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# USE OF REPROCESSED URANIUM: CHALLENGES AND OPTIONS

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# USE OF REPROCESSED URANIUM: CHALLENGES AND OPTIONS

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# FOREWORD

Significant growth of nuclear energy generation is anticipated during this century as a consequence of improved awareness of environmental concerns and assurance of energy supply in both developed and developing countries. To meet this demand for the future growth of nuclear energy, development of proliferation-resistant and more eco-friendly fuel cycle technologies are of paramount importance. Addressing this issue, there have recently been proposals for the internationalization of nuclear fuel cycles. Many of these proposals call for the development of innovative ways of the closing fuel cycle as well as the complete recycling of fissile and fertile materials. It should be noted that the current generation of nuclear power plants uses only a small fraction (0.5%) of the energy potential of the fuel. Recycling of fissile and fertile materials is an attractive option for not only improving the fuel utilization, but also reducing radioactive waste accumulation.

The IAEA is giving continuous attention to the collection, analysis and exchange of information on innovations in the nuclear fuel cycle, in particular the back end of the fuel cycle, owing to recent increased interest by several IAEA Member States.

Recognizing the importance of this subject, the IAEA published a report entitled 'Management of Reprocessed Uranium: Current Status and Future Prospects' (IAEA-TECDOC-1529), which provided an overview of facilities, inventories and recycling programmes in pertinent countries; however, it focused on management overview and did not include more technical details. Considering the increased interest of the Member States, the Agency conducted a technical meeting (TM) on 'Reuse options for reprocessed uranium' in Vienna in August 2007 with support from a working group (WG). The TM received 23 papers and attracted 52 experts. The proceedings of the TM will also be published later as a separate report.

The WG reviewed a number of issues on the use of reprocessed uranium and prepared this report. This report aimed to review the technical and economic issues involved in storing, handling, conversion, processing, transport, fabrication, incore fuel performance and spent fuel management.

The valuable contributions of the WG in the drafting and review of the report are greatly appreciated. The IAEA wishes to express its gratitude to S.M. Fensom (United Kingdom) for chairing the WG and P. Teyssier (France) for his significant contribution in drafting this report. The IAEA officer responsible for this publication was H.P. Nawada of the Division of Nuclear Fuel Cycle and Waste Technology.

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## SUMMARY

The main objectives of this report are to provide a complete overview of the opportunities for the use of reprocessed uranium (RepU) in reactors and to highlight the challenges faced by the industry and the options currently available and being explored.

This report builds on the contents of IAEA-TECDOC-1529, which summarized the inventories, facilities and recycling programmes of Rep U in Member States. It reviews the recycle strategies previously adopted by owners of RepU, notes the potential influence of national policies, highlights the experience gained both by nuclear power plant (NPP) operators and their suppliers, identifies the options currently available and under consideration, and finally, considers the status of the market for RepU.

This report is intended as a practical handbook both for NPPs seeking to use RepU and also for those corporations who have the capability to provide services related to RepU.

The report first provides an update of the estimated stocks of RepU at present and the additional inventories that could still be recovered from spent light water reactor (LWR) fuel, which is currently in interim storage. It then considers several examples of strategies for use of Rep U developed in the past by utilities and identifies the factors that have emerged as a result of this experience and continue to affect the use of RepU. Taking careful account of the discussion at the TM organized by the IAEA in August 2007, the most significant challenges are considered to be:

- Difficulties for suppliers of RepU processing services to forecast the nuclear fuel market demands for RepU;
- The need to comply with the ALARA principle, taking into account the in-growth of daughter products of  $^{232}\text{U}$  after each stage of chemical separation;
- The constraints arising from the present licensing limits of 5%  $^{235}\text{U}$  in LEU fuel for LWR fuel for reactor loading and spent fuel processing and transportation;
- The lack of facilities for cleaning cylinders that have contained enriched  $\text{UF}_6$  prepared from RepU.

Despite these challenges the following solutions have already been identified and tried:

- Blending RepU with fresh uranium in the course of enrichment;
- Blending RepU with enriched uranium;
- Double cascade centrifuge enrichment aimed at reducing concentration of even isotopes in the enriched product;
- Direct enrichment of RepU in centrifuges;
- Mix of the above-mentioned solutions;
- Laser technologies to separate isotopes;
- Use of RepU in first cores, which have lower initial enrichment that reloads.

Section 3 provides an overview of the recycle routes, including re-enrichment, blending with low enriched uranium (LEU) or high enriched uranium (HEU), and also direct recycle. This section also reviews the issues associated with the storage and transport of RepU in all forms and concludes that there are no significant problems associated with the transport of RepU although some still need to be implemented. Further, this section highlights planned future investment in new facilities and considers the potential developments in the re-enrichment route to purify RepU of the undesirable even isotopes of uranium.

The report reviews the experience of loading RepU into reactors and its in-reactor behaviour. It concludes that for almost all reactor operators the experience has been overwhelmingly positive from a technical standpoint. The particular issue of over-enrichment required to compensate for the presence of  $^{236}\text{U}$  is highlighted and the significant implications of the widely applied 5%  $^{235}\text{U}$  limit for reactor operation are discussed. The management of spent enriched reprocessed uranium (ERU) fuel is also considered, and it is concluded that there are no significant problems.

Section 4 gives a checklist of questions that need to be addressed both by utilities and supplier. Some guidance is provided on how to develop the answers specific to a utility's requirements.

The report considers the factors that characterize the market for RepU and concludes that it lacks maturity. RepU should fill between 10 and 20% of annual uranium needs (depending on the burnup of the spent fuel reprocessed). In 2006, however, RepU loaded into reactors was 2.3% of world reactor needs, and current forecasts up to 2015 show no significant increase in the RepU share. The report considers how an economic comparison can be undertaken between fuel produced from RepU and fuel produced from natural uranium.

The report provides some suggestions on initiatives that might allow increasing maturity of the RepU market, including:

- Defining a standardized RepU product;
- Investigation of ways to lift the 5% limit of  $^{235}\text{U}$  enrichment;
- Use of RepU in first cores of new reactors;
- Maintaining and encouraging competition among suppliers;
- Better sharing of RepU experience;
- Reassessment of the specifications of fabrication plants.

An interesting proposal made during the preparation of this report concerned the creation of an international forum to promote the necessary conditions in which a RepU market might develop and become self-sustaining.

# 1. INTRODUCTION

## 1.1. BACKGROUND

Owing to rapidly growing demand for energy, especially in some regions of the world, concerns over energy resource availability, climate change, air quality and energy security suggest a larger and more important role for nuclear energy in the future. For wider acceptance of growth of nuclear energy, some of the critical issues associated with nuclear waste management, reactor safety, economics, sustainability and non-proliferation are being addressed by both the nuclear industry and governments. A key aspect of sustainability is the recycle of the products of reprocessing — plutonium and RepU. This report focuses on the specific technical and general economic aspects of the use of RepU for electricity generation.

The IAEA and the OECD Nuclear Energy Agency (OECD/NEA) have issued several publications on nuclear material management: (a) depleted uranium (DU) [1]; (b) high enriched uranium (HEU) [2]; (c) reprocessed uranium (RepU) [3]; and (d) fissile and fertile materials in general [4, 5]. It should be noted also that the report on 'Management of Depleted Uranium' [1] was published through the joint efforts of the OECD/NEA and the IAEA. In particular, the report on RepU entitled 'Management of Reprocessed Uranium: Current Status and Future Prospects' (IAEA-TECDOC-1529), published in February 2007 [3], gave an overview of facilities, inventories and recycling programmes of RepU in selected and pertinent countries; however, it focused on management overview and did not include more technical details. Thus, the IAEA's Technical Working Group on Nuclear Fuel Cycle Options and Spent Fuel Management (TWG-NFCO), in their 2004 annual review meeting, discussed and suggested that the IAEA include an activity to prepare a new report on the reuse options of reprocessed uranium after conducting a technical meeting (TM) at which Member States would be invited to report on their experience and future plans. The TM, which received 23 papers, was hosted by the IAEA in Vienna on 29–31 August 2007, and attended by 52 participants. [6]. This report has taken careful consideration of the papers submitted and the views exchanged during the TM as well as contemporary developments [7].

There is a significant interest in Member States to develop advanced and innovative technologies for nuclear fuel cycles while minimizing waste and environmental impacts on the basis of innovative fuel cycle approaches where the recycle and reuse of valuable material plays a crucial role. Since RepU contains some residual  $^{235}\text{U}$ , the amount of which depends on discharge burnup and type of reactor, it could be used, after suitable processing, as fresh fuel in reactors for energy generation. The recycle of RepU as fuel would reduce the overall environmental impact by the entire fuel cycle.

RepU can be used in different routes for energy generation (as shown in Fig. 1). First, it can be used directly, meaning without re-enriching it. Second, it can be used after increasing its  $^{235}\text{U}$  content by a physical re-enrichment process such as centrifugation or by blending it with low enriched uranium (LEU) (e.g. 14–17%  $^{235}\text{U}$ ) or HEU. Third, it can be used after blending it with LEU (below 5%  $^{235}\text{U}$ ) or natural uranium (NU)<sup>1</sup>. A fourth possibility is to use it by some combination of the above processes to meet the fuel specification requirements for given reactors. The genesis for different routes of re-enrichment could be linked to the consideration of the control of minor uranium isotopes (such as  $^{232}\text{U}$ ,  $^{234}\text{U}$  and  $^{236}\text{U}$ ) in the final processed RepU product. The reactors could be light water reactors (LWRs), heavy water reactors (HWRs), advanced gas cooled reactors (AGRs), light water-cooled, graphite-moderated reactors (RBMKs) and fast reactors (FRs).

## 1.2. SCOPE

This report focuses only on use options of RepU in nuclear energy generation. RepU may also find non-energy applications (such as shielding materials in spent fuel casks) or other industrial applications, which are, however, not dealt with here.

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<sup>1</sup> Natural uranium is used for downblending RepU which has high  $^{235}\text{U}$  content.

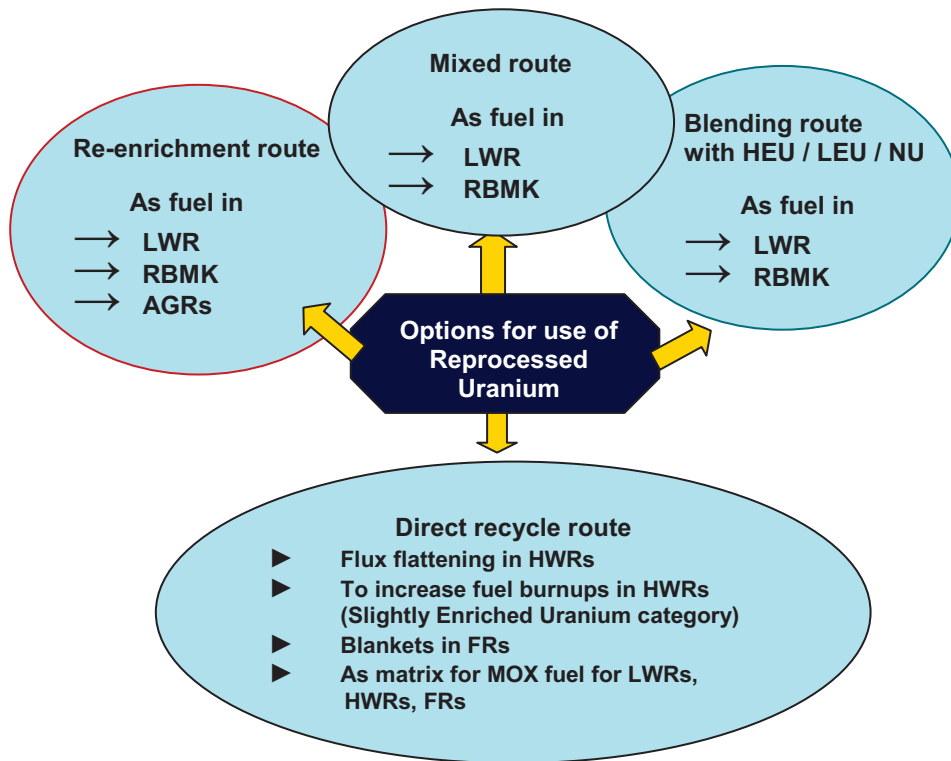


FIG. 1. Different strategies for the use of RepU.

In some countries, spent fuel has been viewed as a national energy resource. Several countries manage inventories of RepU belonging to utilities in foreign countries as the result of their commercial service contracts for the reprocessing of spent fuel. In some of these countries, recycled materials are already being used. Signs of increased interest in the potential for use of RepU are being observed in part due to the recent dramatic rise in the spot market price of natural uranium. Against this background, however, a market for RepU processing is not yet well developed. Furthermore, a collective resource of key information (technical issues, process routes, transport methods, reactor performance, etc.) has not been developed and there is currently no forum to share and review such information.

A number of Member States (Belgium, China, France, Germany, India, Italy, Japan, Kazakhstan, the Netherlands, the Russian Federation, Spain, Sweden, Switzerland, Ukraine, the United Kingdom and the USA) have either RepU inventories in storage, or RepU processings, or recycling programmes. Some Member States (such as Argentina, Canada and the Republic of Korea) are considering recycling concepts involving RepU in pressurized heavy water reactors (PHWRs).

### 1.3. OBJECTIVE

The purpose of this report is to review of technical and economic issues involved in storing, handling and reusing RepU for nuclear energy generation. Hence, it should be of significance to many Member States and an important resource to be used as a practical handbook both for NPP operators and for corporations interested in providing services related to RepU.



## 2. CURRENT STATUS, OPPORTUNITIES AND CHALLENGES

The purpose of this section is to give an overview of the availability of RepU and of the current status in its use, as well as to identify the main technical and non-technical factors that provide opportunities and challenges related to the management options for RepU.

The consensus of reactor operators and fuel suppliers is that the main factors affecting the management options for RepU are, to a different extent and depending on the utility (in alphabetical order):

- Burnup: Utility drive towards higher burnups of fuels;
- Economics and competitiveness;
- Experience: The extent to which previous experience can be translated into future plans;
- Inventories of RepU and who owns them;
- Obligation codes: Restrictions attached to batches of RepU;
- Policy issues: National and regulatory policies related to nuclear power, reprocessing and recycle of fissile materials;
- Quality of RepU material;
- Storage services provided by suppliers.

Each of these factors is discussed further in Section 2.2.

### 2.1. CURRENT STATUS

#### 2.1.1. Current inventories and future arising of RepU

The total inventory of RepU already separated and accumulated in stockpiles at the end of 2005 has been estimated at some 45 000 tonnes [5], though with varying qualities and with especially large quantities with very low  $^{235}\text{U}$  assays. Under past and present technical and economic conditions, immediate recycling of reprocessed uranium was (and partly still is) not considered attractive in most cases. Most RepU has therefore been converted from the liquid uranyl nitrate hexahydrate (UNH) form obtained after reprocessing into forms better adapted to long-term storage — generally solid oxide forms (either  $\text{UO}_3$  or  $\text{U}_3\text{O}_8$ ) — and sent to storage facilities.

The three countries that hold significant inventories of separated RepU (the United Kingdom, France, and Japan) are among the four that have and/or continue to operate reprocessing facilities (the United Kingdom, France, the Russian Federation and Japan).

In addition to the existing stockpiles, more than 120 000 tonnes of RepU could still be recovered from spent LWR fuel that is presently in interim storage.

##### 2.1.1.1. Inventories in the United Kingdom

In the United Kingdom, stocks of reprocessed uranium come from two different sources: first, the reprocessing of metal fuel from the Magnox reactors (yielding Magnox depleted uranium, or MDU); and second, from the reprocessing of oxide fuel from AGRs and LWRs.

The larger volume of RepU is derived from the reprocessing of irradiated fuel from the Magnox reactors, an activity that is still ongoing. The bulk of this material is owned by the United Kingdom's Nuclear Decommissioning Authority (NDA). Approximately 41 000 t U of Magnox fuel has been reprocessed (of which 17 000 t U has been recycled already), resulting in a stock of 24 000 t U MDU, which is currently being stored. Following the planned closure of the remaining Magnox reactors by 2010, it is currently estimated that there will be in excess of 30 000 t U of MDU available by around 2012. The MDU has been recovered in the form of  $\text{UO}_3$  and the current inventory has a  $^{235}\text{U}$  content of typically 0.4%. Due to the low fuel burnup, the content of  $^{232}\text{U}$  and  $^{236}\text{U}$  isotopes is also low.

There are also significant quantities of RepU from the reprocessing of oxide fuel from AGRs and LWRs in the Thorp reprocessing facility. This material is owned by the NDA, British Energy and a number of Thorp's overseas reprocessing customers. Currently, there is over 2 000 t U of AGR-derived RepU, with the potential for up to 5000 t U in total, depending on future reprocessing schedules. In addition, there are stocks of RepU belonging to overseas utility customers. These stocks are contracted to be repatriated to their owners. The isotopic composition of the RepU originating from Thorp varies, with the  $^{235}\text{U}$  content typically in the range of 0.8 to 1.0%.

#### *2.1.1.2. Inventories in France*

In France, one reprocessing facility has been operating at Marcoule (UP1 plant, south of France), and the current facility is located at La Hague (UP2-800 and UP3 plants, Normandy).

Production in the UP1 plant was terminated at the end of 1997, after 40 years of operation. In 1998, the plant started its decommissioning programme. The remaining 2800 tonnes of RepU stored at Marcoule should be processed before the end of 2009. As of today, the two operating plants located at La Hague (UP2-800 started in 1994 and UP3 started in 1990), can be considered as a single industrial platform that has a licensed capacity of 1700 t HM/year. The former UP2-400 plant, which started in 1966, is now under decommissioning.

In total, AREVA NC has separated more than 45 000 t of RepU, 23 000 of which is from the reprocessing of fuel from gas-cooled reactors, and more than 22 000 tonnes is from the reprocessing of LWR spent fuel.

The RepU derived from spent GCR fuel has an average  $^{235}\text{U}$  assay below 0.4%, and given the additional separative work required to meet desired enrichments, there are currently no foreseen circumstances in which recycling of this material using conventional direct re-enrichment would be deemed economic. RepU derived from spent LWR fuel is sent to Pierrelatte in the UNH form for conversion into  $\text{U}_3\text{O}_8$  or  $\text{UF}_6$ , according to the recycling routes chosen by RepU owners. Since there is some delay between RepU separation at La Hague and recycling in reactors, RepU is converted into the stable  $\text{U}_3\text{O}_8$  chemical form and temporarily stored before being used. The denitrification facilities in Pierrelatte have converted RepU in the form of UNH into  $\text{U}_3\text{O}_8$  to be stored prior to its future recycling. The conversion facility of Comurhex has converted reprocessed uranium from various customers since 1972. Two of these three facilities are scheduled to be shut down at the end of 2008, TU5 being the sole unit remaining in activity.

Électricité de France's (EDF) RepU is stored at Pierrelatte (France).

#### *2.1.1.3. Inventories in Japan*

In Japan, the reprocessing products coming out of the Tokai Reprocessing Plant (TRP) are in the form of  $\text{UO}_3$  and of a nitric solution containing both Pu and U (termed 'Pu+U mixed nitric solution').  $\text{UO}_3$  powders are packed into dedicated drums and stored. Current stocks are approximately 800 t U as  $\text{UO}_3$ .

The Pu+U mixed nitric solution is denitrated ('co-denitration of Pu and U'). The product is oxide material, a mixture of  $\text{PuO}_2$  and  $\text{UO}_2$ . This material is stored at TRP, until further notice.

#### *2.1.1.4. Inventories in the Russian Federation*

The Russian Federation has very limited RepU stock as all its RepU coming from the reprocessing plant RT-1 at Mayak (with the exception of the material with an  $^{235}\text{U}$  assay of about 17% needed to blend western utilities' RepU (see Section 3.5) is recycled immediately into RBMKs.

### **2.1.2. Example of strategies developed in the past by utilities**

A large proportion of the fuel manufactured for the United Kingdom's AGR reactors prior to the mid-1980s was made from RepU derived from the reprocessing of spent fuel from the United Kingdom's Magnox reactors. Some 17 000 t U of RepU in the form of  $\text{UO}_3$  was transported from Sellafield to Springfields and converted through the main line facilities to produce  $\text{UF}_6$ , which was then re-enriched by centrifuge technology at Urenco, reconverted to  $\text{UO}_2$  and fabricated into fuel. The low burnup of the Magnox fuel gave rise

to RepU with relatively low levels of  $^{232}\text{U}$  and  $^{236}\text{U}$ , and consequently, the levels of  $^{232}\text{U}$  and  $^{236}\text{U}$  remained relatively low even when re-enriched. The conversion facilities, however, need to deal with the challenge of the daughter products of  $^{232}\text{U}$  and also  $^{99}\text{Tc}$  and  $^{106}\text{Ru}$ . Springfields' conversion facilities used to process the RepU experienced, in particular, a progressive buildup of  $^{99}\text{Tc}$  in the plant and high levels of  $^{106}\text{Ru}$  in waste streams, which provided a challenge to effluent licences. The conversion of Rep U in main-line facilities at Springfields was discontinued in 1982, and the conversion facilities have since been decommissioned.

German utilities started a RepU recycling project in the early 1980s with one enriched reprocessed uranium (ERU) fuel assembly made at Siemens/KWU's fuel fabrication facility at Lingen, Germany (now owned by AREVA NP) and loaded into the Obrigheim PWR. The enrichment of the ERU fuel rods was increased to 3.5%  $^{235}\text{U}$  to compensate for the presence of  $^{236}\text{U}$  and was equivalent to 3.2%  $^{235}\text{U}$ . At that time, the average burnup was 32 GW·d/t HM. During the mid-1980s, the average burnup increased to 37 GW·d/t HM and a second project involved enrichment of RepU at Urenco's centrifuge plant at Almelo (the Netherlands) and the manufacture of four ERU fuel assemblies, which were loaded into the Neckarwestheim-1 PWR in 1986 and 1987. It became clear that as utilities moved to higher burnups and therefore higher enrichments, the over-enrichment to compensate for the presence of  $^{236}\text{U}$  could become a limiting factor. Once the burnups exceeded 44 GW·d/t HM, the 5.0% limit meant that the recycle of RepU enriched through centrifuge facilities was deemed no longer practical or economic. In the early 1990s, however, cooperation between Siemens and JSC Maschinostroitelny Zavod (JSC MSZ, or MSZ) at Elektrostal (Moscow region, Russian Federation) brought a solution based on the blending of RepU with higher enriched inventories. This approach achieved the required enrichment with much lower  $^{236}\text{U}$  concentrations and, therefore, a lesser requirement for over-enrichment. The economic assessments made at that time are no longer of relevance because the market conditions have changed completely. According to the German utility Energie Baden-Württemberg (EnBW), the indirect owner of the Obrigheim and Neckarwestheim-1 NPPs, the lessons learned from this experience are that it is necessary to identify for each reactor, as early as possible, the technical and legal limits and hurdles, and to clarify which ERU fuel loading possibilities may be realized.

