - CEA

Research reactor fuel is typically made by chemically transforming UF6 into U-metal (called metallisation in this document). This can be done through hydrogenation (UF6 → UF4) followed by a calcio-thermal or magnesio-thermal process (UF4 → U metal), but other methods of metallisation exist, some starting from uranium oxide (eg. electrochemical).

Although there is no longer any European facility to transform UF6 into U metal on a semi-industrial scale, significant know-how still exists. A European metallisation facility would guarantee that this knowledge stays and continues to be developed in Europe.

For the other reactor or fuel concepts, the deconversion requirements could be different (see table below), but deconversion can be done with existing facilities (UF6 → UO2).

Table 3: Needs for metallisation and deconversion

Fuel chemical composition	Application	Fabrication	Deconversion
U3Si2	Research reactors and accident tolerant fuel (ATF) concept	U-metal	UF6 → U-metal
U-Mo alloy	Research reactors and ATF concept	U-metal	UF6 → U-metal
U-Zr alloy	Fast reactors, Lightbridge fuel for LWRs	U-metal	UF6 → U-metal
UN	Fast reactors (sodium or lead-cooled)	U-metal	UF6 → U-metal
UO2	Various	UO2	UF6 → UO2
UCO	TRISO particles for high temperature reactors	UO2	UF6 → UO2
UCl3 / UCl4	Molten salt (fast) reactors	UO2	UF6 → UO2
UF4	Molten salt reactors	UF4	UF6 → UF4

8. Transport

The transport of nuclear material in various forms and compounds between multiple production facilities is an essential aspect in the nuclear fuel cycle. Nuclear material must be shipped under safe conditions whether it is inside the fence of a single site or between different sites on public roads. The regulation of nuclear safety and radiation protection are national responsibilities. The transport of nuclear material, however, is very often an international business and therefore requires an international standardisation of regulations. The International Atomic Energy Agency (IAEA) issues specific requirements through its publication "Regulations for the safe transport of radioactive material" which are regularly updated and which need to be adopted by Member States as part of their national regulations.

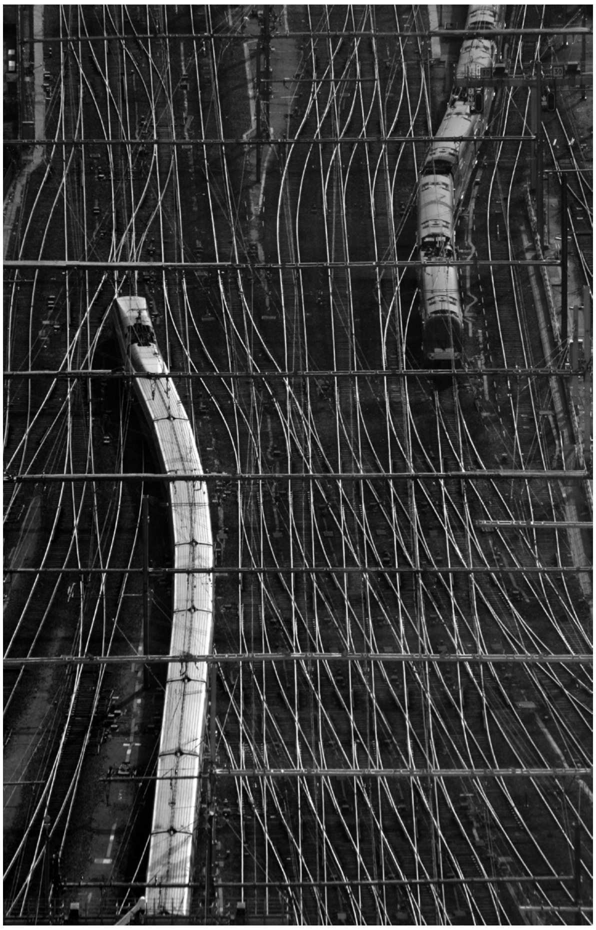
Furthermore, regarding non-proliferation issues, specific care has to be taken to limit the attractiveness of transported goods. In particular, enriched material has to be transported from the enrichment plant to the deconversion plant when producing any enriched fuels, HALEU metal in particular. Large quantities of UF6 enriched up to 5% are commonly and frequently transported nationally and internationally from one site to another by road, rail and sea. For example, UF6 is transported from the uranium enrichment site where it has been enriched to the fuel fabrication site where it is deconverted to UO2 powder before pelletising.

In our case, we can imagine three different situations:

- transport occurs within a site (meaning that the enrichment facility and the metallisation facility are on the same nuclear site),
- transport occurs between two sites but within the same European country, or
- transport occurs between two sites in two European countries.

In the three cases, we assume that the quantities are limited to a few tonnes per year, dispatched in several transports, but we keep in mind that a scale-up is possible if the technologies of advanced reactors or accident-tolerant fuel emerge. The transport could be carried out by road, rail or sea.

In the first situation, security requirements are reduced as they are partly covered by the external fence. In the third case, one should not underestimate the need to get safety and security agreements, not only for the cask, but also for the means of transport in the different countries on the road.



©N. Palomäki

The transport is performed in accordance with national and EU regulations based on internationally agreed minimum standards (IAEA SSR-6), which require certified packages: low-enriched UF6 is transported in standardised and internationally approved cylinders in combination with additional protective shipping packaging (PSP) to protect the cylinders from accidents during transportation.

UF6 cylinders must be in accordance with the provisions of international standard ISO 7195 and/or the US American standard ANSI N14.1. Various cylinder models are defined linked to the maximum enrichment of 235U allowed: for uranium enriched at 5% max, a standard "30B" cylinder is allowed to transport up to 2277 kg of UF6. For higher enrichment, the standards provide 5-inch cylinders with a total capacity of less than 25 kg of UF6 with no limit in enrichment of 235U. These cylinders can be filled with material enriched at 19.75%. However, if they are transported on a public road, a PSP would have to be developed and internationally approved. Currently, there is no adequate PSP for 5-inch cylinders for the international transportation available.

As an example, for the middle demand scenario (1500 kg per year of U metal, i.e. 2223 kg/yr of UF6) this would mean the transport of 90 5-inch cylinders spread over the year. Depending on the operational mode of the metallisation (batch mode), this could mean between 9 and 15 casks per transport. For the high demand scenario, it would be only two times more.

In conclusion, for the sole need of the research reactors and the targets for radioisotopes, the capacity of the existing standard 5-inch cylinders should be sufficient for transport on public roads. A PSP would have to be designed and approved by the competent authorities.

However, a significant increase in the quantities resulting from the development of advanced reactors would require the design and certification of a new container with a larger capacity. Such a development is costly, takes time and is considered to be outside the scope of this work. Moreover, a new cylinder model (to transport more than 25 kg of UF6 enriched at 19.75%) must be introduced into ISO 7195/ANSI N 14.1 and also approved by the competent transport authorities to be transported according to IAEA SSR-6.

Nevertheless, as of December 2018, there have been first concrete industry initiatives for developing a new cylinder (30B-20) which is designed to accommodate up to 1600 kg of UF6 at an enrichment of up to 19.75%.

9. Business model

Three scenarios were proposed to Orano and Urenco according to the estimated market demand: a low scenario with a volume target of 800 kg per year; a middle scenario with 1500 kg per year and a high scenario for 3000 kg per year.

The two companies were asked to assess the possibility of providing uranium metal at a price of or below €20 k/kg. Additionally, the possibility to include in the study facilities such as long-term guaranteed collected volumes and interest-free loan (similar to the hypothesis made for the previous report) was proposed.

The cost for metal HALEU production is made up of three components:

- Feed material, LEU enriched up to 5% in a UF6 form, produced through the currently existing supply chain. Its price depends on how the market price of those components evolves. The price of the feed material in the final metal HALEU is not dependent on the scenario, as the same amount of feed material will be used per kg of final product.
- Enrichment from 5% to 19.75% will require specific investments, as civil enrichment installations are currently not designed for these high assays.
- Metallisation of the HALEU, which will require investments in R&D as well as construction and licensing, as no industrial or semi-industrial production capacity currently exists in the EU.