Starting from the early 1990s, the Siberian Group of Chemical Enterprises (SGChE) in the Russian Federation has provided industrial scale RepU processing services through direct enrichment. Since 1993, Joint Stock Company Mashinostroitelny Zavod (JSC MSZ) has fabricated ERU fuel for the former German company Siemens-KWU (now for the French company AREVA NP) (see above). A total of 1693 fuel assemblies (673 t U) and 126 t U of fuel pellets were fabricated. The pellets were used for the production of ERU fuel assemblies at Lingen (Germany).

EDF studied the possibility of recycling RepU in PWRs in the early 1980s and took delivery of the first ERU fuel from AREVA NP, manufactured at its facility in Romans, France in 1987. From 1987 to 1990, these precursor fuel assemblies were loaded into the Cruas-4 NPP. In 1994, the first ERU reload was introduced into the same reactor. At the time of the first ERU reload, EDF had started a new core management for the Cruas NPP with fuel at 3.7%  $^{235}\text{U}$ . It was decided to use ERU fuel with the same enrichment of 3.7%  $^{235}\text{U}$  without compensation for the presence of  $^{236}\text{U}$ . In a next step, EDF enhanced the energy content of the ERU up to the equivalence with enriched natural uranium (ENU) by increasing the reload batch size, i.e. by increasing the number of ERU subassemblies from 40 to 44 without changing the enrichment (see also Section 2.1.2.). Subsequently, and after obtaining appropriate licences, EDF increased the enrichment of the ERU fuel to 4.1%  $^{235}\text{U}$  in order to compensate for the presence of  $^{236}\text{U}$ . According to EDF, the lessons learned are that licensing requirements and any safety studies must be addressed early and that very careful calculations of over-enrichment are necessary to avoid the loss of equivalent full-power days (EFPDs).

The Swiss operator Kernkraftwerk Gösgen (KKG) has developed a strategy aiming at recycling the entire arisings of both RepU and plutonium from its reprocessing contracts. KKG has also expressed a willingness to accept RepU fuel incorporating RepU belonging to other owners.

The individual strategies of the Swiss utilities concerning the recycling of RepU are as follows:

**(a) Mühleberg NPP**

The Mühleberg BWR is operated by BKW FMB Energie AG (BKW). All the RepU recovered under the reprocessing contracts has been commercially disposed of through sales, swaps and loans.

**(b) Leibstadt NPP**

The Leibstadt BWR is operated by Nordostschweizerische Kraftwerke AG (NOK). The reprocessed uranium recovered under the reprocessing contracts is recycled in the form of PWR fuel assemblies in NOK's Beznau reactors.

**(c) Beznau NPPs**

The Beznau NPPs are operated by NOK. The reprocessed uranium recovered under the reprocessing contracts is recycled in the form of PWR fuel assemblies. The re-enrichment of the reprocessed uranium is performed in the Russian Federation by blending with high enriched uranium (MEU/HEU).

The fabrication contracts for ERU fuel assemblies cover the needs of the Beznau NPPs up to the second half of the next decade.

**(d) Gösgen NPP**

The reprocessed uranium recovered under the reprocessing contracts is recycled in the form of PWR fuel assemblies. The re-enrichment of the reprocessed uranium is performed in the Russian Federation by blending with high enriched uranium. As in the case of the Beznau NPPs, the fabrication contracts for ERU fuel assemblies cover the needs of the Gösgen NPP up to the second half of the next decade.

It can be seen from the above that the industry has adopted different strategies to use RepU and that no single strategy has emerged as the preferred model.

### **2.1.3. Current status of the RepU market**

In spite of the significant stocks of RepU available for recycle, a market for RepU itself has not been fully developed. Section 6 addresses more thoroughly a number of market related issues.

RepU belongs to the 'secondary sources' in the nuclear fuel market. However, uncertainties about future uranium demand and the capability of current operating and firmly identified uranium mining projects to timely adjust to future demand have not resulted in significant initiatives to increase the annual recycle of RepU. Forecasts for uranium demand and supply are detailed in the fuel market report of the World Nuclear Association (WNA) [9], the 'Red Book' published by the OECD/NEA and the IAEA [10], as well as in a paper [11].

It is reasonable to assume that if RepU could have been introduced readily as an alternative component of supply, it could have reduced the volatility in prices for uranium oxide concentrates (UOC). Views expressed at the TM in August 2007 [6] suggest the main reasons that this has not occurred are:

- There is a lack of standardization of RepU materials, namely in the isotopic contents/ chemical forms;
- The capacities of the recycle supply infrastructure are limited;
- The recycle supply infrastructure is not fully adapted to the potential demand;
- There are uncertainties as to what reactor operators need now and how requirements may develop in the future.

## **2.2. FACTORS AFFECTING USE OF RepU**

### **2.2.1. Economics and competitiveness**

The economics and competitiveness of RepU processing needs to be addressed from the point of view of:

- The prices for natural uranium;
- The costs of RepU processing;
- The RepU management costs in the case that it is not further processed into fuel, but rather placed into temporary storage and eventually disposed of in a permanent repository.

Historically, utilities have found it difficult to identify satisfactory levels of competition in the RepU market, and therefore, a link between prices and perceived costs. Individual utilities have acted independently

and have not been able to rely on market prices for services for RepU in the same way in which these have been available for NU.

### **2.2.2. Translating past experience into future strategies**

Experiences gained over the last ten years are much more relevant than those gained in the preceding 20 years. This is due to the more recent diversification of RepU products and recycle routes, particularly the industrial scale application of the blending route (see Section 3.5.1).

However, due to this diversity of the RepU product and also of the recycle routes adopted in different countries, there has been relatively limited opportunity for technical cross-fertilization and for transferring strategies from one country to the other.

### **2.2.3. National policies related to RepU**

Each country that opts for nuclear power must establish a national policy on the treatment of spent fuel — whether to reprocess the spent fuel, commit it to direct storage facilities or maintain the possibility of both options. Countries that built a relatively large NPP fleet had greater incentives to implement a reprocessing policy and also to construct a domestic reprocessing capability (e.g. France, India, Japan, the Russian Federation, the United Kingdom). The USA is a notable exception, since it took a decision to suspend reprocessing activities already early in 1977. In addition, there are several countries that have only a small NPP fleet and have decided to implement a policy of overseas reprocessing. Examples of countries that initially followed this option are Belgium, Germany, Italy, the Netherlands, Spain, Switzerland and Sweden.

In practice, the reprocessing option is likely to be more complex than direct disposal, since it requires more process steps, more stakeholders and also may require related policies regarding the management of the plutonium and also of the RepU. However, ultimate disposal of waste arising from reprocessing should be made simpler due to the lower heat it generates and its shorter-term radiotoxicity than spent fuel from which it originates. Overseas reprocessing additionally requires intergovernmental agreements to be put in place as well as high profile arrangements for the return of residues from the reprocessing facilities. Historically, it has been the case for Western democracies that the reprocessing option critically depends on continuing publicly accepted justification. This has increasingly become the situation for all countries in recent years, and there are only few examples of governments that can decide on reprocessing without gaining public support. Experience has shown that obtaining and maintaining the necessary levels of public acceptance is as much the responsibility of the utilities as it is of the government.

The utility cannot avoid the need for licences and agreements for every process step. These include fuel export licences, fuel transport licences, commercial agreements to reprocess spent fuel and store the reprocessing residues and products (whether RepU or plutonium), product container transport licences, product quality certificates, recycle agreements, etc. The applications for such licences and agreements are unlikely to be submitted or agreed without reference to the larger picture, and the ability of a utility to demonstrate a real commitment to the recycling of fissile materials may be important to maintain one of the key components of the justification of the reprocessing option at the national level.

The options for managing RepU can be conveniently categorized as follows: to recycle; to dispose of as a waste; or to store as a potential resource pending a future decision [12]. National policies relating to the management of RepU are generally less in evidence than those for plutonium or for the wastes and residues (i.e. wastes converted into a form suitable for return to the country of origin) arising from reprocessing. Some countries have identified RepU as a national energy resource and have required utility owners of RepU to develop plans for its recycle. In these circumstances, the RepU is likely to be treated as an asset, and there may be financial drivers for early recycle rather than storage. In most countries, the RepU inventory is identified as being owned by utilities rather than as a national inventory.

It should be noted that national policies on nuclear power and reprocessing have not remained constant. In Germany, for example, an industrial scale reprocessing facility (Wiederaufarbeitungsanlage Wackersdorf, WAW) was under construction in the late 1980s, but increasing political opposition against it resulted in its cancellation. At that time, German utilities were nevertheless still able to commit spent fuel to reprocessing in foreign reprocessing facilities (namely France and the United Kingdom), but a further change in national



TABLE 1. POLICIES IN SEVERAL COUNTRIES

Country	Reprocessing Policy	Domestic Reprocessing	Spent Fuel Management
China	In favour	Pilot	Interim storage
France	In favour	Yes	Reprocess
Germany	Against according to the Atomic Energy Act	Facilities closed	Previously reprocess, now interim storage
India	In favour	Yes	Reprocess
Japan	In favour	Yes	Reprocess
Russian Federation	In favour	Yes	Reprocess
Switzerland	Against according to moratorium	No facility	Reprocess + interim storage
United Kingdom	In favour	Yes	Reprocess for AGR, LWR under review
USA	Under review	Facilities closed	Interim storage

policy has prevented further reprocessing contracts. Table 1 summarizes the current national policies as of 2007 in a number of countries that have used or declared a RepU policy.

In some of the countries recycling of RepU has been carried out on a large scale. The previous report on RepU [3] has comprehensively dealt with recycling programmes as well as facilities for recycling RepU. It is worth noting that utilities in some countries that operate NPPs and continue to promote nuclear power, but that currently do not support reprocessing, may nevertheless be willing to allow recycling of RepU and Pu in their NPPs (e.g. Switzerland and Germany). As stated in the introduction, several countries are researching the use of RepU in their innovative reactor development [6]. The research efforts at the Oak Ridge National Laboratory in the USA are within the context of evaluating the future plans for the Department of Energy's Global Nuclear Energy Partnership (GNEP) [21]. As currently devised, however, GNEP would dispose of RepU that might not be necessary if it could be reused in LWRs [24].

In the absence of a national policy for the management of RepU, the individual utilities will make decisions on the management of RepU primarily on a strategic or an economic basis. According to individual utilities' approaches, the RepU may be treated in their financial accounts as an asset having a positive value, an asset with zero value or as a liability. Section 6 of this report discusses some of the factors that the utilities may take into account in order to perform this assessment and also to keep such decision under review.

In December 2006, the Japanese Government announced the future of nuclear policy in Japan in a study referred to as Rikkoku Planning [25]. This study indicates the Government's intention to maintain an independent Japanese nuclear industry and the strategic reinforcement of the nuclear fuel cycle. Its position is that the main purpose of domestic RepU is domestic use. RepU is currently positioned only as a strategic resource against future demand.

The United Kingdom provides a recent example of the review and development of policy related to the management of RepU at a national level. In the United Kingdom, the NDA was set up in April 2005 to take strategic responsibility for the United Kingdom's nuclear legacy. As part of its strategic commitment, during 2006 the NDA commenced an evaluation of the potential asset value or liability of the United Kingdom's substantial stocks of civil separated plutonium and uranium, which includes the United Kingdom-owned stocks of RepU. This review emphasized the need to take account of the development of prices in the uranium market, the status of the RepU market, potential technical developments and changes to the availability of recycle routes.

The various options are summarized in a study commissioned by the NDA and recently published in the United Kingdom [26]. This study evaluated multiple scenarios for the disposition of the NDA's stocks of RepU and also depleted UF<sub>6</sub> (tails). With respect to RepU, the study considered the consequences of each of the following options:

- Declare RepU as waste;
- Store RepU pending a decision to use or declare it as waste;
- Consider RepU as a secondary sources of uranium and recycle it to the optimum extent possible.

The NDA's study concluded that a decision on the way forward for the United Kingdom will depend on an assessment of:

- Future price projections for natural uranium;
- The future demand for uranium required to supply worldwide nuclear power generation capacity.

#### 2.2.4. Storage services

In general, RepU is stored by the reprocessor or the potential processor. When interim storage extends for some time, RepU needs to be converted into a more stable form than the direct output of the reprocessing facility. For example, AREVA NC has implemented a commercial facility (TU5) at the Pierrelatte site to convert UNH stemming from the La Hague reprocessing plants into  $U_3O_8$ . The storage service can be offered on a contractual basis by the supplier. Conditions of storage vary considerably. Most of the current inventories of RepU are stored as  $U_3O_8$  in AREVA's facilities in France and as  $UO_3$  in the NDA's facilities in the United Kingdom.

#### 2.2.5. Utility drive towards higher burnup of fuels

Most LWR and CANDU operators are moving to higher nuclear fuel burnups that result in spent fuel with increased levels of  $^{232}U$  and  $^{236}U$ .

After the reprocessing of such higher burnup fuels, the resulting RepU is considered to be of 'lower quality', in particular, with higher levels of  $^{232}U$  and  $^{236}U$  compared to the residual  $^{235}U$  content. This may in turn, depending on the recycle route chosen, lead to radiation protection issues and fuel performance issues. It should be noted that higher burnup strategies go together with higher initial enrichment and, therefore, do not necessarily result in lower spent fuel  $^{235}U$  content [27].

#### 2.2.6. Issues related to RepU quality

Quality limitations for enriched  $UF_6$  to be produced from the RepU are set by the American Society for Testing and Materials (ASTM) in its specifications [28]. At the same time, most of the fuel fabricators usually set stricter and more detailed limits for the content of different impurities and fission products in their specifications.

Table 2 gives an example of the typical concentration limits set in the specification of different fabricators which comply with the limits set by the ASTM C 996-04 [29].

TABLE 2. TYPICAL IMPURITY LEVELS IN REPROCESSED URANIUM

Element	Example of different quality parameters content limits in the fabricator's specifications
$^{99}Tc$	$\leq 10$ Bq/g U
$^{232}U$	$\leq 0.01$ $\mu g/g$ U
$^{241}Pu$	3 Bq/g U
$^{106}Ru$	10 Bq/g U
Boron	$\leq 0.5$ ppm
Silicon	$\leq 50$ ppm

The fabricators' specifications make it necessary for suppliers of RepU processing services, after taking into account any decontamination factors achievable in their processes, to determine the respective specification limits for RepU received into their facilities, especially when RepU is processed through direct re-enrichment. As an example of requirements for RepU, MSZ in the Russian Federation receives RepU oxides ( $\text{UO}_3$  or  $\text{U}_3\text{O}_8$ ) and checks it for compliance with requirements of ASTM 788. Additional requirements are:

- Content of  $^{232}\text{U}$  less than 2.0 E-7%;
- $\alpha$ -activity of transuranium elements less than 150 Bq/gU.

The main problem arising in this regard is that many of the batches of RepU had been produced long before the moment when the utilities took the decision to actually recycle it. The contracts for reprocessing spent nuclear fuel usually did not contain strict requirements either on the quality of RepU or on the scope of measurements. This occurred because at the time, the utilities had no specific plans regarding further use of the RepU and, therefore, were unaware of the requirements for RepU recycling. As a result, the owners of such RepU cannot always provide sufficient reliable information on the content of certain impurities to the suppliers of RepU processing services; some elements were not measured at all; for some elements only a group value was given; and in some cases, only respectively high upper limits were set). An additional problem is that, due to the decay process, the concentration of some decay products in the RepU changes during the long storage period (see Section 3.4.1.). This growth of daughter products can be calculated provided that accurate data on the  $^{232}\text{U}$  content is available.

Due to these reasons, it is important for a utility and a supplier of RepU processing services to agree on the way to define the actual quality of the material, including any requirement to prepare new samples or to perform new analyses.

A further problem may arise related to the homogeneity of a batch of RepU. The production process for RepU may be a batch process or a continuous process. The batch production process generally produces a batch with a high level of homogeneity. In the continuous production process the product may exhibit variations, such as a significant degree of non-homogeneity in uranium isotopes and also in some impurities. In case the RepU is not homogenized, it is necessary for the customer to have a representative sample(s) in sufficient quantity. In the absence of a representative sample, the actual quality of material can be defined only after its dissolution by the processor which then excludes the possibility to reject the material.

### **2.2.7. Obligation codes**

Obligation Codes are used by the Euratom Supply Agency (Euratom, or ESA) to control the movement of uranium in and out of the European Union (EU) in accordance with bilateral agreements between Euratom and certain uranium producing/processing countries.

As regards RepU, material that carries, for example, the A Code must obey the terms of the Euratom/US bilateral agreement such as that A-coded material cannot be transported to a country that does not have a bilateral agreement with the USA.

Similar constraints also apply to Canadian and Australian coded material (C Code and S Code, respectively).

There are also two other important obligation codes, non-obligated (N Code) and 'peaceful use assured' (P Code). RepU that carries these N or P Codes is not subject to the terms in any of the above bilateral agreements.

Obligation codes can be swapped between equivalent weights of  $^{235}\text{U}$ ; however, the code swaps do have to comply with certain guidelines applied by Euratom. For example, one such guideline is that the two batches of material involved in the exchange must be of a comparable chemical form ( $\text{UO}_3$ ,  $\text{U}_3\text{O}_8$ , depleted uranium (DU), etc.), but cannot be in the form of spent fuel. ESA approval of obligation code exchanges must be obtained by the owners of the material involved; ESA may impose conditions on the approval. An example of a condition imposed by ESA is that once the code on a specific batch of RepU has been swapped, it cannot be involved in another code swap again.



### 2.3. CHALLENGES

At the TM in August 2007, the attendees identified the most significant future challenges [6], which include the following (addressed in later sections):

- Difficulties for suppliers of RepU processing services to forecast the nuclear fuel market demands for RepU;
- Compliance with the ALARA principle, taking into account the in-growth of daughter products of  $^{232}\text{U}$  after each stage of chemical separation;
- The 5.0%  $^{235}\text{U}$  licensing limits for reactor loading, processing and transport;
- The lack of facilities for cleaning cylinders containing ERU.

### 2.4. OPPORTUNITIES

Discussion at the TM in August 2007 also achieved a broad consensus that there are a number of opportunities associated with the use of RepU:

- While there are uncertainties in UOC prices, RepU is not dependent on a volatile commodity price.
- It supports sustainable policies of nuclear energy growth and closed fuel cycle policies.
- The use of RepU assists security of supplies.
- It provides additional options in procurement strategies for the utilities.
- Performance of the ERU fuel can be equivalent to enriched natural uranium (ENU) (may not require substantial modification of core-management, can be easily achieved with certain configurations, e.g. first cores).

### 2.5. POTENTIAL SOLUTIONS

Some solutions have already been developed and implemented, and other potential solutions have been identified. Furthermore, in some cases detailed assessments have been completed [3]. These solutions include:

- Blending RepU with fresh uranium in the course of enrichment;
- Blending RepU with enriched uranium (LEU to HEU);
- Double cascade centrifuge enrichment;
- Direct enrichment of RepU in centrifuges;
- Mix of the above-mentioned solutions;
- Laser enrichment.

The areas of use which have not yet been adopted, but have been identified as having the most promising future potential are as follows:

- RepU in CANDUs (see Section 3.8.2);
- RepU in first cores in reactors (see Section 3.8.1);
- RepU in fast reactors (see Section 3.8.1);
- RepU as a component of mixed uranium-plutonium oxide (MOX) fuel (see Sections 3.8.2 and 3.9.2).

Section 3 of this report provides a more detailed description of the recycle routes that can deliver or contribute to these solutions.

### 3. STAGES IN IMPLEMENTATION OF DIFFERENT OPTIONS

#### 3.1. OVERVIEW OF RECYCLE OPTIONS

As introduced in Section 2, an electric utility operating NPPs has different routes technically possible for using reprocessed uranium by turning it again into nuclear fuel and loading it into its nuclear power plants. The utility does not request, per se, a given technical route, but a specific fuel product. Thus, the route chosen may depend on the required end product and the RepU quality ( $^{232}\text{U}$ ,  $^{235}\text{U}$  and  $^{236}\text{U}$  assays), and is also determined by price and/or cost issues and the RepU rate of consumption. It may also depend on government policies or specific governmental approvals.

The aim of this section is to describe in principle the various potential routes, specify the necessary steps for each route and present examples of applications at each step, by country. The chemical forms of RepU are identified, the storage methods are described and the transport practices are explained. This section highlights the potential routes that are already available and provides an explanation of the current status of each route.

RepU out of a given treatment (processing) plant is by nature not a standard product. Its enrichment in the fissile isotope  $^{235}\text{U}$  varies, and it may contain chemical impurities, and different lots may have different isotopic compositions. The front end supply chain has been and will be further developed to be flexible enough to accommodate the variability of the raw product and the evolving needs of the utilities. Even for a given route and processing technology, a facility may need to be either re-licensed or modified to accommodate evolving qualities of RepU, essentially due to higher burnups of originating fuels. Some features of the raw RepU may lead to choosing preferably one route. For example, a high  $^{236}\text{U}$  content may require blending of products of different origins in order to reach the desired reactivity of the fuel bundle without exceeding the licensed  $^{235}\text{U}$  assay, all along the supply chain and in the reactor.

The possible routes for the use of RepU are summarized in Table 3. They include direct use (without any re-enrichment), re-enrichment (with the consequential arising of tails), blending of RepU with higher enriched material and finally a ‘mixed route’, which involves both the re-enrichment of the RepU and some blending with other material.

It should be particularly noted that the routes differ significantly in the rate of consumption of RepU per fuel assembly. Table 3 covers the replacement of standard  $\text{UO}_2$  fuel by RepU fuel in PHWRs, LWRs and RBMKs. The possible use of RepU as a carrier for MOX fuel and fast reactor uses are not addressed in this table.

In addition, it should be noted that there is a scheme to use partly treated<sup>2</sup> spent fuel from PWRs in CANDU reactors, which is under study at the Korea Atomic Energy Research Institute (KAERI), Republic of Korea. This scheme is known as the Direct Use of Spent PWR fuel in CANDU (DUPIC). Since the DUPIC scheme does not involve specific use of separated RepU and is still under development, it is not dealt with in Table 3 and has been excluded from all considerations in this report.

Table 3 does not highlight any details of the experience of using each of the routes. No information is included for example on quantities, dates, customers or suppliers of RepU.

Table 4 provides examples of routes employed for the recycle of RepU in Europe, Japan, the Russian Federation and the USA, and identifies the supplier of the relevant services. This table, which is not necessarily comprehensive, concentrates on routes which have been developed to a commercial scale. On the other hand, many of the developmental works that might evolve into potential new routes are not compiled in the table<sup>3</sup>.

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<sup>2</sup> The treatment involves: (a) removing the cladding, (b) oxidizing and reducing the fuel material at high temperatures, and (c) re-fabricating the fuel. Therefore, most non-volatile fission products, Pu and MAs are retained with the  $\text{UO}_2$  fuel.

<sup>3</sup> For example, trials were carried out by KAERI, Republic of Korea, in a CANDU reactor to demonstrate the quality of  $\text{UO}_2$  powder produced by the Modified Dry Route (MDR) process developed by BNFL Springfields (now Toshiba/Westinghouse). These trials included slightly enriched uranium (SEU) produced from NU and RepU. However,  $\text{UO}_2$  pellets were produced from the RepU oxide powder prepared on a laboratory scale (no industrial-scale facility). There are also collaborative efforts to evaluate the recycling of uranium in CANDU reactors by Atomic Energy of Canada Limited (AECL), KAERI and British Nuclear Fuels plc, under the project RUFIC (recovered uranium fuel in CANDU) [13–15]. ORNL performed reactor neutronics calculations on the use of RepU in CANDUs considering advanced fuel design, viz. CANFLEX [23]. CANFLEX is a name derived from CANDU FLEXible Fuelling.