The two studies were made independently of one another, and the results are summarised in the following table.

Table 4:
Estimated feasibility of HALEU production by European industry with a price ≤ €20 k/yr

	800 kg/yr	1500 kg/yr	3000 kg/yr
Orano	YES but with innovative financing solutions	YES	YES A production price appreciably below the target price could be achieved. With innovative financing solutions, a production price comparable to present market prices could be achieved.
Urenco	NO	YES but with innovative financing solutions	YES. A production price below the target price could be achieved depending on the contracted quantities above 1500 kg/yr and/or with innovative financing solutions.

Both companies made the following assumptions:

- Enrichment and metallisation have been considered as a single project (colocation) which would be built on an existing nuclear site of the respective company (for economic and security reasons);
- Setting up of long-term supply contracts in line with the forecast lifetime of the centrifuges, in accordance with established practice in the nuclear fuel cycle industry;
- Use of commercial UF6 at 5% as feed material for the HALEU workshop.

If such a project is quickly started, both companies say that production could begin as early as 2025. However, it could only be engaged with strong guarantees from customers on price and volume.

According to Orano, in the third scenario a price appreciably below the €20 k/kg target can be reached. Furthermore, innovative funding/financing solutions can contribute to reach a production price comparable to or below current market price (≈ €12 k/kg). This partly contradicts the conclusions of the 2013 report, in which it was stated that 'the price of 20 k€/kg must be considered as an order of magnitude necessary to contribute to the balance of a European self-sufficiency project'.

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According to Urenco, a production price below the target price of €20 k/kg target can be achieved and would be priced according to an agreed mechanism that would offer volume discounts on quantities above the minimum order quantity of 1,500kg/year.

It must be noted, though, that this volume scenario is quite optimistic.

Both companies have different views on metallisation: Orano is confident it can rely on its expertise in designing and operating metallisation installations. Optimisations on the processes at Orano's disposal could be pursued to improve the project's efficiency and economic performance.

Urenco deems that technical consideration must be given to the design of the process engineering and waste management of a modern, commercial scale production facility.

10. International cooperation

The evaluation of demand combined with the volumes needed for economic sustainability suggests that international cooperation could be helpful or may be necessary (depending on how the demand evolves) to maintain the price of HALEU below or around €20 k/kg in the long run.

When analysing the international scene outside Europe for civil enrichment, the countries to be analysed are limited: China, Russia, Japan and the US (with very limited capabilities in India and Pakistan). The only enrichment and metallisation installations with a capacity to produce HALEU for civilian uses currently operating are in Russia and, possibly, in China.

In the United States, the debate on reinstalling an enrichment capability for civil HALEU and military HEU for propulsion has been ongoing for quite some time. In addition to the need for HALEU for the research reactors, for which available stocks may be depleted as early as 2035, several parties have petitioned the US government to assure a reliable HALEU supply in support of a potential fleet of advanced reactors and advanced fuels currently under development in several DOE-sponsored or privately sponsored projects. If such a need indeed increases the demand for HALEU, stocks may even be depleted before 2035.

Furthermore, the currently available stock of HEU in the US reserved for naval reactor applications is considered sufficient to meet currently predicted needs up to approximately 2060[11]. The US has therefore also identified a strategic interest to eventually develop a domestic enrichment capability up to HEU for defence applications. Such a facility is in principle capable of producing HALEU as well. The DOE recently awarded a contract to American Centrifuge Operating, LLC, to demonstrate the production of HALEU in a cascade of US-designed centrifuges, which in principle could later be expanded to HEU production for naval reactors.

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Different scenarios for a cooperative civil HALEU production between Europe and the United States could be explored, such as having a facility in the US with European participation (which will have to be defined) or having a facility in Europe with a US contribution. A third possibility could be having two facilities based on a (at least partly) common design in order to reduce the cost. This would, of course, bring more redundancy.