TABLE 3. OVERVIEW OF POSSIBLE RepU RECYCLING ROUTES FOR USE IN THERMAL REACTORS

Route	End Use (Reactor Type)	Conversion to UF <sub>6</sub>	Re-Enrichment	Tails Arising	Rate of Consumption of RepU per Assembly <sup>a</sup>	Dedicated Fabrication Line
Direct use	PHWRs <sup>b</sup>	No	No	No	High	Not necessarily
Re-enrichment	PHWRs	Yes	Yes	Yes	High	Not necessarily
Re-enrichment	LWRs	Yes	Yes	Yes	High	Yes
Mixed route	LWRs	Partly	Yes	Yes	Medium	Depends on the mix
Blending	LWRs / RBMKs	No	No	No	Low	Not necessarily

<sup>a</sup> This relates to the net consumption of reprocessed uranium per assembly loaded in the reactor.

<sup>b</sup> In PHWRs, the direct use is possible only if the residual <sup>235</sup>U assay is higher than 0.711%.

TABLE 4. EXAMPLES OF ROUTES USED IN THE PAST OR AT PRESENT FOR RECYCLING OF RepU (COMMERCIAL USE OF RepU)

Route	End-use	Conversion	Blending or re-enrichment	Fuel fabrication
A	Europe	To UF <sub>6</sub> by AREVA NC	Re-enrichment by UEC <sup>a</sup>	AREVA NP in Romans-sur-Isere, France
B	Europe	To U <sub>3</sub> O <sub>8</sub> by AREVA NC; to UF <sub>6</sub> by SGChE in Seversk	Re-enrichment by SGChE <sup>b</sup> in Seversk	AREVA NP in Romans-sur-Isere, France
C	Europe	To U <sub>3</sub> O <sub>8</sub> by AREVA NC	By re-enriching and blending with HEU or LEU up to 17% in the Russian Federation	TVEL in Elektrostal (in some cases just pelletizing and then assembly manufacturing at AREVA NP in Lingen, Germany)
D	Japan	To UF <sub>6</sub> by AREVA NC	Re-enrichment by UEC	MNF <sup>d</sup> at Tokai in Japan
E	Japan	Conversion at JAEA <sup>c</sup> in Ningyo-Toge	Enrichment at JAEA <sup>d</sup> in Ningyo-Toge	MNF and JCO <sup>e</sup> at Tokai in Japan
F	Russian Federation	To UF <sub>6</sub> by SGChE in Seversk	By blending with HEU or LEU up to 17% in the Russian Federation or mixed route	TVEL in Elektrostal
G	United States of America	No conversion	Blending of HEU by NFS <sup>f</sup> in Savannah River <sup>g</sup>	By AREVA NP, Inc. in the USA within the framework of the BLEU programme

<sup>a</sup> UEC = Urenco Enrichment Company Limited.

<sup>b</sup> SGChE = Siberian Group of Chemical Enterprises.

<sup>c</sup> MNF = Mitsubishi Nuclear Fuel.

<sup>d</sup> JAEA = Japan Atomic Energy Agency.

<sup>e</sup> JCO = Japan Nuclear Fuels Conversion Company, subsidiary of Sumitomo (former name).

<sup>f</sup> NFS = Nuclear Fuel Services, Inc.

<sup>g</sup> Non-power reactor highly enriched reprocessed uranium.

For further details, including the historical use of RepU, refer to IAEA-TECDOC-1529 entitled ‘Management of Reprocessed Uranium’ [3] and the proceedings of the IAEA TM of August 2007 [6].

The schemes (routes) listed in Table 4 and their facilities must evolve with the evolving quality of RepU, and with the utilities’ and the regulators’ requirements.

In order to manage the new challenges mentioned in Section 2, adjustments of capacities and/or investments in new facilities should be considered in the front end part of the ERU fuel cycle, with the following in mind:

- Refurbished and/or new RepU treatment (processing) plants should offer more modern features.
- Additional conversion capacities would be needed in case the physical re-enrichment or the mixed route is chosen.
- Additional/new enrichment capacities should be dedicated to RepU. The centrifuge technology, because it is modular, allows devoting specific cascades to RepU enrichment, which is not possible with gaseous diffusion. However, the centrifuge technology does not allow direct selective re-enrichment of  $^{235}\text{U}$ , which is an interesting, even desired, economic application for ERU. Laser enrichment techniques, if they would become available at an industrial scale, are expected to offer such selectivity.
- Suppliers and utilities should also work together with safety authorities at national and international levels on the conditions under which the present limit of 5%  $^{235}\text{U}$  for LWR fuel could be increased. This would mean reconsidering the regulations and standards, at least for ERU fuel.
- The specifications of fabrication plants must be reassessed so that they can accept ERU with higher  $^{232}\text{U}$  assays.

Several developments are envisaged in different countries. In France, AREVA is performing an in-depth assessment of the market evolution to define the characteristics of a new RepU conversion facility as part of a newly proposed industrial scheme (see Section 3.4.3.2). Japan may also consider a RepU conversion facility to complement the Rokkasho-mura reprocessing plant.

These new supply chain facilities will have to be designed to comply with more stringent nuclear safety standards and regulatory constraints to take into account the evolution of the characteristics of the reprocessed uranium stemming from used uranium oxide (UOx) fuel. Higher concentration of minor isotopes ( $^{232}\text{U}$ ,  $^{234}\text{U}$  and  $^{236}\text{U}$ ), due to higher burnups, must be anticipated and integrated in the design data to overcome today’s limitations and constraints, and offer a long-term capability to manufacture ERU fuel.

## 3.2. MANAGEMENT AND STORAGE

### 3.2.1. RepU product: Chemical form and quality

The output of reprocessing plants may take different chemical forms: uranyl nitrate hexahydrate ( $\text{UO}_2(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ ) or oxide ( $\text{UO}_3$ ). Depending on the route, this raw material can be processed immediately or stored prior to further use. Uranyl nitrate is an oxidizing compound, in a liquid form when hydrated (UNH), and if not processed immediately, has to be converted into  $\text{U}_3\text{O}_8$ . From a technical standpoint, there is no restriction on the storage of  $\text{U}_3\text{O}_8$ , which is a very stable powder. In contrast,  $\text{UO}_3$  is, to some extent, hygroscopic, and storage conditions should be controlled to ensure that moisture uptake is minimized.

In the initial storage of RepU, the following poses potential issues:

- Retrieving material from a specific batch. This can be complicated since RepU is not as fungible as NU.
- Storage capacities on nuclear site. Since not all material stemming from treatment plants is processed, the storage capacity for RepU is in constant evolution.
- Storage and transport of RepU with a  $^{235}\text{U}$  assay greater than 1% (criticality reasons and radiation protection issues).

### 3.2.2. Storage in the form of UNH

Liquid UNH is in practice only temporarily stored before being transferred to processing facilities. It is not stored for the medium or long term in this form.

### 3.2.3. Storage in the form of $U_3O_8$

$U_3O_8$  is stored in 213 L standard drums; they can be stacked in warehouses. Containers containing depleted uranium (tails of enrichment process of natural uranium) can be used as shielding in the warehouse.

### 3.2.4. Storage in the form of $UO_3$

In the United Kingdom, RepU is produced in the form of  $UO_3$ .  $UO_3$  produced from the reprocessing of spent Magnox reactor fuel (MDU) is currently stored in 213-litre mild steel drums.  $UO_3$  produced from the reprocessing of LWR fuel is stored in 50 L stainless steel drums.  $UO_3$  is, to some extent, hygroscopic, and therefore, there is the risk of the absorption of water from the atmosphere. Under such circumstances, the surface layer may form a solid crust of hydrated  $UO_3$ , which needs to be broken up prior to emptying the storage drum or further processing the product. This risk is minimized in the case of the 50 L drum by use of a rubber seal between the drum and the drum lid, which is mechanically crimped onto the drum. There are also criticality issues associated with hydrated  $UO_3$  (which implies smaller drums of 50 L for material with a  $^{235}U$  assay greater than 0.95%, against 213 L standard drums for  $U_3O_8$ ) [32].

In Japan, the products after reprocessing at the Tokai Reprocessing Plant (TRP) are  $UO_3$  powder and Pu+U mixed nitric solution.  $UO_3$  powders are packed into dedicated vessels (see Fig. 2) and Pu+U mixed nitric solutions are co-denitrated to oxide materials  $PuO_2+UO_2$ . The latter materials are stored at TRP.

### 3.2.5. Quality of RepU and quality control

With respect to current inventories of RepU, it must be considered a non-standard product, from the standpoint of isotopic composition, physical (homogeneity of the product) and chemical form.

A number of utilities have made it clear that they would prefer consideration of a standardized chemical form in the future. Since the current RepU product cannot obviously meet such a requirement, the front end supply chain has to address this problem. A utility operating an entire reactor fleet is in a better position to decide upon a RepU management strategy that leads to a more homogeneous material.

There are issues related to inhomogeneous material. It is not a problem in France, where UNH is produced by large homogeneous batches before conversion to similar size batches of  $U_3O_8$ , but it may be an issue in the United Kingdom where  $UO_3$  is produced by a continuous process giving rise to smaller batches. In this case,

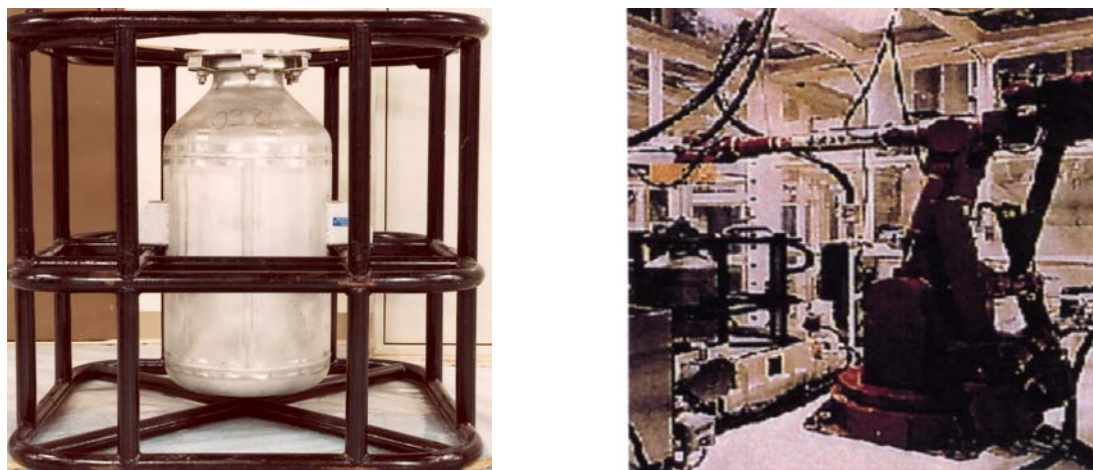


FIG. 2. The  $UO_3$  vessel and vessel-handling equipment at Japan.



TABLE 5. DEVELOPMENT OF ANALYTICAL METHODS FOR REPROCESSED URANIUM CHARACTERIZATION AT THE IAEA

Nuclides	Analytical method		Lower limits (Bq/g U)
	Standard methods	Advanced method	
<sup>237</sup> Np	TTA-Solvent extraction → α-spectrometry	TTA-Solvent extraction; Anion exchange → α-spectrometry	
<sup>238</sup> Pu, <sup>239</sup> Pu, <sup>240</sup> Pu	TTA-Solvent extraction → α-spectrometry	TTA-Solvent extraction; Anion exchange → α-spectrometry	10 <sup>-4</sup> -10 <sup>-5</sup>
<sup>241</sup> Am, <sup>244</sup> CM		TTA-Solvent extraction; Anion exchange → α-spectrometry	

TTA=Thenoyl-trifluoro-acetone, TOPO=tri-n-octyl phosphine oxide.

samples taken from individual batches at the time of production are required by customers to check the quality of RepU.

In the Thorp process, samples are taken during the drumming phase of each RepU production campaign. The RepU being drummed is constantly sampled using a screw feeder, and these samples are combined to produce a homogeneous campaign sample which is representative of the whole RepU production campaign (a large RepU production campaign, i.e. over 75 t U, may have two or more campaign samples with each sample representing portions of the entire RepU campaign). Campaign samples range in size from 100 g to 300 g of UO<sub>3</sub>, depending on the size of the parent RepU campaign.

If a campaign sample were to be re-analysed, the results would only be comparable against the analytical results for the entire campaign. If compared to a single drum, both the original and new results would be expected to vary, since certain analyses will vary across the entire RepU campaign following the variations in the spent fuel.

The plutonium and uranium recovery by extraction (PUREX) process is capable of a high degree of separation of uranium from other elements, and as a consequence, the impurities are often present only at very low levels. Some of the impurities analysed are therefore being measured at the limit of detection. Therefore, if re-analyses were undertaken, deviation from the original results for those particular impurities could be anticipated. In this regard, new analytical methods for the characterization of RepU are being developed (see Table 5) [33-40].

### 3.3. TRANSPORT

#### 3.3.1. Licences

A number of licences have to be in place prior to the shipment of RepU. An export licence must be obtained from the competent authority of the home country of whoever is acting as the transporter for the RepU. For example, if a United Kingdom company were arranging the transport of RepU to the Russian Federation, the export licence would be granted by the United Kingdom Competent Authority following consultation with the Russian Government. An export licence details the quantity of RepU to be exported and the <sup>235</sup>U enrichment bands into which the RepU falls.

A corresponding import licence is granted by the destination country's competent authority and is usually applied for by the RepU processing company. The timescales required to obtain export and import licences may be significant.

All packages involved in the transport of RepU, which are specifically designed to prevent the loss of containment of RepU, must be licensed by the competent authority of the country in which the package owner resides. These package licences must also be validated by the competent authority of the country in which the package will be used. Licence approvals and validations can take up to 18 months to receive and are usually granted for three to five years.

### 3.3.2. Transport of RepU in liquid forms

After the reprocessing operations, the RepU is in liquid form (UNH) (hereinafter referred to as 'RepU UNH') and must be converted into a more appropriate physical form for storage pending further use. The three main forms are  $\text{UO}_3$ ,  $\text{U}_3\text{O}_8$  and  $\text{UF}_6$ .

In France, the RepU UNH is routinely transported from the reprocessing plant in La Hague to the Pierrelatte site for conversion. In the United Kingdom, 'fresh' UNH prepared from processing unirradiated uranium is transported routinely by road in a purpose-designed tanker from the Springfields site to the Sellafield site. There is no experience in the United Kingdom, however, of transporting RepU UNH.

If the utility does not plan to recycle the RepU immediately, the preferred option is to store it in the stable oxide form of  $\text{U}_3\text{O}_8$ . When the utility wants to use rapidly the material via the direct re-enrichment route, the RepU is converted into  $\text{UF}_6$ . For the time being, no UNH is sent directly to the  $\text{UF}_6$  conversion facility outside France. For such long international transport, it would be necessary to check in detail the safety and security issues.

### 3.3.3. Transport of the $\text{U}_3\text{O}_8$

In France, since all UNH quantities stemming from La Hague are not immediately recycled, the UNH is denitrified in the TU5 workshop in Pierrelatte, with  $\text{U}_3\text{O}_8$  as an end product. This  $\text{U}_3\text{O}_8$  material can be sent to another facility outside France (i.e. in the Russian Federation) for conversion into  $\text{UF}_6$  (see Section 3.3.2.). The isotopic composition and the impurities content of this  $\text{U}_3\text{O}_8$  follow the same ASTM specifications as for the UNH.  $\text{U}_3\text{O}_8$  with assays under 1% in  $^{235}\text{U}$  is stored in 213 L standard drums. Transport of these filled drums does not pose any specific problem.

### 3.3.4. Transport of the $\text{UO}_3$

The type of transport package required for transport of RepU depends on the enrichment of the material being exported. RepU in the form of  $\text{UO}_3$  which has  $^{235}\text{U}$  enrichment less than 1% can be transported in an IP-2 rated package as defined in the IAEA Transport Regulations. In practice, this means that RepU as  $\text{UO}_3$  which has  $^{235}\text{U}$  enrichment less than 1% can be transported in 50 L drums within a standard ISO freight container. The RepU in the form of  $\text{UO}_3$  with a  $^{235}\text{U}$  enrichment equal to or greater than 1% must be transported in a package rated to IP-2 IF standard and it must demonstrate that in accident conditions the RepU contained within the package cannot form a critical mass [11]. In practice, this means that RepU in the form of  $\text{UO}_3$  with a  $^{235}\text{U}$  enrichment equal to or greater than 1% must be transported either with each 50 L drum surrounded by an overpack or in specially designed ISO freight containers.

The IP-2 and IP-2 IF packages must be assessed against their ability to ensure containment of the RepU and their mechanical strength, handling characteristics, ability to be decontaminated, weight and cost. As  $^{235}\text{U}$  enrichments of RepU increase, the economic viability of certain packages over certain routes can become questionable.

Further packages, such as ISO freight containers, can be used for handling and security purposes without licensing if no containment credit is assumed.

### 3.3.5. Transport of RepU in $\text{UF}_6$ form

Provided that its residual  $^{235}\text{U}$  enrichment is below 1%, non-re-enriched RepU in  $\text{UF}_6$  form is transported in 48Y cylinders, which are the same as those used for ENU. Although the cylinders are the same, their management (e.g. cleaning and storage further to emptying) may differ due to the heels (see Section 3.3.6.).

### 3.3.6. Transport of ERU in $\text{UF}_6$ form

ERU in the form of enriched  $\text{UF}_6$  is transported in the same 30B cylinders as those used for ENU.

As long as the cylinders remain filled and the period since the filling is kept short, there are no major radiological issues, and the same transport system as for the 30B cylinders filled with ENU can be used from the enrichment facilities to the fuel assembly manufacturing facilities.

The major issue specific to the ERU appears when the 30B cylinders have been emptied at the fuel manufacturing facility. The 'empty' cylinders contain a high concentration of  $^{232}\text{U}$  daughter products (known as 'heels') and, due to significant radiological doses [41], special measures should be implemented for their storage and their transport compared to standard empty 30B cylinders.

### **3.3.7. Transport of the ERU powder ( $\text{UO}_2$ )**

The containers used for the transport of ENU powder (in form of  $\text{UO}_2$ ) can be used also for ERU powder, provided a specific sheet related to the ERU material is added to the transportation licence. For instance, AREVA NP uses TNF-XI packages to deliver ERU powder to Japan. There is no ERU-dedicated powder transport container fleet.

### **3.3.8. Transport of $\text{UO}_2$ pellets**

The qualification of fuel vendors for fuel fabrication is often a very lengthy process. It may be important, therefore, that the reactor operator can retain the same fuel fabricator for ENU fuel and ERU fuel. In such circumstances, the capability to transport fuel pellets is a key opportunity to de-link the supply chain. The transport of ERU pellets presents no additional challenges when compared with the transport of ENU pellets. The newly developed packages are for multi-purpose shipments, such as alpha contaminated technological wastes in drums,  $\text{UO}_2$  powder, pellets, or part of fuel rods and liquid wastes [42]. These types of packages are now widely used and can be adapted to various possible contents in various transport configurations. All of this new generation of packages is intended to be adapted to the main needs of the test and research reactors, by offering at maximum a standard system that can be modulated for any specific purpose.

### **3.3.9. Transport of the fuel assemblies**

The ERU fuel assemblies are transported in the same casks as for the ENU fuel assemblies [43].

Although not specific to ERU assemblies, logistics issues have to be dealt with by utilities having selected the blending route proposed by the Russian Federation when the ERU assemblies are transported from MSZ to the reactor sites in Western Europe. The casks loaded with ERU fuel assemblies are first transported by rail to a port on the Baltic Sea coast (typically St. Petersburg), where they are loaded onto a ship for sea transport. The casks are then transported to the reactor sites by road.

Experience has shown that a ship travel schedule can vary by several days, up to two weeks, compared to the official schedule. This is especially the case when the Baltic Sea starts freezing in winter. The utilities must therefore reserve relatively large 'windows' (time slots of three to four weeks) for the arrival of the ERU fuel assemblies at the reactor site and have their personnel on stand-by for a significant period of time, without knowing the exact arrival date until the last moment.

In addition, all ERU fuel assemblies of a given reload are shipped in a single transport, which requires a large number of transport casks for a long period of time. Upon arrival on-site, the casks have to be safely stored during the unloading procedure, which can take up to one week. Appropriate large and secure storage place(s) should therefore be available on-site.

As an example, a typical reload of the Gösgen reactor in Switzerland consists of 40 ERU fuel assemblies. These assemblies are transported in AREVA NP ANF-18 casks with a capacity of two assemblies each. Therefore, a transport includes 20 casks loaded on five trucks arriving at the same time at the reactor site. Since about four casks are unloaded per day, one week is needed to bring all the ERU fuel assemblies into the reactor dry storage.



### 3.4. RE-ENRICHMENT ROUTE

The ‘physical re-enrichment route’ is defined in essence by its two major stages: RepU conversion into the chemical form of  $UF_6$ ; and subsequent enrichment in gas centrifuges. However, to be able to implement this route, it is necessary to purify the products by removing chemical impurities or radioactive daughter products of  $^{232}U$ . Also required are several workshops peripheral to the route and associated with various stages of the process, such as cylinder washing, sampling, waste treatment and conditioning, etc.

There are a number of potential chemical impurities in the RepU that may be of particular interest to processors or fuel vendors. These impurities include chloride, sulphate,  $^{99}Tc$  and Pu.

The need to purify RepU from chemical impurities depends on demands placed by NPP fuel fabricators. Most fuel fabricators set their requirements for chemical impurities in amounts specified by international ASTM standards. In several cases, specifically insofar as fabricators from Japan are concerned, requirements for the content of particular chemical elements may be tightened at the request of the fuel fabricator.

An example of the industrial scheme of the conversion/re-enrichment route is the one available in the Russian Federation, in the Siberian Group of Chemical Enterprises (SGChE) (shown in Fig. 3), which involves three stages [44]:

- Radiochemical purification of initial oxides at the radiochemical plant (RCP);
- Conversion of purified oxides into hexafluoride at the conversion plant (CP);
- Enrichment of feed in form of hexafluoride (up to 5%  $^{235}U$ ) at the enrichment plant (EP).

Another example of the industrial scheme of the conversion/re-enrichment route is shown in Fig. 4, corresponding to AREVA NC’s plan for new conversion and enrichment facilities for RepU (see Section 3.4.3) [45].

It should be noted that it is possible to mix routes and industrial schemes. A utility is not forced to choose a specific scheme from its beginning to its very end. However, constraints remain on the final steps associated with fuel fabrication. In particular, there is a need for specific licensing to manufacture ERU fuel.

There are some projects in the Russian Federation, Japan and France to develop new technologies and capacities to take into account the evolution of the RepU composition. Depending on the projects, the intermediary products would be different (such as  $UO_3$ ,  $U_3O_8$ ,  $UO_2$ ,  $UF_4$ , or  $UF_6$  by direct fluorination).

The following sections describe in more detail the different steps involved in the physical re-enrichment route.

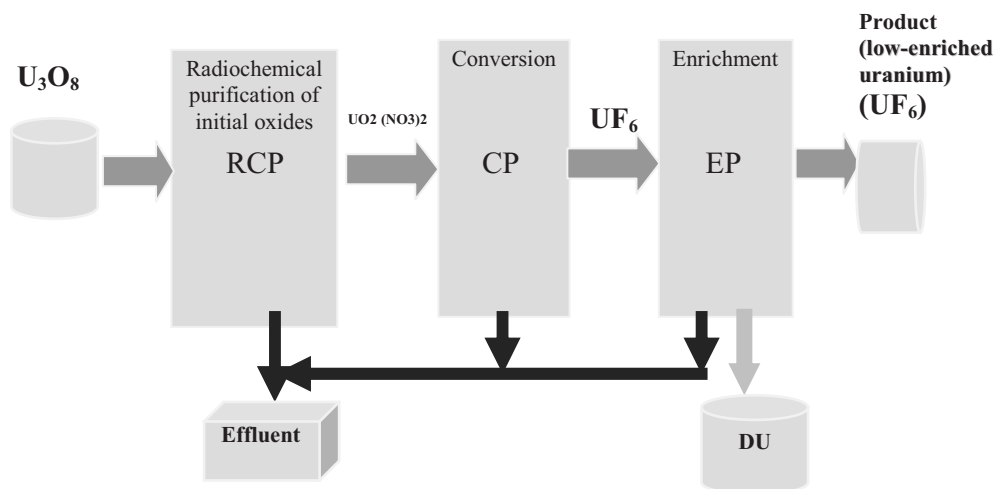


FIG. 3. The scheme for processing reprocessed uranium as uranium oxide within the Siberian Group of Chemical Enterprises (SGChE).

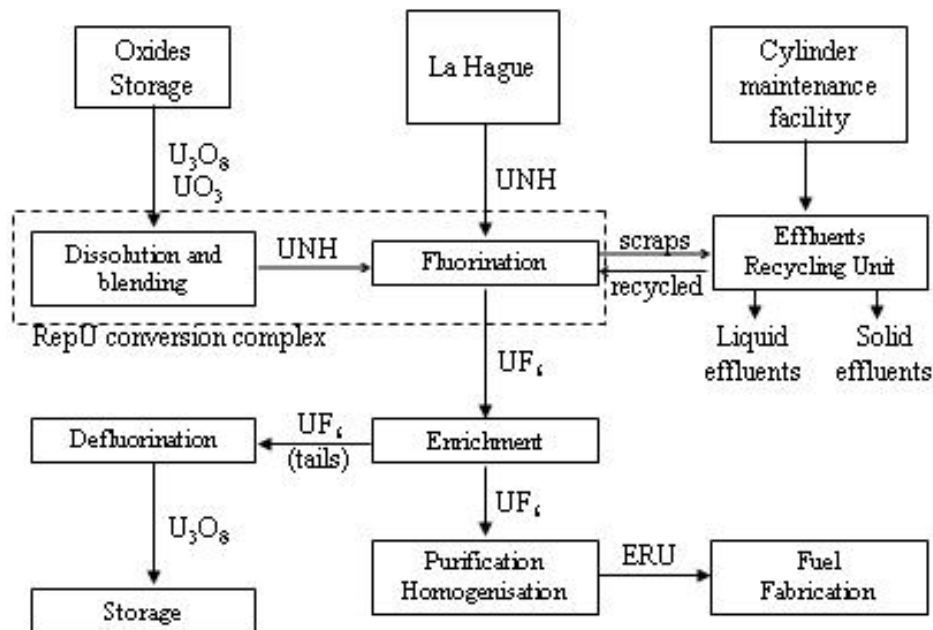


FIG. 4. The AREVA NC RepU recycling project.

### 3.4.1. Chemical purification

In the Russian Federation, RepU undergoes a first stage of purification at the SGChE's Radiochemical Plant [47]. The material above 1%  $^{235}\text{U}$  must be blended down to 1% or less in  $^{235}\text{U}$  prior to the purification step. Then, the SGChE's conversion plant performs conversion of feed uranium (with up to 1%  $^{235}\text{U}$ ) into hexafluoride, which is subsequently shipped to the SGChE's Enrichment Plant. Feed materials for the conversion plant are nitric acid solutions from the radiochemical plant as well as natural uranium oxides or natural uranium tetrafluoride from outside customers.

The radiochemical plant is primarily aimed to purify uranium isotopes from radioactive decay products. The process takes into account radiation safety standards and regulations in force when reprocessed material undergoes further treatment at the conversion and enrichment plants. In this process (at the radiochemical plant), RepU is purified also from chemical impurities other than decay products.

The necessity for purifying RepU from chemical impurities depends on demands placed by NPP fuel fabricators. Most fuel fabricators set their requirements for chemical impurities in amounts specified by international ASTM standards.

As described in Sections 2.3.5 and 2.4, one of the major problems with chemical treatment of RepU is caused by  $^{232}\text{U}$ , which, after having transformed by alpha decay into  $^{228}\text{Th}$ , features a long chain of short-lived and, consequently, highly radioactive elements. In terms of radiative effects, the highest priority hazard in this chain is posed by  $^{220}\text{Rn}$  due to its possible emanation into the air of the working environment and by  $^{208}\text{Tl}$  with decay energy of 2.61 MeV inducing a considerable deterioration in the  $\gamma$ -radiation environment. The  $^{228}\text{Th}$  activity variation with time starting from its most recent radiochemical purification is shown in Fig. 5.

The activity curve illustrates that if the time period between the radiochemical purification of reprocessed uranium and its subsequent treatment is reduced to less than three months, the RepU's  $^{228}\text{Th}$  content will amount to below 10% of the equilibrium value, and therefore the  $^{208}\text{Tl}$  impact on the staff will be minimized.

Radiochemical recycling at SGChE of the oxides originating from French facilities allowed removing the  $^{232}\text{U}$  decay products accumulated in RepU during its long-term storage period. In parallel with the removal of decay products, reprocessed uranium was purified from fission products, transuranic elements and  $^{99}\text{Tc}$ .

Chemical treatment of NU and RepU at the radiochemical plant and the conversion plant is largely carried out separately using special facilities. Nevertheless, some processing lines at these facilities are dual-purpose (i.e. chemical treatment of reprocessed or natural uranium). For example, it is possible to operate the conversion

## 228Th Buildup Analysis

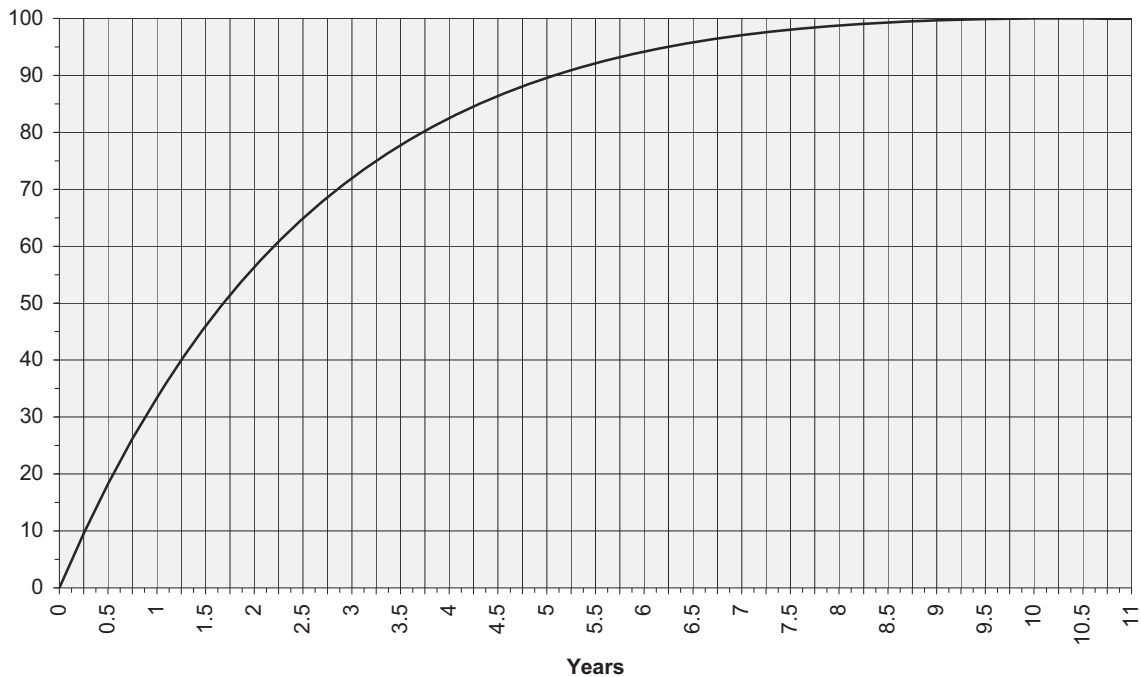


FIG. 5.  $^{228}\text{Th}$  activity curve (in % of equilibrium value).

facility by batch of either natural or reprocessed uranium. However, the facility has to be specially prepared (including washing and some other arrangements) prior to processing each type of feedstock.

In the chemical treatment of RepU at SGChE, the radiochemical plant handles the major part of radioactive wastes produced. The process employs technologies for the conditioning and underground disposal of these wastes.

From the conversion plant, the converted RepU (now in the form of  $\text{UF}_6$ ) is shipped for subsequent enrichment to the enrichment plant, where a special-purpose centrifuge cascade with dedicated lines and collectors is available for RepU hexafluoride enrichment. Pursuant to the Russian Federation's relevant tailings long-term storage regulations, reprocessed uranium tails are stored in the form of uranium hexafluoride.

In the event uranium hexafluoride enrichment is carried out on a contractual basis, the enrichment plant can consider rendering services including washing 'empty' containers of the customer (here the term 'empty' implies that the container may still contain heel). In particular, requisite facilities for washing 48Y and 30B containers are available at the enrichment plant.

Between 1992 and 1998, 1307.4 tonnes of RepU delivered from France as uranium oxide was processed at SGChE according to this scheme.

The average isotopic composition of material stemming from French facilities and recycled at SGChE is shown in Table 6 [44].

As the result of direct enrichment of this feedstock at the enrichment plant, low-enriched uranium hexafluoride with a  $^{235}\text{U}$  content of 3.0 to 4.95% was obtained. The  $^{232}\text{U}$  content in the end product therewith amounted to 1 E-6 %, the  $^{234}\text{U}$  content up to 0.1%, and the  $^{236}\text{U}$  content up to 1.4%.

Based on the previous experience of SGChE with the re-enrichment of RepU in hexafluoride form (which resulted in an increase in radiation levels of the sublimation equipment at the enrichment plant), SGChE prefers RepU feedstock to be shipped as oxides.

The availability of the purification, conversion and enrichment stages at SGChE allows to attain minimization of the periods between the different processing stages by RepU processing sequence scheduling and therefore to minimize the plant staff radiation load induced by decay products such as  $^{208}\text{Tl}$  and  $^{220}\text{Rn}$ .

TABLE 6. ISOTOPIC COMPOSITION OF MATERIAL STEMMING FROM FRENCH FACILITIES AND RECYCLED AT SGChE

Chemical form of feedstock	Quantity (t U)	Feedstock isotopic composition (% of U total)			
		<sup>232</sup> U	<sup>234</sup> U	<sup>235</sup> U	<sup>236</sup> U
Hexafluoride	349.3	8.8 E-8	0.0172	1.062	0.3374
Uranium oxide	1307.4	1.24 E-7	0.0159	0.822	0.3427
Total uranium	1656.7	1.17 E-7	0.0162	0.872	0.3416

TABLE 7. ISOTOPIC COMPOSITION OF REPROCESSED URANIUM AFTER DILUTION WITH LEU

Parameters	Feed reprocessed uranium <sup>a</sup>	ERU product <sup>a</sup>	ENU product <sup>a</sup>	Blend of two products <sup>a</sup>
<sup>232</sup> U	2.0 E-7	1.27 E-6	1.0 E-8	1.99 E-7
<sup>234</sup> U	0.024	0.137	0.049	0.0622
<sup>235</sup> U	0.99	4.8	4.8	4.8
<sup>236</sup> U	0.45	1.586	0.009	0.246
Uranium mass, kg U	—	0.15	0.85	1.0
Separation work input, SWU	—	0.769	5.788	6.557

<sup>a</sup> The numbers given for <sup>232</sup>U, <sup>234</sup>U, <sup>235</sup>U and <sup>236</sup>U mean % of U total.

### 3.4.2. Purification from minor uranium isotopes

The control of minor uranium isotope concentrations in RepU is performed in the Russian Federation using dilution with LEU [47]. However, it is envisaged to perform purification from minor isotopes also with the help of centrifuge cascades [44].

#### 3.4.2.1. Dilution with LEU in the Russian Federation

The concentration of minor uranium isotopes in the end product obtained from RepU can be reduced by diluting it with a product of the same enrichment, but stemming from NU. This dilution avoids Separative Work Unit (SWU) losses, other than when blending RepU with medium- or highly-enriched uranium. Table 7 illustrates this dilution. (The dilution ratio between ERU product and ENU product is 0.15: 0.85.)

Table 7 shows that when ERU is diluted with the natural uranium product in the ratio of 0.15 to 0.85, the <sup>232</sup>U content in the blend is the same as in the RepU feedstock, and the <sup>236</sup>U content is even lower. The drawback of this option is the need to involve pure feedstock while obtaining an increasing amount of the product of a quality suitable for RepU. Also, the consumption of RepU is reduced by a factor of 1/0.15 = 6.66 compared to the re-enrichment without dilution.

The selected ratio between ERU product and ENU product (ratio is 0.15/0.85 in Table 6) is dependent on the licensing limits (acceptance criteria) for chemical impurities of the fuel fabrication plants.

#### 3.4.2.2. Russian concept for purification of <sup>232</sup>U in cascades

The adverse effect of <sup>232</sup>U in RepU can theoretically be reduced by using a centrifuge cascade to purify RepU from <sup>232</sup>U. The flowchart of the related cascade is shown in Fig. 6. The Russian Federation assessed the possibility to construct such a cascade and demonstrated the feasibility of its creation [44].

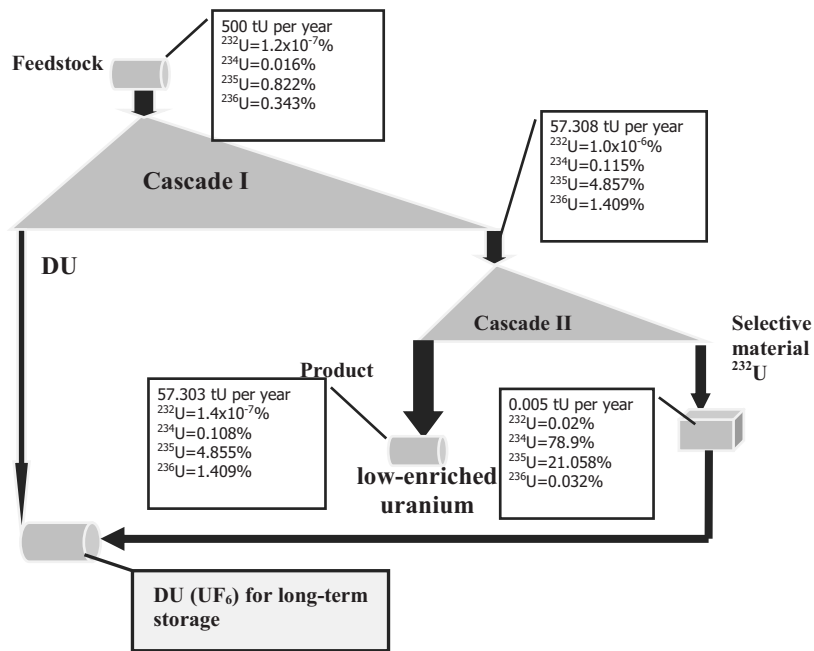


FIG. 6. Cascade for the purification of LEU from  $^{232}\text{U}$ .

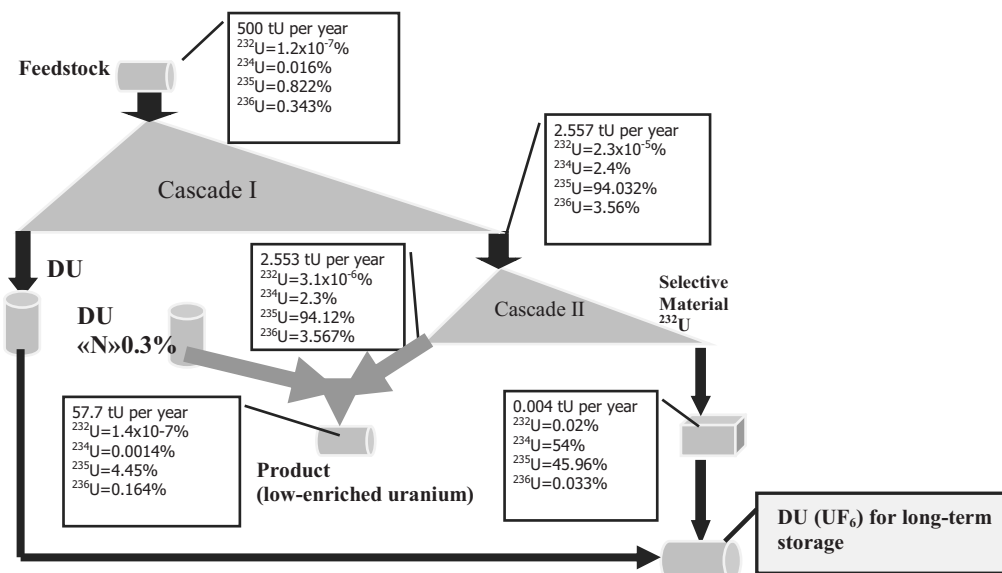


FIG. 7. Cascade for the purification of LEU from  $^{232}\text{U}$  and  $^{236}\text{U}$ .

### 3.4.2.3. Russian concept for purification of $^{232}\text{U}$ and $^{236}\text{U}$ in cascades

SGChE experts, in collaboration with Rosatom experts, assessed the feasibility of creating a dual-purpose cascade designed to purify RepU from both  $^{232}\text{U}$  and  $^{236}\text{U}$  (see Fig. 7) [44].

The idea stemmed from the assumption that, if reprocessed uranium is enriched to high concentrations of  $^{235}\text{U}$  (up to 90% and above),  $^{236}\text{U}$  as a heavier isotope will go to tails, and purification from this isotope will therefore take place. The next cascade performs after-purification of the obtained HEU from  $^{232}\text{U}$ , and the product material obtained from the second cascade is blended with a diluent (tails, feed or low-enriched  $\text{UF}_6$  of intermediate enrichment) in order to obtain LEU.  $^{232}\text{U}$  is extracted from the product material and the selective material (uranium with a very high assay of  $^{234}\text{U}$  and  $^{235}\text{U}$ , but also concentrating the  $^{232}\text{U}$ ) is then mixed with the tails of the first cascade and transferred to long-term storage (see Fig. 7). Therefore, the total  $^{232}\text{U}$  concentration in the tails obtained will not exceed its concentration in feed  $\text{UF}_6$ .

Prior to its technical realization, this concept requires additional feasibility studies. Double cascading could possibly be economical with future RepU with a very high content in even-numbered (unwanted) isotopes.

### 3.4.3. Conversion stage

As of the end of 2007, the conversion stage (conversion of  $\text{UO}_2(\text{NO}_3)_2$  into  $\text{UF}_6$ ) (see Section 3.4. and Fig. 4) is possible only in the Russian Federation.

There are some projects in the Russian Federation, Japan, and France to develop new technologies and capacities to take into account the evolution of the RepU composition. Depending on the projects, the intermediary products would be different (such as  $\text{UO}_3$ ,  $\text{U}_3\text{O}_8$ ,  $\text{UO}_2$  or  $\text{UF}_4$ , or  $\text{UF}_6$  by direct fluorination). As an introduction to the conversion of RepU, the following describes the past French scheme that was available at Pierrelatte, as well as the future plans for conversion of RepU.

#### 3.4.3.1. Past French conversion scheme

The past French scheme for purification and conversion, and for associated issues and solutions is detailed in Fig. 8. After precipitation of ammonium di-uranate (ADU), the uranium material is calcined and reduced to  $\text{UO}_2$ . Subsequently, hydrofluorination is performed using HF in rotating furnaces. The  $\text{UF}_4$  is then converted to  $\text{UF}_6$  in a flame reactor. Residues are finally burned in a plate reactor [45].

This process has proven very reliable over the years with a production of both high quality  $\text{UF}_4$  and  $\text{UF}_6$ . In the long term, however, several issues have to be addressed:

- Minimization of waste. With the precipitation of ADU using ammonia, a liquid effluent is produced that has to be treated before disposal. Also, the excess of unreacted  $\text{F}_2$  that is not burned in the flame reactor creates  $\text{CaF}_2$  sludge after the neutralized treatment with the  $\text{Ca}(\text{OH})_2$  agent.
- Handling of residues. Some impurities tend to concentrate in the residues, making them difficult to handle. Table 8 summarizes the properties of key impurities in the process.

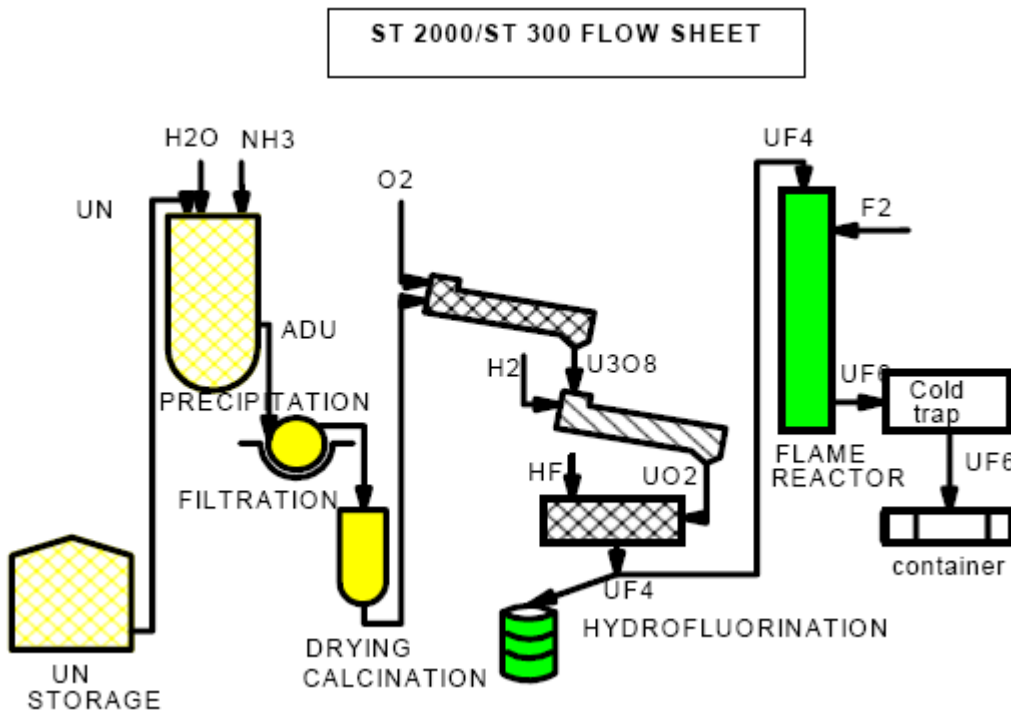


FIG. 8. Fluoride conversion process previously used at Pierrelatte.