Other research reactor facilities outside Europe and the United States could be contacted to evaluate their interest in this subject.

The Nuclear Energy Agency would likely be the most appropriate forum for such an international discussion.

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[11] Request for information DE-SOL-0008552 for supply of enriched uranium, Jan. 2017.

11 Conclusion

Taking into account the new context (predictable end of the US stock, possible emergence of new fuel and reactor concepts), the report has drawn a panorama of HALEU demand for the next decades. Although there is great uncertainty because some of the research reactors are quite old and their replacement is only partly decided, we find that the world needs for HALEU could be around 3000 kg/yr for research reactors and radioisotopes. If new concepts for reactors or fuels emerge, the quantity could rapidly increase by a factor of two or three already in the prototype phase.

To secure its own needs, Europe will probably require a minimum of 800 kg per year for the research reactors and medical radioisotope targets. The quantity could double if some other needs outside Europe are also taken into account.

The European enrichment capability is seen as being well controlled and guaranteed. The metallisation process is still directly available. As no metallisation installation is operated anymore, significant European expertise must be maintained through a new project. In both cases, new facilities will have to be designed and built. A more detailed assessment (beyond the scope of this study) could be very valuable to reduce the uncertainties on the investment and operational cost estimates.

It has also been concluded that the transport of UF6 at 19.75% between an enrichment facility and a metallisation facility, in particular between different countries, even for small quantities, will require the development and certification of a new protective shipping package (whose detailed assessment is beyond the scope of this study). For much larger quantities, a new container (and the corresponding protective shipping package) must be designed to accommodate higher volumes.

To estimate the economic feasibility of building a facility in Europe, three scenarios have been proposed to the industrial partners. They independently assess the possibility of producing 800 kg/yr, 1500 kg/yr and 3000 kg/yr at a targeted price of €20 k/kg.

In the three scenarios, the price of a kg of metal HALEU contains an amount that is directly linked to the feed material (UF6 at 5%), regardless of the scenario. In the low scenario, Orano concluded that the targeted price will be difficult to reach without some innovative solution for the investment whereas Urenco concluded that it is not possible to guarantee a production price below the target price for a dedicated production facility. For the two other scenarios, the price of HALEU could be (significantly) lower than the targeted price. However, in all three cases, this would imply a long-term commitment of the customers, consistent with all other western investments in the nuclear fuel cycle industry.

Medical irradiation target ©Framatome - Cyrille Dupont

It is recognised that the European stakeholders should exchange information in a coordinated manner with potential international partners, the first of them being the US.

12. Next steps

Securing the supply of HALEU for European needs – research reactors and targets for medical radioisotopes – should remain a subject to scrutinise carefully.

The group of experts recommends:

- mandating the European stakeholders to further define the conditions for having an enrichment and metallisation facility in Europe through a common project supported by the EU,
- carefully following any changes in the available stockpile to avoid any breach in supplying the European operators,
- carefully following the development of high density HALEU fuel, which could impact the rate of consumption of the present stockpile,
- carefully following the development of new concepts of reactors (advanced reactors) and fuels, which could also impact consumption by drastically increasing the demand,
- exploring the possibility of having a dedicated working group at NEA to discuss this issue in an international context,
- envisaging R&D funding within Horizon 2020 (and the programme which will follow Horizon 2020) to update and further optimise the process for metal HALEU,
- making national regulators aware of the eventual erection of a metal HALEU fabrication facility,
- discussing with the US DOE overall (civilian) needs and ways to guarantee a safe, redundant, lasting and sustainable supply of metal to HALEU.