TABLE 8. FLUORIDE COMPOUNDS ARISING IN THE CONVERSION PROCESS

Element	Compound	Ebullition or Sublimation Point	Remark	Potential Issues
Pu	PuF <sub>6</sub>	63°C	PuF <sub>6</sub> + UF <sub>4</sub> => PuF <sub>4</sub> + UF <sub>6</sub> PuF <sub>6</sub> + NiF <sub>2</sub> => PuF <sub>4</sub> .NiF <sub>2</sub> + F <sub>2</sub>	For ashes treatment
Np	NpF <sub>6</sub>	54°C	NpF <sub>6</sub> is more volatile and stable than NpF <sub>4</sub> . NpF <sub>6</sub> + UF <sub>4</sub> => NpF <sub>4</sub> + UF <sub>6</sub>	For ashes treatment and for UF <sub>6</sub> quality
Tc	TcF <sub>6</sub> TcF <sub>5</sub> TcOF <sub>4</sub> TcOF <sub>3</sub>	55°C 50°C/200°C 165°C 100°C	All compounds are volatile. <sup>99</sup> Tc is difficult to predict during enrichment	For UF <sub>6</sub> quality
Ru	RuF <sub>5</sub> RuF <sub>6</sub> RuOF <sub>4</sub>	230-270°C decomposes in RuF <sub>5</sub> at 200°C 180°C	All compounds are volatile, but <sup>106</sup> Ru has often decayed and is present in small amounts in UNH	—
Sb	SbF <sub>5</sub> SbF <sub>3</sub>	140°C sublimes at 200°C	As concerns arsenic and technetium, antimony can be problematic; however, <sup>125</sup> Sb is present in UNH in a small quantities	—
Th	ThF <sub>4</sub>	Non volatile (melts above 900°C)	Daughters of Th will accumulate in residues	For ashes treatment and for UF <sub>6</sub> fabrication

- Thorium isotopes (<sup>234</sup>Th and <sup>228</sup>Th) do not yield volatile fluorides and have daughters of relatively short lifetime. Therefore, a high irradiation level at the plate reactor may arise. Typically 1–2 mSv/h can be found at contact of the plate reactor and 10–20 mSv/h at contact of the drums collecting ashes.
- Treatment of ashes from the plate reactor. In such materials, the actinide level may depend strongly on the quality of the UNH and the F<sub>2</sub> excess during fluorination, for example, as high as 15 000 Bq/g U for <sup>237</sup>Np. A special facility must be designed to recover and purify the uranium present in the ashes.

#### 3.4.3.2. Future French conversion scheme

A special AREVA project is designed to give the company's customers integrated solutions for the recycling of stockpiles of RepU oxides as well as of fresh reprocessed uranium coming from La Hague or other treatment facilities [45].

The project will handle every necessary step of the RepU recycling process, thus achieving sustainable development objectives:

- RepU conversion complex;
- Capacities for the re-enrichment of RepU in the second unit of the Georges Besse II enrichment plant (NU/RepU mixed unit);
- Purification/homogenization of the enriched UF<sub>6</sub> before delivery to the fuel fabricator;
- Defluorination of tails and its storage in oxide form;
- Management of 48Y and 30B cylinders (washing, recertification, storage);
- Effluents and scraps recycling unit and final waste management.

The facilities will integrate both mature proven technologies and innovative processes developed by the AREVA Research and Development (R&D) Department. The objectives are to achieve high quality and productivity levels while limiting personnel radiation exposure and dose rates, as well as to reach high standards for environmental protection. The project will include the following improvements:



- Thermal denitration of the UNH (instead of ammonia precipitation). This patented process produces highly reactive  $\text{UO}_3$  and avoids the generation of liquid effluent. Moreover,  $\text{HNO}_3$  will be recovered from the gaseous stream and recycled into the process.
- Scraps and effluent treatment with a dedicated facility called the Scrap Recovery Unit (SRU).

AREVA is also conducting R&D programmes to minimize wastes from the fluorination process (minimize  $\text{CaF}_2$  sludge, optimize secondary fluorination reactor).

The recycling facilities will be integrated on the Tricastin site. Thus, the new infrastructure will allow optimizing the lead time of the ERU fuel manufacturing process, thereby reducing irradiation/exposure levels throughout the operations. It will also minimize external transportation.

#### 3.4.3.3. Future Japanese conversion schemes

In Japan, the JAEA has completed the development of the conversion process for RepU. The feed material is  $\text{UO}_3$  that has been produced from the reprocessing plant at Tokai. The  $\text{UO}_3$  is changed to  $\text{UO}_3 \cdot n\text{H}_2\text{O}$ ,  $\text{UO}_2$ ,  $\text{UF}_4$  and finally converted to  $\text{UF}_6$ . The development of uranium conversion technology commenced in 1976. Due to the change of raw material from natural uranium to RepU, the following studies were required for the research and development: (a) the reactivity improvement of  $\text{UO}_3$  from the Tokai Reprocessing Plant, (b) the criticality, shielding, exposure control, etc. arising from RepU, and (c) the acquisition for designing a commercial-scale conversion plant. The technological development was carried out by various tests, from a laboratory-scale test to a practical scale until October 1999. As a result, important results were obtained for the conversion plant, and  $\text{UF}_6$  was supplied to the uranium enrichment plants [48]. JAEA has also developed an innovative method, namely using the microwave denitration method for the co-conversion of uranium and plutonium [49].

The new reprocessing plant at Rokkasho [50] constructed by JNFL is expected to commence commercial operations in 2009. This reprocessing plant is designed to produce 800 t U as  $\text{UO}_3$  each year. JNFL has been running the enrichment plant near this site.

#### 3.4.4. Enrichment stage

Today, physical re-enrichment of RepU is undertaken only in facilities using the centrifuge technology with dedicated capacities. Such facilities have been available as of the end of 2007 at Urenco's Almelo facility in the Netherlands and at SGChE's enrichment plant in Seversk in the Russian Federation, and will be offered by AREVA NC in its Georges Besse II enrichment plant in France (see Section 3.4.3.), currently under construction. There are no particular differences in the enrichment process between natural uranium and reprocessed uranium; however, some measures must be taken in the handling of the product and dedicated lines are adapted (shielding or 'washing' of the enrichment line with slightly irradiated uranium).

Compared to the blending route (see Section 3.5.), the main disadvantage of the physical re-enrichment of RepU is the buildup of even-numbered uranium isotopes in the product. Furthermore, as with the enrichment of NU, enrichment of reprocessed uranium generates tails (depleted reprocessed uranium).

##### 3.4.4.1. Re-enrichment in the Russian Federation

SGChE employs the gas centrifuge technology. From 1992 to 1998, SGChE performed commercial-scale conversion and direct enrichment of RepU imported from France. Over seven years, SGChE processed a total of about 1700 tonnes RepU (see Section 3.4.1.). In 2004, SGChE resumed the processing of imported RepU [44].

Table 9 shows the isotopic composition of feed RepU, LEU obtained in the separation cascade as well as feedstock consumption and separation work input per 1 kg of product.

Table 9 shows that the concentration of  $^{232}\text{U}$  in the end product has increased by a factor of 6.4, of  $^{234}\text{U}$  by a factor of 5.7, and of  $^{236}\text{U}$  by a factor of 3.5. The end product constitutes 15 % of the feedstock mass, the balance of which flows to tails. Pursuant to the following sections, handling of the end product obtained from RepU is most adversely affected by a high content of  $^{232}\text{U}$ , which features the highest concentration factor when enriched.



TABLE 9. TYPICAL ISOTOPIC CONTENT OF RepU FEEDSTOCK, LEU AND DEPLETED URANIUM (DU) IN THE DIRECT RE-ENRICHMENT PROCESS IN THE RUSSIAN FEDERATION

Parameters	Reprocessed uranium feedstock <sup>a</sup>	DU <sup>a</sup>	LEU (end product) <sup>a</sup>
<sup>232</sup> U	2.0 E-7	1.0 E-8	1.27 E-6
<sup>234</sup> U	0.024	0.0036	0.137
<sup>235</sup> U	0.99	0.3	4.8
<sup>236</sup> U	0.45	0.244	1.586
Uranium mass, kg U	6.522	5.522	1.0
Separation work input, SWU	—	—	5.129

<sup>a</sup> The numbers given for <sup>232</sup>U, <sup>234</sup>U, <sup>235</sup>U and <sup>236</sup>U mean % of total U.

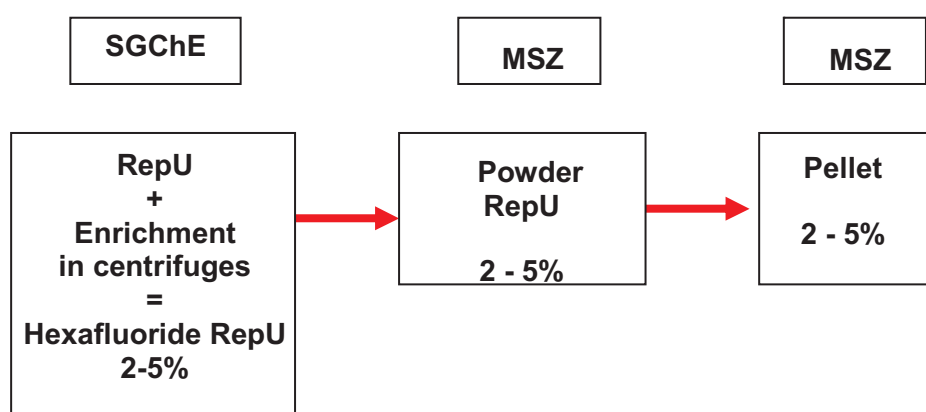


FIG. 9. Blending scheme at SGChE and MSZ to compensate for <sup>236</sup>U.

At SGChE, RepU is enriched in centrifuges to required enrichment levels considering issues such as compensation for higher levels of <sup>236</sup>U. Subsequently, at MSZ, the RepU fuel assembly is manufactured after the following steps (a) conversion process to make oxide powder, (b) preparation of press powder, and (c) UO<sub>2</sub> pellet fabrication. Figure 9 depicts various stages of this blending scheme at SGChE and MSZ.

#### 3.4.4.2. Re-enrichment in Japan

In 2005, in Japan, the Japan Atomic Energy Agency (JAEA) was formed after merging the Japan Atomic Energy Research Institute (JAERI) and the Japan Nuclear Cycle Development Institute (JNC). The latter had developed Japan's original centrifuges since the 1970s and commenced operation of the pilot plant in 1980 and of the demonstration plant at Ningyo-Toge in 1990 [51].

The cumulative throughput of RepU in the Pilot Plant was around 40 t U fed from 30B cylinders (due to licensing arrangements and regardless of the enrichment of the feed material) and the cumulative throughput of RepU in the Demonstration Plant was around 300 t U fed from 48Y cylinders (licence granted for 48Y cylinders).

The isotopic compositions of the feed for the Demonstration Plant (48Y cylinders) and of the product (30B cylinders) are shown in Table 10. The figures are averaged over more than 20 cylinders. The ratio of the <sup>236</sup>U isotope between the feed and the product is almost the same as that of the ratio of the <sup>235</sup>U isotope. In the case of JAEA's approach, the cascades were fine-tuned to meet the <sup>235</sup>U assay required by the customer, not giving particular consideration to the assay of the tails. If commercial centrifuge enrichment services were to be provided, a necessary approach would have been to blend different output assays to meet the customer's requirements.

TABLE 10. TYPICAL URANIUM ISOTOPIC COMPOSITION OF RepU IN THE STORAGE VESSEL

	RepU feed UO <sub>3</sub> powder	RepU feed UF <sub>6</sub> in 48Y cylinders	End product UF <sub>6</sub> in 30B cylinders
<sup>232</sup> U	0.85 ppb	0.59 ppb	< 10 ppb
<sup>234</sup> U	0.0016 wt%	0.0016 wt%	0.073 wt%
<sup>235</sup> U	1.045 wt%	1.046 wt%	4.440 wt%
<sup>236</sup> U	0.278 wt%	0.269 wt%	0.881 wt%

In Table 10, the differences in isotopic values between UO<sub>3</sub> powder and UF<sub>6</sub> in 48Y cylinders are only due to the sampling process and sampling uncertainties. The UO<sub>3</sub> powder is very inhomogeneous, the sampling is much more complex, and the most reliable value is the 0.59 ppb.

### 3.5. BLENDING ROUTE

The Russian company JSC TVEL, via its subsidiary JSC Mashinostroitelny Zavod (MSZ), uses two technologies for the fabrication of uranium dioxide powder, prior to the fabrication of the RepU fuel material into LWR fuel pellets [47, 52–53]:

- Blending of the customer’s RepU with LEU at up to 17% <sup>235</sup>U;
- Mixed blending with LEU.

#### 3.5.1. Blending of customer RepU with LEU at up to 17% <sup>235</sup>U

RepU feed material is received from customers. It is blended with RepU stemming from reprocessing of LEU at up to 17% <sup>235</sup>U (‘17%-RepU’), which is received from the Mayak reprocessing facility [47].

Processing of uranium oxide is carried out following the standard ADU scheme, which consists of the following main operations:

- Preliminary dry mixing of RepU and 17%-RepU oxide powders in the required proportions to achieve the required enrichment;
- Dissolving in nitric acid with subsequent filtration;
- Uranyl nitrate extraction and re-extraction in a centrifugal extractor cascade;
- Precipitation of poly-uranate with subsequent filtration, drying and baking (note: there is no calcination in this process);
- ERU dioxide recovery in hydrogen with subsequent screening and magnetic cleaning.

Stages carried out in the blending scheme (see Fig. 10) are described below:

Mayak

- (a) Preparation of U<sub>3</sub>O<sub>8</sub> from RepU with average enrichment of 14–17% <sup>235</sup>U.

MSZ

- (a) Simultaneous dissolution of RepU oxides and obtaining of the solution of required enrichment with compensation of <sup>236</sup>U.
- (b) ADU process.
- (c) Preparation of press powder.
- (d) Pellet fabrication.

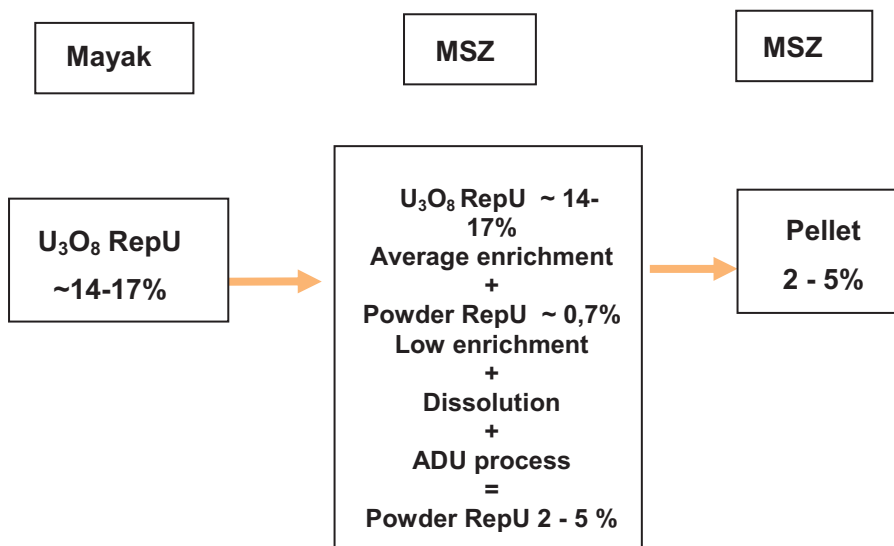


FIG. 10. Blending scheme at Mayak and MSZ.

### 3.5.2. Mixed blending with LEU

RepU feed material is received from the customer and enriched up to 3% <sup>235</sup>U at SGChE. LEU (enriched up to 5%) is received from SGChE or another Russian enrichment plant. The ERU at 3% ('3%-ERU') and LEU (5% <sup>235</sup>U) are in hexafluoride form.

The pellet fabrication process consists of the following main operations:

- 3%-ERU hexafluoride evaporation and sublimation;
- Conversion to oxyfluoride in hydrogen with separation for after-purification;
- Defluorination and recovery to dioxide in hydrogen and water steam;
- Dioxide screening and advanced separation.

In the next stage, the LEU (5% <sup>235</sup>U) and the 3%-ERU dioxide powders are dry mixed and homogenized in the necessary proportions to achieve the required enrichment.

Stages carried out in the mixed blending scheme (see Fig. 11) are described below:

SGChE

- (a) Preparation of low enriched (approximately 3% <sup>235</sup>U) uranium hexafluoride from RepU;
- (b) Preparation of LEU (approximately 5% <sup>235</sup>U) hexafluoride from natural uranium.

MSZ

- (a) Powder dry mixing: Obtaining of powder of required enrichment with compensation of <sup>236</sup>U.
- (b) Preparation of powder.
- (c) Pellet fabrication.

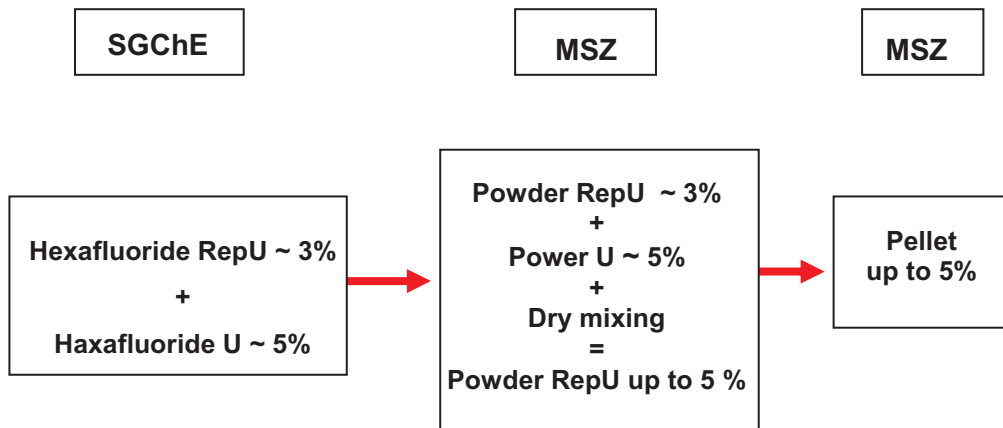


FIG. 11. Mixed blending scheme at SGChE and MSZ.

### 3.6. ERU MATERIAL MANAGEMENT

#### 3.6.1. Purification

Depending on the  $^{232}\text{U}$  content of the ERU leaving the enrichment plant, the specifications of the fabricator and on the time before delivery to the fuel fabrication facility, purification of the ERU may be necessary prior to fuel fabrication (re-conversion, pelletizing, etc.).

Gaseous purification is carried out by the gaseous transfer of RepU from one cylinder to another. In this simple but long process (which can last several months per reactor reload), the non-volatile  $^{232}\text{U}$  decay products which are partly strong gamma emitters (see Fig. 5 in Section 3.4.1.) remain in the first cylinder where they have accumulated since this cylinder was filled with enriched RepU (ERU).

Utility practice: EDF is now using RepU originating from spent fuel with burnups higher than those of previous reloads (see, for example, the assay evolution in Table 10). Purification, which could sometimes be avoided in the past using a just-in-time approach, is therefore becoming essential. Moreover, when the  $^{232}\text{U}$  assay is too high, ERU will not be stored in the same cylinder beyond a certain duration in order to limit the radiation exposure of the operators when handling empty cylinders. Therefore, if ERU is to be stored for a longer time, it must also be transferred to another cylinder. These operations presently take place in AREVA NC's transfer workshop at Tricastin (see Section 3.6.2) They require a large number of cylinders that must be cleaned before reuse [27].

#### 3.6.2. Experience in homogenization and purification of enriched $\text{UF}_6$

In France, at the Tricastin site, the transfer workshop (TE) has been used since 1996 to carry out purification and homogenization campaigns of RepU in the form of  $\text{UF}_6$  prior to enrichment and of enriched RepU (likewise in the form of  $\text{UF}_6$ ) prior to delivery to the fuel fabricator. Table 11 lists the RepU campaigns at the TE workshop [14].

These transfers are important in the recycling process, because the gaseous transfer from one 30B cylinder to another one eliminates the  $^{232}\text{U}$  daughter products that remain in the first cylinder (see Section 3.6.1.). This operation allows delivering 'low irradiation cylinders' to the fuel fabrication facility. The 'emitter cylinders' showing high radiation levels are then stored for a decay period and should be washed before reuse. Another advantage, although secondary, is to have a more homogeneous material in terms of isotopic composition, since several 30B cylinders (typically five of them) are usually mixed in the process.

For enriched RepU, the level of  $^{232}\text{U}$  has increased from a few ppb/U in the early days of RepU recycling to a value currently reaching 15 ppb/U or more, which requires shielding during the operations, close monitoring of personnel exposure, and specific measures for handling and storage of emptied cylinders. This stage of cylinder management has become a more common practice with the increase of the  $^{232}\text{U}$  level in reprocessed

TABLE 11. HISTORY OF RepU CAMPAIGNS AT THE TE WORKSHOP

Year	Campaigns	Quantity (t U)	<sup>235</sup> U Assay
1996	1	34.9	3.70
	2	23.9	3.70
	3	17.4	3.70
1997	1	17.6	3.70
1998	1	21.4	3.70
	2	20.1	3.95
	3	20.8	3.95
1999	1	16.5	3.95
2000	1	18.4	3.95
2001	1	17.8	3.95
2002	1	18.7	3.95
2003	1	18.3	3.95
	2	101.1	0.80
	3	25.5	3.95
2006	1	19.1	4.00

uranium as high levels of irradiation at the contact of the cylinders containing heels (10 mSv/h) are reached within a shorter period of time.

AREVA's experience also covers 48Y and 30B cylinder management, such as storage and washing. However, washing can no longer be performed in the TE workshop due to the evolution of regulatory requirements, but is planned to be performed in the new Pierrelatte RepU processing facility (for the future French conversion scheme, see Section 3.4.3).

The specification for the maximum <sup>232</sup>U content in ERU entering the fuel fabrication plant needs to be adjusted to allow recycling RepU batches stemming from high burnup fuels. A careful selection and blending of RepU batches in the stockpile is required, therefore, if one wants to keep the <sup>232</sup>U content below the present limitation of the fabrication plant.

### 3.6.3. Lead time issues

Throughout the whole process of RepU recycling, time constraints are a key parameter to limit irradiation of the staff caused by the decay products of <sup>232</sup>U. With the increase of burnups of used power reactor fuels and therefore increased <sup>232</sup>U levels in the reprocessed uranium, the time constraint is reinforced [41].

In the 1990s, the average <sup>232</sup>U level in RepU before enrichment was approximately 1.0 ppb/U and the alpha activity of the daughters reached about 1670 Bq/gU 19 months after purification at La Hague. Currently, the <sup>232</sup>U level has risen to an average of 1.8 ppb/U in RepU, and in 2020, it may reach 3.5 ppb/U. With such material, the above-mentioned activity of 1670 Bq/gU will be reached in only four months.

Radiation measures performed on 'heeled' cylinders (e.g. RepU 48Y and 30B cylinders emptied for purification purpose, but still containing product in the heel) has allowed AREVA to simulate the expected radiation level of cylinders and the irradiation level of the staff depending on the age of the product and the <sup>232</sup>U level. This modelling will allow optimizing the whole programming of ERU manufacturing, taking into account units specifications as well as logistics services needed across the recycling process.

A fleet of heeled cylinders must be washed before reuse; this operation is a necessary stage of a sustainable large scale RepU recycling solution.

#### 3.6.4. Management of the UF<sub>6</sub> containers

An example of the process performed at AREVA NC's fuel fabrication plant in Romans [54] is summarized below:

- The ERU containers are the same as those in use for ENU;
- The maximum authorized UF<sub>6</sub> quantity (ENU, ERU) on site is 285 t U;
- The dose rate level on contact with a filled ERU cylinder shows radiation self-absorption (gamma radiation emitted from <sup>232</sup>U decay products are absorbed partially by the material in the container);
- The dose rate level on contact of heeled containers is higher than that of filled containers.

In addition, the main radiation protection measures are described as follows:

- The storage of each individual cylinder on the storage area is limited in time;
- The presence of the operators on the storage area is limited in time;
- A dedicated area has been allocated to the ERU-filled cylinders not used for fabrication within three months and to the heeled cylinders with a dose rate higher than 2 mSv/h;
- There are weekly radiation rate measurements around the area;
- There is radiation measurement on each incoming cylinder with search of the maximal radiation value;
- Weekly inspection of every cylinder with search of the maximal radiation value is performed;
- Employees operating in the area are equipped with dosimeters.

### 3.7. FUEL FABRICATION STAGE

Four facilities of the Fuel Sector of AREVA NP are licensed to manufacture ERU fuel assemblies with specific local requirements: Richland (USA), Lynchburg (USA), Romans (France) and Lingen (Germany). The Romans facility is the reference AREVA facility for ERU fuel assembly fabrication [54].

The facilities of MSZ are licensed to manufacture ERU fuel assemblies for pressurized water reactors (PWRs), boiling water reactors (BWRs), RBMKs and water cooled and water moderated reactors (WWERs).

In addition, Mitsubishi Nuclear Fuels (MNF) is licensed to manufacture ERU fuel in Japan, and pelletizing is possible at the Ulba facility in Kazakhstan, owned and operated by NAC KazAtomProm.

The manufacturing of the fuel assemblies is performed through several process steps. The plant receives the enriched natural or reprocessed UF<sub>6</sub> (in France in 30B cylinders, in the Russian Federation in containers of Russian design), which is first converted into UO<sub>2</sub>. The UO<sub>2</sub> powder is produced by dry route re-conversion, which leads to a high quality powder with stable characteristics due to good process stability and permanent control of the working parameters.

After blending different lots to achieve the desired fuel enrichment, the powder is pre-compacted, granulated and pressed into pellets on a rotary press. Then the green pellets are sintered in a furnace under dry hydrogen atmosphere. The sintered pellets are wet-grinded (dry-grind at MSZ) and inspected before temporary storage. Finally, the pellets are loaded into the rods, and the fuel rods are assembled into fuel assemblies.

The manufacturing process for the ERU fuel is the same as the one implemented for the ENU fuel. However, in France, the ERU fuel is fabricated on lines with special radioprotection features, as explained in Section 3.7.2. Once manufactured, ERU fuel assemblies are packed into transport containers and shipped to the utility.

The ERU fuel fabrication stages are basically the same as with ENU. At certain stages, the same equipment can be used, but nevertheless, some specific precautionary measures need to be taken.

#### 3.7.1. Reconversion stage

For the reconversion of UF<sub>6</sub> into UO<sub>2</sub>, all the kilns can be used with the following principles:

- No further mixing between ERU and ENU takes place, even if the  $^{235}\text{U}$  contents are the same (in-depth cleaning);
- At the end of the campaign, the kiln rotates without producing in order to empty the kiln to the maximum possible extent before the next load;
- The first produced batch of the next campaign is isolated and analysed before a possible use;
- An in-depth cleaning is performed at the end of the campaign;
- No specific radioprotection measures are taken.

### 3.7.2. Pelletizing stage

In France, before the ongoing upgrading of the Romans fuel fabrication facility, only one processing line could be used for the pelletizing operations (from blending of the powder to grinding of the pellets). This line had specific protections for ERU:

- Additional confinements around the equipment (blending, granulation, pressing, sintering, grinding) with glove boxes;
- Airlock access for the containers;
- Lids on the pellet box supports;
- Enclosure on the entering boxes containing the pellets to be sintered.

In the Russian Federation, all pelletizing lines at MSZ can be used to process RepU. All have the same protection measures. In Kazakhstan, the Ulba plant can produce pellets made from RepU.

### 3.7.3. Rod and assembly manufacturing

The manufacturing process of ERU and ENU fuel rods and assemblies is the same. However, additional shielding and specific radiation protection measures are implemented for some operations to limit worker exposure, especially for the two following stages: pellet loading into rods and the rod loading into the assembly.

### 3.7.4. Management of the ERU scraps and other ERU process residues

#### 3.7.4.1. *The hydrofluoric acid from ERU*

Hydrofluoric (HF) acid is obtained during the dry re-conversion process, which transforms  $\text{UF}_6$  into  $\text{UO}_2$  powder.

At the Romans fuel plant, the HF from ERU is treated by the same process as the one from ENU.

Some specific measurements are regularly performed on the HF acid generated during the re-conversion process. Most of the results are below the detection limit. The uranium content (around  $0.12 \mu\text{gU/L}$ ) is largely below the customer specification (3 ppm). The  $^{99}\text{Tc}$  activity of  $0.22 \text{ Bq/L}$  is below that of uranium and is without any consequence on the management and the further usage of the HF.

#### 3.7.4.2. *ERU scraps recovered from powder manufacturing and pelletizing*

At the Romans fuel plant, a specific labelling of the scraps is implemented. The treatment through the recycling shop in Romans is the same wet process as the one applied to ENU. The final residues are sent to AREVA Pierrelatte to be compacted, put into concrete and sent to the French National Waste Management Agency (ANDRA) for final disposal.

### 3.7.5. Transport of fuel assemblies

The AREVA forged cermet cylinder (AREVA-FCC) containers are licensed for transport of ENU and ERU fuel assemblies. Indeed, the internal structure of the FCC leads to a dose rate reduction of 10 to  $20 \mu\text{Sv/h}$  in comparison to the former reinforced concrete cement (RCC) containers.



### 3.8. DIRECT RECYCLE

Direct recycling of RepU is its use in reactors without re-enrichment of the RepU. Direct recycling is of greater importance to countries that have power programmes based on NU as a fuel. In some reactor designs, there is the potential to replace NU by SEU, in which case RepU becomes especially attractive as it offers the possibility to provide fuel of SEU characteristics without the cost of the enrichment stage. As explained in Section 3.1, the DUPIC scheme is not considered to be within the scope of this report and is therefore not described under this heading. Along the same lines, use of RepU, as in making blanket and core fuel for fast reactors, is not described in detail owing to limited availability of the information.

#### 3.8.1. Direct recycle in India

The initial core of a PHWR composed entirely of fresh natural UO<sub>2</sub> fuel will have an unacceptably high power in the central core region unless some means of flux flattening in the absence of differential burnup is provided. One of the means to achieve the desired flux flattening is by placing depleted uranium fuel bundles in the central region of the core. RepU with depleted <sup>235</sup>U has been used on a relatively large scale for flux flattening in the initial cores of Indian PHWRs [55].

As PHWRs use natural uranium (0.7% <sup>235</sup>U) and as average PHWR fuel burnups are just around 6,700 MW-d/t-HM, the uranium recycle scheme in PHWRs in India differs from the practices applied in most other countries using LWRs, in the following way:

The UNH solution (RepU) is directly converted to uranium oxide and there is no re-enrichment process carried out. There is, therefore, a direct use of RepU with a depleted fissile isotope content (i.e. <sup>235</sup>U content lower than 0.7%). RepU has found application in flux flattening of initial PHWR cores, as a substitute for NU to conserve the available limited uranium resource.

RepU has also been used as a fertile matrix for breeding fissile material in fast reactors.

The concentration of other uranium isotopes in the RepU (<sup>232</sup>U, <sup>234</sup>U and <sup>236</sup>U) is also low due to the low burnup of the NU fuel from which it has been derived. Hence, its radiation and neutron physics characteristics are almost similar to those of NU, except for lower <sup>235</sup>U content.

#### 3.8.2. Direct recycle in other countries

PHWRs reactors developed in Canada (CANDU type) are heavy water-cooled and were initially designed and operated using natural uranium as fuel. At year-end 2007, there were 23 CANDU reactors in operation and six under construction around the world.

The CANDUs' natural uranium fuel cycle offers simplicity of fuel design, ease of fabrication, and benefits from the ready availability of NU. However, a unique feature of the CANDU reactor design is its ability to use alternative fuel cycles other than NU, without requiring major modifications to the basic reactor design. These alternative fuel cycles, which are known as advanced fuel cycles, use a variety of fissile materials, including SEU with a <sup>235</sup>U content up to 1.2%, RepU and MOX.

The RepU derived from LWR fuel reprocessing programmes might contain 0.9 to 1.0% <sup>235</sup>U and would need re-enrichment for use in LWRs, but CANDU reactors have a sufficiently high neutron economy to directly use RepU as fuel without enrichment. The RepU from spent LWR fuel can be considered as a lower cost source of enrichment at the optimal enrichment level for CANDU fuel pellets.

The use of RepU fuel offers significant benefits to CANDU reactor operators. The RepU fuel improves fuel cycle economics by increasing the fuel burnup, which enables large cost reductions in fuel consumption and in spent fuel disposal. The RepU fuel offers enhanced operating margins that can be applied to increase reactor power. These benefits can be realized using fuel production technologies and practices, and with almost negligible changes to fuel receipt and handling procedures at the reactor.

AECL has developed the enhanced CANDU 6 design, which offers the potential to maximize the benefits of introducing SEU fuel. AECL's plans are for the first step in CANDU fuel cycle evolution to use of SEU, including recovered uranium from reprocessed LWR spent fuel. The use of relatively low enrichment (up to 1.2% <sup>235</sup>U) will result in a two- to three-fold reduction in the quantity of spent fuel per unit of energy production, reductions in fuel cycle costs, and greater flexibility in plant operations, as stated above.

The 43-pin element CANFLEX® (CANDU FLEXible fuelling) fuel bundle will be an optimal fuel design. Peak linear pin power ratings will be reduced by 15-20% with CANFLEX fuel, if compared to current bundle power rating. Depending on burnup and fuel temperatures, the fission gas release within the fuel pin will be reduced. Critical heat flux and critical channel power will be also increased, due to optimized heat removal characteristics of the bundle. This feature can be used to increase margins in operating reactors, or increase the plant output.

The Institute for Nuclear Research (INR) Pitesti in Romania has analysed the feasibility of using RepU fuel with 0.9–1.1% <sup>235</sup>U in the CANDU 6 reactors of the Cernavoda nuclear power plant. Using RepU fuel would produce a significant increase in the fuel discharge burnup, from 170 MW·h/kg U currently achieved with NU fuel to about 340 MW·h/kg U. This would lead to a reduced fuel cycle cost and a large reduction in spent fuel volume per full power year of reactor operation [56].

The fuel bundle design with RepU fuel, known as RU-43, is being developed by INR Pitesti and is now at the stage of final design verification. Early work has been concentrated on RU-43 fuel bundle design optimization, safety and reactor physics assessment. The changes in fuel element and fuel bundle design contribute to the many advantages offered by the RU-43 bundle. Verification of the design of the RU-43 fuel bundle is performed in a way that shows that design criteria are met, and is mostly covered by proof tests such as flow and irradiation tests. The present version of the RU-43 fuel bundle design is the result of a long process of analyses and improvements, in which successive preliminary design versions have been evaluated.

### 3.9. OTHER USES OF RepU

#### 3.9.1. Japanese process for co-denitration of U and Pu

JAEA has successfully operated the Tokai Reprocessing Plant (TRP) introduced from French technology since the start of the hot test operation in 1977 [58]. TRP had reprocessed of about 1 136 tonnes of spent fuel by the end of March 2007.

The research and development on plutonium fuel in Japan started in January 1966 with 260 grams of plutonium brought into the Plutonium Fuel Development Facility (PFDF) at JAEA's Tokai works. Later on, after Japan–USA nuclear negotiations, JAEA started the original method to produce MOX fuels. TRP uses the PUREX process that has become the most common reprocessing technology.

Until the end of March 2007, TRP had reprocessed about 88 tonnes of ATR (Fugen) spent fuel, about 644 tonnes of BWR fuels, about 376 tonnes of PWR fuels, and about 9 tonnes of fuel from the Japanese Power Demonstration Reactor (JPDR).

Figure 12 shows the accomplishment of MOX fuel production via the co-denitration route applied at JAEA's Tokai facilities.

#### 3.9.2. Using RepU as a matrix for MOX fuel

JAEA has developed plutonium fuel fabrication technologies through MOX fuel production for the experimental fast reactor 'Joyo', the prototype Fast Breeder Reactor (FBR) 'Monju' and the advanced thermal reactor 'Fugen' at different plutonium fuel fabrication facilities [59]. The accumulated number of the MOX fuel assemblies fabricated in these facilities has amounted to approximately 1700.

JAEA's MOX fuel fabrication infrastructure comprises three facilities, namely PFDF (see Section 3.9.1), the Plutonium Fuel Fabrication Facility (PFFF) and the Plutonium Fuel Production Facility (PFPP). JAEA has 30 years of experience in MOX fuel fabrication. The total amount of MOX fuel fabrication reached approximately 170 tonnes as of the end of December 2001 (see Fig. 13). No fuel pin failure has been found after irradiating this MOX fuel.

The Japanese prototype Fugen Nuclear Power Station (ATR) was first loaded with MOX fuel in 1978 and started operations in 1979. Over its lifetime, it burned a total of 772 MOX fuel assemblies. RepU that had been processed at the Tokai plant was first introduced in four MOX fuel assemblies into the Fugen reactor in 1983. Furthermore, some 3.3 tonnes of RepU from the reprocessing of fuel from the Japan Power Demonstration

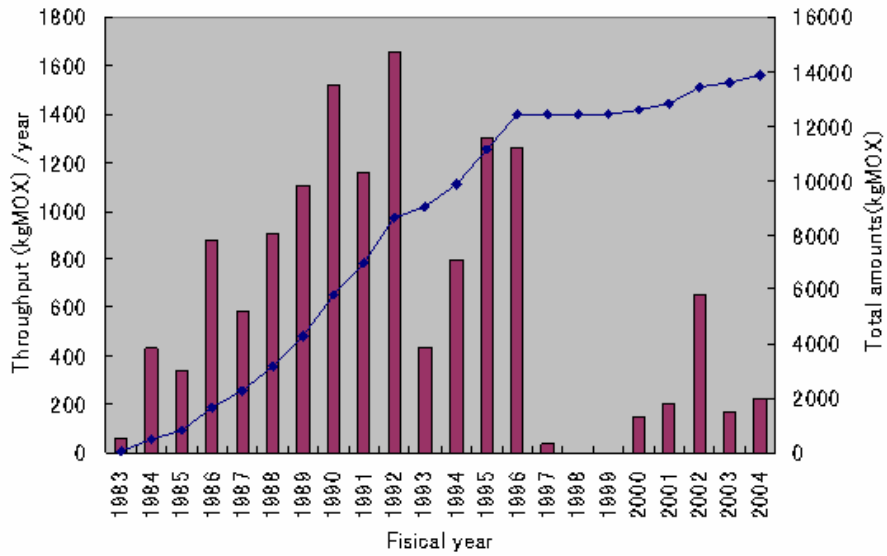


FIG. 12. MOX fuel produced via co-denitration at the Tokai works.

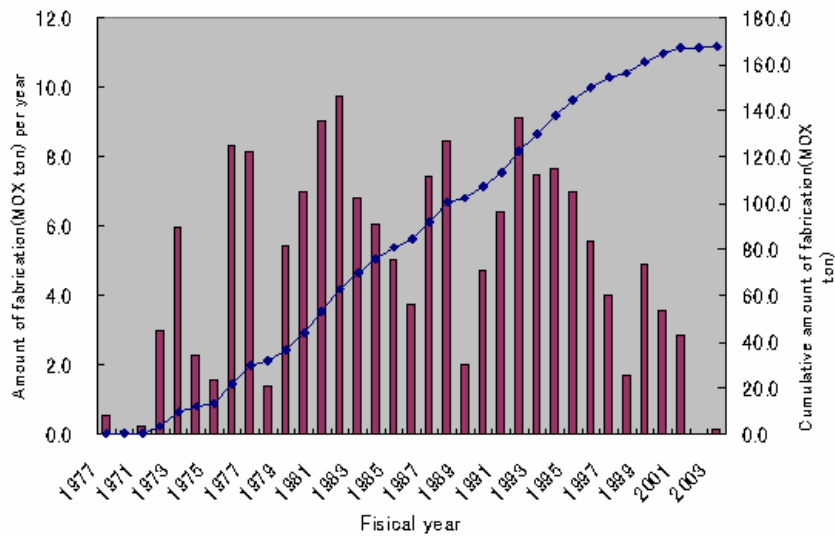


FIG. 13. Total annual and cumulative production of MOX fuel in Japan.

Reactor (JPDR) were mixed with NU and loaded into Fugen. In 1986, spent MOX fuels from Fugen were reprocessed, converted to  $UO_2$ , and remade into fuel, which was re-loaded into Fugen in 1988. The Fugen reactor was shut down in 2001. The decommissioning licence was granted by the Japanese Government in February 2008.

## 4. LOADING INTO THE REACTOR AND BEHAVIOUR OF RepU

### 4.1. INTRODUCTION

There is significant experience for the use of reprocessed uranium. In Europe, ERU fuel assemblies have been successfully loaded in PWRs and BWRs. Both enrichment technologies were used: physical re-enrichment using centrifuge cascades, i.e. for utilities in France [27] and Belgium [61]; and blending with medium or high enriched uranium, i.e. for utilities in Germany [31], the Netherlands [64] and Switzerland.

It should be noted that the utilities recycled the reprocessed uranium arising from their own reprocessing contracts. Savings of natural resources or economical incentives were not the driving forces; the recycling of reprocessed uranium was mainly driven by political or industrial reasons.

The intergovernmental agreements linked to the reprocessing contracts request the utilities to repatriate or to use their inventories of recycling materials as soon as possible. For industrial reasons, utilities with reactors reaching the end of their operation life also want to use all their inventories of recyclable materials (plutonium and reprocessed uranium) in their own reactors in order to minimize difficult decisions concerning the future of their remaining stockpiles (final disposal, sale, transfer to other utilities or countries, etc.).

Therefore, optimum fuel cycle costs, although important, were not the top priorities. However, once a technically and economically attractive industrial solution was proposed by the Russian industry (blending process), the recycling programmes accelerated.

For further use of the reprocessed uranium stockpiles (not linked to own reprocessing contracts), the economic aspects will take on much more importance since these materials will then have to compete with natural uranium.

### 4.2. USE IN LWRs

#### 4.2.1. Re-enrichment issues

In addition to the three isotopes  $^{234}\text{U}$ ,  $^{235}\text{U}$  and  $^{238}\text{U}$  contained in the NU, RepU contains four additional isotopes:  $^{232}\text{U}$ ,  $^{233}\text{U}$ ,  $^{236}\text{U}$  and  $^{237}\text{U}$ . The  $^{234}\text{U}$  and  $^{236}\text{U}$  isotopes are neutron-absorbing isotopes, and over-enrichment of  $^{235}\text{U}$  is needed to compensate for the lack of reactivity compared to equivalent ENU assemblies. At constant enrichment in  $^{235}\text{U}$ , additional ERU assemblies would be needed to keep the same energy production (see Section 2.1.2).

A standard limit for most of the facilities in the nuclear fuel cycle is 5%  $^{235}\text{U}$ . When a utility has already loaded ENU fuel assemblies in the reactor with an enrichment at or close to 5%  $^{235}\text{U}$ , full compensation for the lack of reactivity of the ERU fuel assemblies is not possible [62]. Therefore, more fuel assemblies would be needed per reload. For example, the Gundremmingen B BWR in Germany must load about 3.5% more ERU assemblies than ENU fuel assemblies for the same fuel cycle length.

The safety authorities do not generally differentiate between ERU and ENU fuel assemblies for criticality calculations. The presence of neutron absorbers in the ERU fuel is not taken into account.

For licensing or operational reasons, the maximum enrichment allowed for reactor operation could be limited to a much lower value than the 5%  $^{235}\text{U}$  limit. Some regulatory authorities even limit the enrichment of the ERU assemblies to a value lower than the limit of the ENU assemblies. Larger reload batch sizes would then be needed to compensate for the lack of reactivity of the ERU assemblies. For example, at equilibrium cycle, the Doel 1 reactor in Belgium would have to load four to eight more ERU assemblies than the Doel 2 reactor (technically almost a 'copy' of Doel 1) loaded with ENU fuel assemblies.

Since the utilities want to keep the same fuel cycle lengths for economic reasons, inaccuracies in the determination of the level of over-enrichment may lead to significant loss of equivalent full-power days (EFPD). Good accuracy of the computer codes and of the modelling methods is needed in order not to penalize the energy production. As illustrated by the in-core fuel management for the Doel 1 reactor in Belgium, the over-enrichment should be determined in order for the ERU fuel assemblies to have the same reactivity as the ENU fuel assemblies at the end-of-cycle (EOC) core average burnup. It should also be taken into account that

the reactivity of the RepU assemblies at the beginning of cycle (BOC) would be lower, since the  $^{234}\text{U}$  acts like a burnable poison and the reactivity curve versus burnup is flatter. (For the isotopic comparison of ERU and ENU with the same enrichment in  $^{235}\text{U}$ , see Table 6).

The level of over-enrichment and/or the number of additional ERU assemblies depends strongly on the re-enrichment process of the RepU.

In the physical enrichment process using centrifuges cascades, all uranium isotopes, with the exception of the  $^{238}\text{U}$ , are enriched together with the  $^{235}\text{U}$ , the isotopes lighter than the  $^{235}\text{U}$  being more enriched than the  $^{235}\text{U}$ .

Therefore, the concentration of the neutron absorbing isotopes in the ERU – the  $^{234}\text{U}$  and  $^{236}\text{U}$  isotopes – is significantly increased, and large over-enrichment would be needed to compensate for the lack of reactivity. For PWRs in Europe, in case of physical enrichment, the following examples of necessary over-enrichment of the ERU assemblies were found:

- GKN II in Germany: 4.59% for ERU assemblies, compared to 4% for ENU assemblies;
- Doel 1 in Belgium: 4.25% for ERU assemblies, compared to 3.8% for ENU assemblies;
- KKG in Switzerland: 4.85% for ERU assemblies, compared to 4.3% for ENU assemblies;
- Borssele in The Netherlands: 4.8% for ERU assemblies, compared to 4.4% for ENU assemblies;
- Cruas in France: 4.1% for ERU assemblies, compared to 3.7% for ENU assemblies.