Abbreviations

BR2	Research Reactor 2, Belgium
CEA	Commissariat à l’Énergie Atomique et aux Energies Alternatives, France
DOE	Department of Energy, USA
FRM II	Forschungsr-Neutronenquelle Heinz Maier-Leibnitz (FRM II), Germany
HFR	High Flux Reactor, Netherlands, the Netherlands
JHR	Réacteur Jules Horowitz, Cadarache, France
LVR-15	Multi-purpose Research Reactor, Rez, Czechia
MARIA	Multi-purpose Research Reactor, Swierk, Poland
NEA	Nuclear Energy Agency, OECD, Paris
NCBJ	National Centre for Nuclear Research, Poland
NRG	Nuclear Research and consultant Group, the Netherlands
RCR	Research Centre Rez, Czechia
RJH	Réacteur Jules Horowitz, France
OECD HLG MR	OECD High Level Group Medical Radioisotopes
OSIRIS	Material Testing Reactor, Saclay, France
PALLAS	Research Reactor, replacing HFR Petten, the Netherlands
SCK•CEN	Studiecentrum voor Kernenergie, Centre d’Etude de l’Energie Nucléaire, Belgium
TUM	Technische Universität München, Germany

Annex

Annex 1: Business case

ORANO has assessed the production cost for metallised HALEU, considering a production process located only on the ORANO site in Tricastin, for enrichment as well as metallisation. A dedicated building would be necessary. Given that the volumes of the final product considered are relatively small, but with a specific challenge linked to assays above 5% (and below 20%), enrichment up to 19.75% and metallisation have been considered as a single project to improve cost efficiency.

Moreover, the following assumptions have been taken into account:

- Project starts (i.e. beginning of feasibility study) in 2019, facility is commissioned in 2025 and production starts in 2026;
- The facility (in accordance with the life duration of the centrifuges) has a life duration of 25 years;
- UF6 enriched at 4.95% (EUP) is used as feed for a specific HALEU enrichment workshop. As a consequence, the components of this feed already available (natural uranium, conversion and enrichment up to 4.95%) can be provided through the available ORANO installations in Tricastin (Philippe Coste – Georges Besse II facilities);
- Price of this 4.95% UF6 feed has been considered according to low and high scenarios, so as to segregate the share of feed components (dependant only on the already existing markets) in the metal HALEU price;
- No interest free loan or innovative funding/financing solutions have been taken into account;
- Volumes produced have been considered as sold in the year they are produced. This hypothesis implies a guarantee from the customers on volumes as well as prices.

Conclusions for the three scenarios are the following:

- Low-800 kg/yr: it is not possible to guarantee a production price below €20 k/kg during the 25 years life duration of the facility. Price of the feed would account for 20-30% of the total price for 1 kg of metal HALEU, according to the price scenario for market components (U3O8, conversion and SWU). However, innovative funding/financing solutions such as interest-free loans or preferential interest rates can help to reach a production price below the target mentioned above.
- Middle-1500 kg/yr: a production price below €20 k/kg can be reached, considering the assumptions mentioned above, in both low and high scenarios for feed price. The price of the feed would account for 30-40% of the total price for 1 kg of metal HALEU.

- High-3000 kg/yr: a production price appreciably below €20 k/kg can be reached, considering the assumptions mentioned above. The price of the feed would account for 45-60% of the total price for 1 kg of metal HALEU. Innovative funding/financing solutions such as interest-free loans can help to reach a production price comparable to or below current market price.

- In each case, metallisation is the main contributor in the share of the price directly attributed to metal HALEU. This fact underlines that the key challenge for HALEU production for research reactors resides in the capability to metallise enriched uranium.

- In each case, the overall price for 1 kg of the metal HALEU product is inherently linked to the price hypothesis of market components (U3O8, conversion and SWU up to 4.95%). Thus, project optimisations on a metal HALEU production project will only impact a proportion of the €20 k/kg mentioned above.

The first step for such a project is to confirm this first assessment and optimise the design of the facility. Given the uncertainty of a potential future metal HALEU market, some financial R&D support will be necessary to perform this work. Metallisation being the main technical challenge, it should be the key focus of this study. It will require specific authorisation since metallisation is a very sensitive technology. Thus, such a work will constitute the first design step towards a European capacity, a means to maintain and develop expertise on metallisation in Europe to guarantee security/independence of supply for Europe.