For a given RepU feed, the higher the enrichment of the target ENU, the higher the required over-enrichment of ERU assemblies to achieve the same performance (energy generated with the assembly). The above figures are indicative, since the level of the over-enrichment (in the range of 0.5–0.6%  $^{235}\text{U}$  above 4%  $^{235}\text{U}$ ) depends strongly on the initial quality of the RepU, which depends on the burnup of the spent fuel assemblies from which the RepU is issued.

While the level of the over-enrichment will not be an issue when the RepU fuel assemblies constitute the initial core of an LWR reactor, the large over-enrichment needed for reload ERU fuel assemblies, especially when the RepU is physically re-enriched, may quickly result in exceeding the technical limits of the fuel cycle facilities (5%  $^{235}\text{U}$ ) or the limits imposed by the safety authorities for the operation of the reactor. To compensate for the lack of reactivity of the ERU assemblies, the reactor operator would then have to increase the reload batch sizes and the incore fuel management would not be anymore optimized. This forced move away from the optimum use of the fuel assemblies would have significant detrimental effects on the fuel cycle costs.

To limit the potential negative economical impact of the ERU assemblies on the reactor operation, their over-enrichment should be kept at the lowest possible level while maintaining the same reactivity as an ENU fuel assembly. One of the solutions selected by the utilities to achieve this is the re-enrichment of the RepU by blending with LEU up to 17%  $^{235}\text{U}$ , which largely meets their requirements from the point of view of reactor efficiency and physics. The blending reduces the concentrations of the neutron-absorbing isotopes and the needed over-enrichment is therefore limited. For PWR reactors in Europe in the case of blending, the following examples of over-enrichment of the ERU assemblies were found:

- GKN II in Germany: 4.16% for ERU assemblies, compared to 4% for ENU assemblies;
- KKG in Switzerland: 4.4% for ERU assemblies, compared to 4.3% for ENU assemblies.

Compared to the physical re-enrichment, in case of blending RepU with LEU (14–17%  $^{235}\text{U}$ ), the needed over-enrichment can be reduced by a factor of 4 to 5. It is therefore much easier to stay with the ERU fuel assemblies below the 5% enrichment limit without penalizing the incore fuel management strategies and, at equivalent enrichment in  $^{235}\text{U}$ , the number of additional fuel assemblies per reload can be greatly reduced, limiting the economical consequences on the fuel cycle costs. A blending solution for processing RepU is proposed by the Russian Federation on an industrial scale.

Other solutions could also be envisaged to limit the necessary over-enrichment:

- For example, the enrichment of the RepU could be carried out by blending with over-enriched natural uranium. This would avoid problems with the unwanted isotopes, but has the disadvantage of incurring blending losses. In effect, use of the RepU would reduce the demand for natural uranium feed, but at the

cost of an increased SWU demand. This option is, therefore, a trade-off between SWU and uranium, and its economic attractiveness depends on the price ratio between these two commodities.

- A second issue would be licensing. Obtaining a product at the right enrichment would most likely require blend stocks of between 5 and 10%  $^{235}\text{U}$ . Such a high level of enrichment would require re-licensing of enrichment and blending facilities, and finding a suitable transport solution for these enrichments. Enrichments below 20%  $^{235}\text{U}$  would normally not be a safeguards issue. Alternatively, a new route would not be necessary if blending down to 5%  $^{235}\text{U}$  or below could be carried out at the enrichment facility.
- To limit the large over-enrichment resulting from the physical re-enrichment, the RepU feed material could also be blended with NU before the enrichment process. This would improve the quality of the RepU feed and limit the concentrations of unwanted isotopes in the ERU.
- Selective enrichment of uranium isotopes using laser technologies might also be a solution, albeit only in future.

#### 4.2.2. In-core fuel management

Concerning in-core fuel management, for a same given  $^{235}\text{U}$  enrichment (ERU and ENU), the increased  $^{234}\text{U}$  and  $^{236}\text{U}$  concentrations (neutron absorbers) in RepU leads, in the reactor, to a decrease of the global core reactivity at the beginning of cycle, and therefore to a reduced cycle length. These ERU isotopic characteristics should be compensated with an over-enrichment in  $^{235}\text{U}$  in order to maintain the equivalence between ENU and ERU in terms of reactivity. Furthermore, the neutron worth of the absorbers (differential boron concentration and control rod worth) is also decreased. This might require the implementation of additional ‘rod cluster control assemblies’ in order to ensure approximately the same shutdown margin as for the equivalent ENU fuel management.

Regarding the introduction of ERU fuel managements, the consequences of this over-enrichment on the safety demonstrations have to be addressed for the overall fuel cycle.

For current fuel management strategies, as far as the equivalence in terms of reactivity between ERU and ENU is maintained while recycling RepU issued from the reprocessing of ENU fuel assemblies at current discharge burnups, the impact on safety aspects remains limited. This is the case for the fuel design for which no major differences with ENU have been observed from the international experience feedback. However, the validity of the models conventionally used for ENU (e.g. fission gas releases vs. burnup) have to be confirmed. The same applies to the reactor behaviour (accident studies). Furthermore, the validity of the assumptions (e.g. residual heat curve) and of results of accident studies must formally be checked (e.g. cooling accidents, reactivity initiated accidents, loss of coolant accidents). Indeed, none of the utilities experienced difficulties. Available margins on nuclear key safety parameters are sufficient to cover the small impact of the ERU assemblies and the differences are largely within the normal variations observed among actual loading plans with ENU fuel assemblies.

This conclusion remains valid as long as the enrichment of the ERU assemblies remains in the same range as the ENU fuel assemblies loaded into the reactor. Should the enrichment level be significantly increased, due to the degradation of the initial quality of the RepU (issued from assemblies at higher discharge burnups in the previous fuel cycles) or new fuel strategies being implemented (especially with enrichment higher than 5%  $^{235}\text{U}$ ), the safety demonstrations should be reconsidered extensively, including the validation of the computer codes and the validity of the experimental database.

Furthermore, for existing plants, design specifics or safety issues may limit the over-enrichment for the ERU assemblies (criticality issues in spent fuel, negative temperature moderator coefficient, etc.).

The first issue is to accurately determine the level of over-enrichment needed to compensate for the lack of reactivity of the ERU assemblies or to more precisely model their lack of reactivity. Simple but conservative models show a tendency to slightly over-predict the reactivity of the ERU assemblies, which could lead to the loss of a few EFPDs of energy.

Since the utilities want to keep the standard fuel cycle lengths of their individual reactors, inaccuracies in the determination of the level of over-enrichment may lead to the significant loss of EFPD. Further improvement of the computer codes and of the modelling methods are therefore needed in order not to penalize the energy production.



The experience shows that no software modifications or additional safety equipment were implemented for the use of the ERU assemblies in the reactors. However, in the case of EDF, a decision was taken to install four additional control rod clusters in the Cruas reactors in order to keep the same safety parameters (i.e. shutdown margin) as for the ENU fuel assemblies and to not revise the safety analysis report.

Concerning the incore fuel management, none of the utilities experienced difficulties. Available margins on nuclear key safety parameters are sufficient to cover the small impact of the ERU assemblies and the differences are largely within the normal variations observed among actual loading plans with ENU fuel assemblies.

### **4.2.3. Issues related to fuel procurement**

#### *4.2.3.1. Management of $^{232}\text{U}$ issues*

A major drawback of the ERU, especially after physical re-enrichment, is the concentration of  $^{232}\text{U}$ , the daughter products of which are strong gamma emitters and continue to increase with time (see Section 3.4.1).

Tight management of project lead times is therefore mandatory to respect the acceptance limits at the processing facilities (conversion, enrichment and fabrication). Intermediate purification of the RepU may be necessary between the processes to reduce the concentration in  $^{232}\text{U}$  daughter products. This is usually achieved by transferring the RepU in gas form into a new cylinder; most of the daughter products remain in the original cylinder (see Sections 3.6.1 and 3.6.2). As of the end of 2007, as a result of the progressive increase of the burnup discharge, the high level of  $^{232}\text{U}$  in RepU systematically implies an intermediate purification when using the physical re-enrichment route. The purification by gas transfer is a long process, which takes around two months for an ERU quantity as  $\text{UF}_6$  equivalent to 40 ERU assemblies. Hence, the purification facility has to be (re)designed to deal with a big quantity of enriched  $\text{UF}_6$  at the same time if the utility wants to get ERU fuel assemblies at higher industrial scale.

A last purification occurs when the cylinders are emptied at the fuel assembly fabrication facility and the ERU is converted into  $\text{UO}_2$ .

The high concentration of  $^{232}\text{U}$  daughter products in the heeled cylinders prevents these cylinders from being reused directly. Thus, they should be first cleaned. However, as of end of 2007, no such cleaning facility is in operation and an ever-increasing number of contaminated cylinders have to be stored. To limit the radiological doses, some companies are filling them with depleted uranium, which acts as shielding material during the storage period.

Since the cylinders cannot presently be cleaned, each cylinder that has been filled with ERU has to be replaced by a new cylinder, which could represent a significant investment.

#### *4.2.3.2. Management of the RepU tails issues*

The physical re-enrichment route allows the utilities to quickly decrease their RepU inventories. However, considerable amounts of depleted RepU quantities (tails of the enrichment process) are generated and will have to be stored for extended periods of time since this fissile material could only be valuably recycled in Generation IV reactors (for example, fast reactors). However, these reactors are not expected to enter operation on an industrial basis before several decades.

The blending route does not generate tails, and the whole material can be recycled in reactors. However, the blending route does not lead to a quick decrease of RepU inventories. A sufficient number of reactors over a long period of time is needed to complete the recycling of the original RepU quantity. For example, in the physical re-enrichment route, assuming an enrichment factor of 10, the reprocessing of ten reloads would be needed to generate the material for the fabrication of one new reload. By contrast, in the blending route of RepU, the material issued from the reprocessing of one reload allows to manufacture another reload.

From the point of view of RepU consumption per ERU assembly (see Table 4 in Section 3.1.), the nuclear community (suppliers and customers) has to define the balance between the amount of tails generated and the rate of consumption of RepU per ERU assembly.



#### 4.2.3.3. *On-site storage of ERU assemblies*

At the time of the delivery on-site, the gamma radioactivity of the ERU assemblies can be more than five times that of ENU fuel assemblies, and it continues to increase with time due to the accumulation of the  $^{232}\text{U}$  daughter products. Nevertheless, the dose rates remain quite low and the on-site handling of ERU fuel assemblies remains the same as for the ENU fuel assemblies. For conservative radioprotection reasons, some utilities still prefer not to store the ERU fuel assemblies in the fresh fuel dry storage. The ERU fuel assemblies are then stored safely under water, but to the detriment of the number of storage places for spent fuel assemblies. Such a policy may cause problems for reactors with limited spent fuel storage capacity.

#### 4.2.3.4. *Obligation code issues*

Some country-specific obligations codes attached to the material origin impose trading restrictions in addition to the standard safeguards requirements of the IAEA. These constraints limit or make more difficult the access of the utilities to some processing facilities.

For example, some obligations codes (i.e. Code C) request the utilities to take back all the material after processing, including the enrichment tails. Other obligations codes forbid sending material to some countries for processing (i.e. Code A material to the Russian Federation). Since the Russian Federation is presently the only country proposing the blending route on an industrial scale, significant quantities of RepU material cannot be enriched using this technology.

#### **4.2.4. Conclusions and recommendations**

Technical solutions to limit the over-enrichment of the ERU fuel assemblies compared to the ENU fuel assemblies to the lowest possible value should be developed to mitigate the incore fuel management issues (resulting from the concentration in  $^{234}\text{U}$  and  $^{236}\text{U}$ ) as well as the radioprotection issues (resulting from the concentration in  $^{232}\text{U}$ ). Furthermore, to take into account the degradation of the RepU quality resulting from the progressive increase of the fuel assemblies' burnups in the previous cycles, and to increase the flexibility in project management lead times, higher acceptance limits at the processing facilities are needed for the initial concentration in  $^{232}\text{U}$  isotopes. This objective should take into account the present design limitations of the different fuel cycle facilities or should be taken into account when designing new or refurbishing existing industrial installations.

For the RepU to be considered in the future as a credible alternate source of supply, the nuclear industry must address this over-enrichment issue. The optimization of the technical possibilities described in Sections 3.3: 'Transport' and 3.4: 'Physical re-enrichment routes' as well as their combination should be analysed in detail to find the best technical/economical compromise.

To give more possibilities to bring the reactivity of the ERU assemblies to the level of the ENU fuel assemblies, the  $^{235}\text{U}$  enrichment limits of the various facilities (reactor and industrial installations) and of the transport system, at least for the new and refurbished projects, should be raised from 5–6%.

Cleaning facilities for the ERU  $\text{UF}_6$  cylinders are needed to limit the number of contaminated cylinders to be stored for long periods of time.

The problems of the obligations codes should be addressed in order not to unduly restrain the possibilities for utilities to select the optimum industrial solutions for the processing of the RepU.

### 4.3. USE IN PHWRs AND AGRs

#### **4.3.1. Use in PHWRs**

RepU has been used in PHWRs in India [55]. The RepU comes from the reprocessing of domestic spent fuel and the fuel fabrication is carried out in the same facilities that fabricate the natural uranium fuel, maintaining, however, a strict separation of NU and RepU. Use of RepU in PHWRs is directly linked to the route 'Direct recycle in India', described in Section 3.8.1.

Since the initial core starting with fresh fuel only shows an unacceptable high power in the central region, RepU assemblies are used to flatten the flux and minimize the time between criticality and attainment of full power. RepU assemblies are also loaded in the equilibrium cores to conserve NU resources.

#### 4.3.2. Use in AGRs

From 1976 to 1996, slightly more than 16 000 t of RepU from Magnox fuel (MDU) had been reconverted to UF<sub>6</sub> and subsequently re-enriched at BNFL's diffusion plant at Capenhurst to an assay of 0.7% <sup>235</sup>U, followed by Urenco's centrifuge plants for use in AGRs to assays of 2.6–3.4% <sup>235</sup>U.

It is technically feasible to recycle the RepU from the reprocessing of AGR fuel at typical burnups back into AGR reactors. The same RepU pellet specification used successfully in the past could be maintained, but this would limit the rate of recycle of RepU. The acceptability of a relaxation in the RepU pellet specification has not been assessed. A potential risk of a revised pellet specification is an increase in dose levels to the utility personnel handling the fuel assemblies in the continuous fuel loading process used in AGR reactors.

Previous facilities in the United Kingdom to process RepU have been fully decommissioned, partly due to radiological reasons and potential challenges to radioactive discharge limits agreed with regulators. Investment in new facilities would be required by the fuel fabricator to process typical RepU from the reprocessing of AGR fuel.

#### 4.4. USE IN RBMKs

The Russian Federation pioneered the introduction of reprocessed uranium into the nuclear fuel cycle. The closure of the nuclear fuel cycle was applied for the first time for reprocessed uranium extracted from spent fuel of commercial graphite-uranium reactors.

During the next stage, the RT-1 production facility was commissioned in 1977 at the Production Association Mayak. There reprocessed uranium extracted from the WWER-440-type reactors was and still is enriched by blending it in nitric acid solution with reprocessed uranium extracted from spent fuel of research reactors and marine application reactors. Obtained UNH of up to 2.6% <sup>235</sup>U is shipped to branch facilities manufacturing fuel pellets, fuel rods and assemblies for RBMK reactors.

#### 4.5. CHECKLIST TO BE ADDRESSED BY UTILITIES AND SUPPLIERS

For utilities interested in using RepU in their reactors, the following provides a series of questions in the form of a checklist concerning RepU and its potential reuse options. Many answers or responses to these questions can be found in this report.

1. Reprocessing service provider (hereafter called 'reprocessor')
  - 1.1 What are the industrial records of the reprocessor? What quantities have been treated already?
  - 1.2 For what time period can the reprocessor store the RepU and at what cost?
  - 1.3 What guarantee does the reprocessor offer in respect of product specification?
  - 1.4 Does the reprocessor have a proven export route for all categories of RepU?
  - 1.5 What lead time does the reprocessor require to guarantee an export campaign?
  - 1.6 How much flexibility is there in the reprocessor's domestic and export programme?
2. RepU product
  - 2.1 What is the specification for the RepU product and the primary container for the RepU?
  - 2.2 How are the RepU batches and the individual containers identified?
  - 2.3 Can the RepU be transported in its current chemical form?
  - 2.4 If the chemical form needs to be changed, does a provider offer this service and what is the lead time?

- 2.5. What is the accuracy of the gross and tare weight measurements of each container?
- 2.6. What is the accuracy of the  $^{235}\text{U}$  value (in per cent) for each individual drum?
- 2.7. Does the RepU batch have any containers with  $^{235}\text{U}$  enrichment greater than 1%?
- 2.8. Are the specifications of the product good enough for sampling?

### 3. Transport

- 3.1. How has daughter (of  $^{232}\text{U}$ ) product in-growth affected the Transport Index/CSI?
- 3.2. Is the RepU in a suitable container for transport?
- 3.3. Does the container need to be prepared for transport? Is further containment required?
- 3.4. Is there a special transport package required for RepU with  $^{235}\text{U}$  enrichment greater than 1%?
- 3.5. Who is arranging the transport logistics?
- 3.6. What method of transport will be used? Road, rail or sea?
- 3.7. What insurance is required for the RepU transport packages?
- 3.8. Is the destination country a signatory to the Paris Convention and did it ratify it?
- 3.9. Who holds nuclear liability throughout the transport?
- 3.10. If nuclear liability is transferred between parties, where does this occur?
- 3.11. What are the constraints on transport (e.g. train lengths, ship payloads, weight limits for trains/trucks/packages/cranes, shielding requirements, over night storage, sea ice)?

### 4. Regulatory constraints

- 4.1. Are any intergovernmental agreements required prior to export?
- 4.2. Are requirements of intergovernmental bilateral agreements understood and being addressed?
- 4.3. What notification/approvals are required by the competent authorities prior to export?
- 4.4. What notification/approvals are required by the processors' competent authorities prior to import?
- 4.5. Do the transport/security authorities in either country need notification prior to shipment?
- 4.6. Are contingency plans in place for delays during shipment?
- 4.7. Are contingency plans in place for possible security issues during transit, such as protests?

### 5. RepU processing service provider

- 5.1. What kind of processing is available? What are the industrial records of the processor? What is the annual processing capacity?
- 5.2. What storage capacity is available? If this assumes stacking of containers, does the store have the capability to stack containers? Is the store seismically qualified to store stacked containers?
- 5.3. Is a criticality detection/alarm system available/required?
- 5.4. Is an automated storage process required?
- 5.5. Is localized shielding required?
- 5.6. What specific information does the processor require each container to have on it?
- 5.7. Will the quantity and quality of the RepU be checked prior to processing?
- 5.8. How will the containers be emptied? Poured? Sucked Washed? Blown?
- 5.9. Does the provider have a cylinder/containers washing facility? What cylinder/container management services does it provide? Who takes ownership of the cylinders/containers?
- 5.10. Will the processor be completing all work streams? Are any subcontracts required?

### 6. Samples

- 6.1. What quality information is available for the RepU?
- 6.2. Is this information sufficient for the customer/processor or is more required?
- 6.3. How many samples are available for each batch?
- 6.4. Can additional samples be taken from the current batch?
- 6.5. What is the size of each sample?

- 6.6. Can samples be sent for independent analysis?
  - 6.7. If independent analysis is made, on what basis will the results be comparable with the original quality data? (Same analytical techniques, accredited laboratories, etc.?)
  - 6.8. What is the age of the RepU? How has daughter product in-growth affected the processing constraints of the RepU?
  - 6.9. What is the burnup history of the RepU? Does the RepU have a high  $^{232}\text{U}$  content?
7. Transport licences
    - 7.1. Are the transport packages licensed in the destination country?
    - 7.2. Are import and export licences required?
    - 7.3. Who is applying for the import and export licences?
    - 7.4. What are the timescales for obtaining import and export licences?
8. Obligation codes
    - 8.1. What obligation codes does the RepU carry?
    - 8.2. Is an obligation code swap required prior to export?
    - 8.3. Is an obligation code source available?

## **5. MANAGEMENT OF SPENT ERU FUEL**

### **5.1. STORAGE OF SPENT ERU ASSEMBLIES IN REACTOR SPENT FUEL POOLS**

Once the criticality studies have been performed to take into account the over-enrichment of the ERU fuel assemblies (possibly up to 6%  $^{235}\text{U}$ ), there are basically no differences between the ERU and ENU spent fuel assemblies for the storage in the reactor spent fuel pools. At equivalent discharge burnups, their technical characteristics are very similar.

### **5.2. TRANSPORT OF SPENT ERU ASSEMBLIES**

The spent ERU fuel assemblies are transported in the same type of casks as for the spent ENU fuel assemblies. When necessary or requested by the safety authorities, an additional content specifically for the ERU assemblies is included in package approval. As of the end of 2007, no credit for neutron-absorbing isotopes has been taken into account in the criticality studies. Criticality studies should be performed to take into account the over-enrichment of the ERU fuel assemblies (possibly up to 6%  $^{235}\text{U}$ ).

### **5.3. DRY STORAGE IN METALLIC CASKS**

Here the same applies as for the transport of spent ERU assemblies (see Section 5.2.). The spent ERU fuel assemblies can be stored in the same type of casks as for the spent ENU fuel assemblies. When necessary or requested by the safety authorities, an additional content specifically for the ERU assemblies may be included in the package approval. As of the end of 2007, no credit for neutron-absorbing isotopes has been taken into account in the criticality studies. Criticality studies should be performed to take into account the over-enrichment of the ERU fuel assemblies.

## 5.4. REPROCESSING

The isotopic composition of the spent ERU fuel assemblies is slightly different from that of the spent ENU fuel assemblies. The concentration of plutonium increases by 5 to 10% compared to an ENU fuel assembly, with a large increase in the concentration of  $^{238}\text{Pu}$ . This increase has an impact on the thermal power of the plutonium. The acceptance specifications of the reprocessing facilities should be modified to take into account such difference in isotopic compositions.

The same maximum initial enrichment and maximum discharge burnup criteria should apply for the acceptance of the ERU and ENU fuel assemblies at the reprocessing facilities.

## 5.5. CREDIT FOR NEUTRON ABSORBING ISOTOPES

To ease the backend issues of the spent ERU assemblies, the possibility to take some credit for neutron-absorbing isotopes should be considered for the criticality studies and enrichments up to 6%  $^{235}\text{U}$  should be taken into account.

# 6. MARKET AND ECONOMICS OF RepU

Several presentations made during the technical meeting in August 2007 addressed the economics of RepU recycling [65]. Based on the information presented in the above references, the following section aims at defining the elements to be factored in when performing an economic analysis, rather than giving the outcome of such analysis.

## 6.1. RepU MARKET SITUATION

### 6.1.1. Current market characteristics

The potential RepU market size is the conjunction of a specific demand from utilities for RepU processing services and the related service offers from nuclear fuel cycle suppliers. There are regulatory limitations in some countries due to restrictive back end policies, including potential bans on using reprocessed uranium as it relates to the closed fuel cycle. On the offer side, while the Russian Federation has set up a supply chain that enables processing the whole arising of RepU (and feed most of it into RBMKs), Western industry has not implemented the needed facilities to burn all available RepU.

The current market for ERU fuel lags far behind the natural uranium market. According to the 2007 WNA's Global Nuclear Fuel Market Report [9], the Western reactor requirements in 2006 were 57 000 t U, of which 2000 t U equivalent were covered by MOX and ERU fuel. In 2006, the Russian reactor requirements were around 7000 t U, of which 500 t U equivalent was covered by ERU. (These figures represent the estimated displacement of natural uranium by recycled reprocessing products.) Thus, the information in the WNA report results in the following market share:

**In 2006, the RepU loaded into reactors represented 2.3% of the world natural uranium reactor needs.**

Taking into account that RepU availability allows displacing part of the NU demand to fuel reactors, and that natural uranium production is lagging behind utilities' annual uranium demand, at a first glance the rational market answer should be to increase the use of RepU. However, there are still secondary supply sources (such as MOX, and LEU derived from Russian HEU) filling the gap between annual uranium demand to fuel reactors and annual natural uranium production, thus reducing the urgency to recycle RepU from the supply side point of view.

Furthermore, there is neither an organized market for RepU/ERU nor a market price for the corresponding products and services. RepU belongs to the ‘secondary supplies’ [9], which remain an essential part of the world uranium supply, but RepU does not benefit from an organized market, contrary to recycle products in other commodities (typically aluminium). Also, for the time being, a zero value is assumed for RepU in the studies assessing the economical potential of ERU.

### 6.1.2. Theoretical future RepU market

From a theoretical viewpoint, i.e. if all spent power reactor fuels was reprocessed:

**The arising RepU could theoretically meet up to 10–20% of the worldwide annual uranium needs for fuel reactors.**

In the case of LWRs, this ratio corresponds to the number of spent fuel assemblies (five to ten) needed to generate one ERU assembly in the case of physical re-enrichment. However, this 10–20% range is dependent on the residual enrichment of the spent fuel, the choice of tails assay when re-enriching the RepU, and the conventional tails assay considered when translating RepU use into natural uranium equivalent.

Using the blending route with LEU lower than 5%  $^{235}\text{U}$ , the Belgian example [66] arrives at NU savings from RepU in the range of 15% of the reactor needs.

The above-mentioned savings (of 10–20% of the world annual uranium needs) mean that all utilities have their spent fuel reprocessed. However, the forecast of RepU use by utilities is much lower, as shown in Figure 14, where MOX and RepU together constitute the ‘recycling upper’ share of the secondary supplies.

Figure 14 gives a comparison of the upper supply case of the WNA 2007 Report [9], and the lower, reference and upper reactor requirement cases (curves with dots). In the upper supply case, the uranium-equivalent supply resulting from the use of RepU amounts to approximately 2 000 t U/year over the 2010–2015 period (which represents less than half of the ‘Recycling upper’ share, the remaining being MOX fuel), to be compared to a global average supply of 92 000 t U and an average world requirement of 73 000 t U over the same period (upper scenario). Based on such figures, the WNA market forecast is the following:

**Over the 2010–2015 period, RepU loaded into reactors would represent 2.5% of the world reactor needs.**

### 6.1.3. Offering

The potential future recycling of RepU depends on the stockpiles of RepU, the available capacities of reprocessing plants (RepU generation) and the routes available to recycle, as well as economic considerations.

To date, about 8000 t U of RepU (not including MDU) have been recycled in the world. The current RepU stocks (including all kinds of RepU extracted from spent power reactor fuel) are evaluated at 45 000 t U from the French and British reprocessing plants. However, a large part of this amount is MDU, the economics of which are questionable. To draw a parallel with the natural uranium mining market, these 45 000 t U of RepU accumulated to date constitute ‘resources’ rather than ‘reserves’. As in the mining industry, such ‘resources’ must be proven economically usable before being turned into ‘reserves’, i.e. readily marketable production.

In addition, the reprocessing plants in France and the United Kingdom, and the one in the start-up phase in Japan have the capability to add a potential flux of several thousands tonnes of RepU per year. The details are specified in Table 12, which lists the main facilities and associated capacities for reprocessing of spent fuel, as of the end of 2007. Future RepU arising will always be dependent on back end policies and the spent fuel processing capacities.

A conclusion that can be drawn from Tables 12, 13, and 14 is that the use of RepU is also constrained by the supply side, with potential bottlenecks both in the back end and front end facilities.

### 6.1.4. Suggestions on the RepU market

Listed below are a number of suggestions of avenues worth exploring to allow maturing of the RepU market:



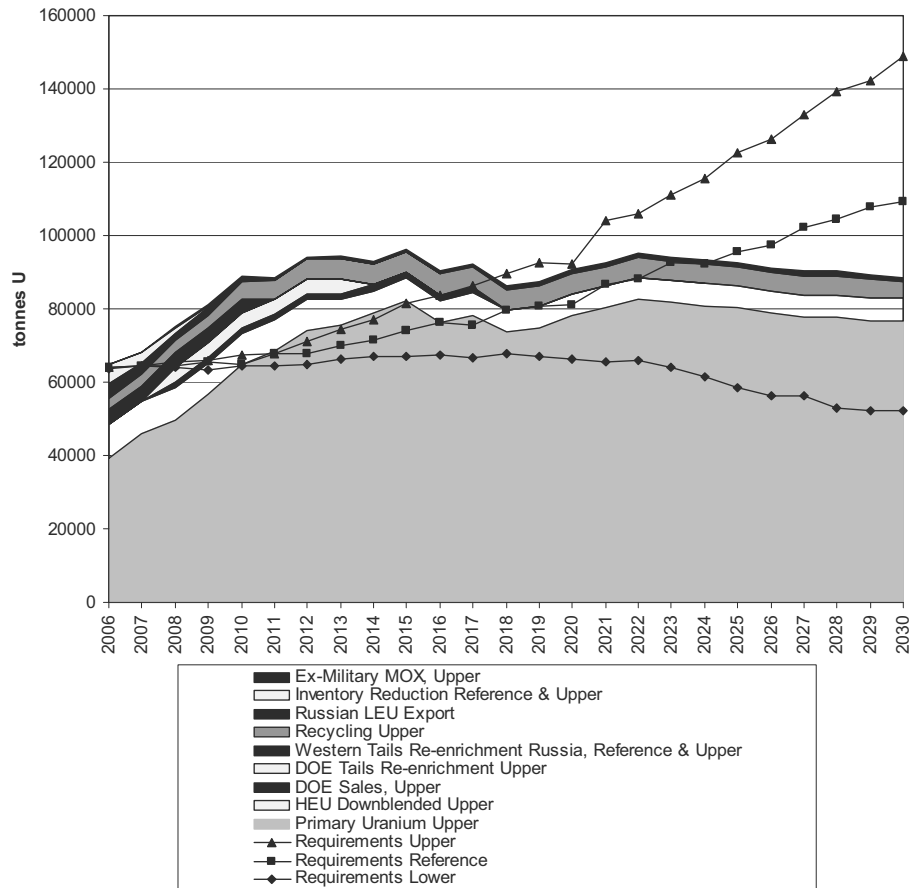


FIG. 14. World uranium demand and supply (upper supply case) – WNA 2007 Global Market Report<sup>4</sup>.

- Defining a standardized RepU (or ERU) product would ease price determination and economic comparisons.
- In order to ensure equivalent product quality, utilities and suppliers should investigate ways to lift the 5% limit of <sup>235</sup>U enrichment. However, the 5% enrichment limit does not hamper the blending route to the same extent as the traditional route (physical re-enrichment of RepU) (see Section 4.2.1).
- The use of ERU in first cores should be investigated, as the fuel’s necessary <sup>235</sup>U assays are lower than for equilibrium reloads.
- Maintain, encourage and develop a certain level of competition among suppliers of RepU processing services in order to allow maintaining competitive prices for ERU compared to ENU.
- A better sharing of experience in the use of RepU, assessment of upfront engineering and licensing effort should be encouraged, notably for those utilities not acquainted with RepU, as well as on obligations on fissile material.
- A competitive RepU market is a key element for the closed fuel cycle option.
- The specifications of fabrication plants must be reassessed so that they can accept ERU with a higher <sup>232</sup>U assay.

<sup>4</sup> Normally the data on uranium demand and supply would have been collected from the reference ‘Uranium 2007: Resources, Production and Demand’, also known as the ‘Red Book’ [10], which is joint report by the OECD/NEA and the IAEA. The Red Book describes a statistical profile of the world uranium industry in the areas of exploration, resource estimates, production and reactor-related requirements. The WNA figure is presented above because it not only gives estimates on U production and world reactor requirements, but also illustrates the contribution of the secondary sources in filling the gap between anticipated production and demand, as well as account for the different fuel procurement strategies of ‘Western’ design reactors (supplied mainly by Western suppliers and producers in Central Asia) and of Russian design reactors (supplied mainly by Russian companies).



TABLE 12. LIST OF THE MAIN OPERATING FACILITIES FOR THE TREATMENT OF SPENT FUEL

Status	Facility, country	Operator/owner	Capacity (a)
Operating	UP2-800 La Hague, France	AREVA	1000 <sup>a</sup>
Operating	UP3 La Hague, France	AREVA	1000 <sup>a</sup>
Operating	Tarapur, India	Department of Atomic Energy	100
Operating	Kalpakkam, India	Department of Atomic Energy	100
Operating	Tokai-mura, Japan	JAEA	90
Start-up	RRP Rokkasho-mura, Japan	JNFL	800
Operating	RT-1 Mayak, Russian Federation	Rosatom	400
Operating at reduced throughput	Thorp, United Kingdom	NDA/ Sellafield Limited	600
Operating	B205, United Kingdom	NDA/ Sellafield Limited	1500

<sup>a</sup> Combined licensed capacity of 1700 t/a for the two plants at La Hague.

TABLE 13. LIST OF FACILITIES FOR THE PROCESSING OF RepU

Stage	Facility/country	Operator/owner	Nominal capacity
Processing for interim storage	TU5, Pierrelatte France	AREVA	1700 t U (UNH into U <sub>3</sub> O <sub>8</sub> )
Conversion	Seversk Russian Federation	SGChE	1500 t U (U <sub>3</sub> O <sub>8</sub> into UF <sub>6</sub> )
Enrichment	Almelo Netherlands	UEC	200 000 SWU
Enrichment	Seversk Russian Federation	SGChE	1 million SWU
Blending	Ozyorsk Russian Federation	Mayak Production Association	n.a.
Blending and conversion to UO <sub>2</sub>	Elektrostal Russian Federation	MSZ	1100 t HM
Fabrication	Romans France	AREVA	150 t HM
Fabrication	Elektrostal Russian Fed.	MSZ	1100 t HM
Fabrication	Wilmington USA	GE	ERU fuel for BWRs 50–60 t HM /a
Fabrication	Tokai Japan	MNF	ERU fuel for LWRs 40 t HM/a

The arising of RepU or the existing stockpiles requires front end facilities to be turned into nuclear fuel. Tables 13 and 14 provide a list of the existing and planned facilities and associated capacities for recycling of RepU, as of the end of 2007.

TABLE 14. LIST OF PLANNED FACILITIES FOR THE PROCESSING OF RepU

Stage	Facility, site	Operator/owner	Capacity
Conversion	URT2, Pierrelatte, France	AREVA	To be determined
Enrichment	Georges Besse II, Pierrelatte, France	AREVA	One dedicated line

On a more general basis, higher burnups for ENU fuel will lead to an increased concentration of minor isotopes in the recovered RepU and will hamper recycle of RepU. Technical solutions must be found and investments may have to be made in the front end part of the ERU fuel cycle.

Concerning specifically the direct enrichment route:

- New conversion facilities are needed.
- New enrichment capacities are also needed. Centrifuge technology, because it is modular, allows devoting specific cascades to RepU enrichment, which is not possible with gaseous diffusion. However, laser techniques, if they became available at an industrial scale, could allow selective re-enrichment of  $^{235}\text{U}$  and could find with ERU an attractive economic application.

## 6.2. ECONOMICS: ELEMENTS TO BE CONSIDERED

This section aims at presenting the key parameters to be factored in when performing an economic analysis of the use of RepU.

### 6.2.1. Variables determining the cost of RepU

A first set of variables, which describes the RepU feed, relates to the quality of the spent fuel available?

- Fresh fuel initial  $^{235}\text{U}$  enrichment (FF235);
- Spent fuel burnup (SFBU);
- Duration of storage of spent fuel or recovered RepU (SFst).

The following three variables can be expressed as a function of the previous set of variables:

- RepU  $^{234}\text{U}$  content (RU234);
- RepU residual  $^{235}\text{U}$  enrichment (RU235);
- RepU  $^{236}\text{U}$  content (RU236).

Note that the  $^{232}\text{U}$  content in RepU will vary over time, but it does not impact the ERU fuel performance. The cost of ERU is impacted by  $^{232}\text{U}$  only if the content of this isotope exceeds radiation protection regulatory limits in the processing facilities, requiring costly investment in such facilities.

Another key parameter influencing the cost of ERU is:

- The targeted ENU equivalent enrichment ( $\text{ENU}_{\text{eq}}$ ).

This  $\text{ENU}_{\text{eq}}$  value is the enrichment level of the ENU fuel to which the ERU fuel should be equivalent in performance. It defines the quantity of SWUs needed for RepU enrichment, taking into account the ERU over-enrichment needed to offset the adverse neutron-absorbing effect of the ERU  $^{236}\text{U}$  content.

The SWU quantity required to produce the desired ERU can be expressed as a function of:

- RepU initial residual  $^{235}\text{U}$  enrichment (RU235);
- The targeted ENU-equivalent enrichment ( $\text{ENU}_{\text{eq}}$ );
- The over-enrichment needed ( $\Delta 235$ );
- The tails assay considered (T235).

The over-enrichment  $\Delta 235$  is defined as that needed so that ERU fuel achieves the same in-reactor performance as ENU fuel.  $\Delta 235$  is a function of RU234, RU235, RU236 and  $\text{ENU}_{\text{eq}}$ . The function is different in the case of each route.

The weighting factors are different depending on the isotope considered. In some models, RU234 is neglected [67].

The blending route with LEU up to 17%  $^{235}\text{U}$  requires the least over-enrichment, and on the contrary the physical re-enrichment route requires the highest over-enrichment (see Section 4.2.1). Over-enrichment increases with increasing  $\text{ENU}_{\text{eq}}$ .

The resulting ERU enrichment needed to achieve equivalent performance with ENU fuel at an assay of  $\text{ENU}_{\text{eq}}$  is:

$$\text{ERU}_{235} = \text{ENU}_{\text{eq}} + \Delta 235$$

Note that T235 is totally arbitrary and typically depends only on prevailing market conditions at the time of the economic study performed.

The economics of ERU fuel are also dictated by the potential value set for RepU and the unitary cost of processing services:

- Value set for RepU (however, this value is usually zero);
- Cost of blending services (blending route);
- Cost of blending material (blending route);
- Unitary cost of conversion and enrichment services, usually expressed as a factor of the ENU service cost;
- ERU fuel fabrication cost, usually expressed as a factor of the ENU fuel fabrication cost (all routes);
- Extra cost, including cylinder management and the tails defluorination.

The processing costs listed above are always higher for RepU than for NU.

The scale effect has a significant impact on cost. To date, the RepU annual throughput has been much lower than in the case of natural uranium with the consequence that fixed costs are allocated over a lower throughput and resulting in higher unit costs of processing for RepU.

The lack of maturity of the RepU supply chain and the limited number of suppliers may introduce additional constraints which could translate into additional costs.

However, if the ENU enrichment level is close enough to 5%, ERU would need to go beyond 5% to reach performance equivalence. There are two ways to perform an economic comparison between ERU and ENU fuel:

- The ‘ISO performance method’: Determine the cost of an ERU assembly achieving the same performance as an ENU fuel assembly. This implies over-enrichment and may lead to considering enrichment beyond 5%.
- The ‘relative output method’: Determine the cost of the ERU fuel relative to the energy output, considering ERU fuel with lower performance. This is the case when ERU fuel loaded cannot achieve the same performance, because the reactor licence forbids over-enriching or going over the 5% limit. This method may then take factor in a loss of kWh, which is extremely unfavourable to ERU. Alternatively, it may factor in factor in larger reload batch sizes (see Section 4.2.1).

Finally, in the case of utilities having already chosen the closed fuel cycle, the costs avoided by the immediate recycling of RepU can be taken into consideration:

- Conversion of the UNH into  $U_3O_8$ ;
- Spent fuel/RepU storage.

From a more general perspective, the recycling of reprocessed uranium should be assessed as one element of the overall cost associated with spent fuel management involving reprocessing.

At ORNL, USA, extensive modelling of various RepU reuse scenarios have been reported [21, 68] and the initial results indicate that the reuse scenarios of RepU are economical in comparison with the no-reuse scenarios.

### 6.2.2. Examples of economic analyses

Taking into account plausible cost ranges for NU, fresh uranium fuel cycle service costs, applicable costs for the re-conversion to  $UF_6$  and the premiums for other recycle services, some examples showing the sensitivity of ERU economics to some of the variables identified above were presented at the TM in August 2007. These examples depend to a large extent on prevailing or forecasted market conditions. The purpose they served was pure sensitivity analysis.

The most significant parameters identified in the papers presented at the TM that impact the RepU and ERU economics are the following:

- Increasing discharge burnup (SFBU) is a strong trend and will undoubtedly lead to a higher residual content of  $^{236}U$  in the RepU (RU236), which is unfavourable;
- Legacy RepU' stockpile with a high residual  $^{235}U$  enrichment in the spent fuel RU235 and a low residual content of  $^{236}U$  in the RepU (RU236) is, on the contrary, very favourable;
- Lifting the 5% limit on  $^{235}U$  content (ERU235) would be favourable;
- The blending route is more favourable than physical re-enrichment, but it depends on the availability of blendstock material. Also, the blending route leads to lower over-enrichment ( $\Delta 235$ ), thus pose less problem as regards the 5% limit.

## 7. SUMMARY AND CONCLUSIONS

### 7.1. SUMMARY OF FINDINGS

#### 7.1.1. Inventories

At the beginning of 2007, the inventories of RepU derived from the reprocessing of uranium metal fuels were approximately 24 000 t U, while those for RepU derived from reprocessing of oxide fuel were 21 000 t U. The inventories of RepU in the Russian Federation are negligible because RepU arising from reprocessing there is recycled at a rate similar to the RepU production rate.

In Western countries, inventories of RepU derived from spent oxide fuel ('oxide RepU') are forecast to continue to rise in the short term. A key factor is the completion of commissioning of the Rokkasho-mura reprocessing facility in Japan, which will result in a significant increase in the capacity of reprocessing plants and is therefore forecast to result in a consequential increase in the annual arisings of RepU. In contrast, there has been no comparable significant investment to commission new facilities for the processing of RepU over the past ten years. In fact, certain facilities previously planned or in operation have ceased to be available for processing RepU or have been identified for decommissioning.

RepU derived from reprocessing of metallic uranium fuels is sufficiently different from oxide-derived RepU in terms of its isotopic content that it should be separately considered in terms of stocks, value and recycle potential. It is advisable not to combine the stocks of metal-derived RepU with oxide-derived RepU, but instead to treat the two materials as having different characteristics, and also to be subject to different economic assumptions.

### 7.1.2. Experience of recycle and reactor loading

There is substantial experience of recycling RepU in several countries and in different designs of reactors. Up to 2007, some 8000 t U of oxide derived RepU had been recycled and some 17 000 t U of Magnox Depleted Uranium (MDU) had been recycled in the United Kingdom. The past experience of processing RepU has largely been very positive, with the practical aspects that differentiate RepU from NU in the processing plants having been resolved. There are, however, some lessons learned that influence the degree to which past experience can be used in future assessments. In addition, certain trends in the characteristics of RepU have been identified that may be significant for those considering the development of additional capacity or new routes for the processing of RepU.

The reactor experience has been overwhelmingly positive, demonstrating no basic differences between ERU and ENU fuel in terms of their performance in the reactor.

### 7.1.3. Lessons learned

A key learning point is that RepU is not a standardized product. This results mainly from three factors:

- The specifications contained in reprocessing contracts were generally agreed many years ago when recycle route requirements had not been identified;
- The chemical form of the products from different reprocessing contracts is different as are the containers in which the RepU is kept;
- The continuous process may produce RepU batches that are not as homogeneous as those produced in a batch process.

As far as LWR fuel is concerned, the presence of  $^{232}\text{U}$  in RepU is very significant for the re-enrichment route. As utility operators move to higher burnups, strategies need to be developed by the industry to cope with the increasing presence of even-numbered uranium isotopes.

The blending route with LEU up to 17%  $^{235}\text{U}$  made available in the Russian Federation has been successful and has become the dominant route to date for processing RepU. This route has no tails arising. The future prospect for this route is limited, however, because of the decreasing availability of blending material. Therefore, the mixed route, involving re-enrichment and blending together, is already gradually replacing the blending route.

Given ongoing and anticipated developments in the natural uranium market (for example, increasing prices for UOC and the emphasis on security of supply through long-term contracts), current intentions of suppliers of RepU processing services include developing facilities to handle RepU and also bringing online new re-enrichment route facilities.

The issue connected with the in-growth of the daughter products of even uranium isotopes (such as  $^{228}\text{Th}$ ) and the consequential increase in the radiological hazard can be relatively easily addressed, but require careful planning and flexibility in the manufacturing process. The  $^{228}\text{Th}$  activity curve reaches a maximum after ten years and reaches 10% of this maximum within three months of the most recent chemical purification stage. Following the ALARA principle, the best method to deal with this hazard in fuel manufacture and handling is to fast-track RepU through the supply chain. Supply dates, lead times and checks on radiation levels from  $\text{UF}_6$  cylinders therefore become a key feature of commercial contracts.

Since mid-2008, there has been a limit of 5%  $^{235}\text{U}$  on power reactor fuel manufacturing, power reactor fuel transport and power reactor fuel loading. In order to compensate for the presence of the  $^{236}\text{U}$  neutron poison and to achieve higher burnups, it is necessary to move this limit up to 6%  $^{235}\text{U}$ . As utilities look for higher burnups, they are approaching the 5% limit with ENU fuel, so it is not only ERU fuel that is driving towards this change. The benefits of moving licences to 6%  $^{235}\text{U}$  are very significant, and it can be expected that the industry will make a concerted effort in this direction in the near future. However, it is to be hoped that licences reaching 6%  $^{235}\text{U}$  will be obtained not only for ENU fuel, but also for ERU fuel.

An alternative solution that avoids the high burnup challenge is to use RepU in first cores. This is not a long-term sustainable solution, since first cores represent only 9% of the total fuel requirements of a reactor designed to operate for 25 years. In light of a potential nuclear renaissance, it nevertheless offers an opportunity that should not be overlooked.

#### **7.1.4. Economic factors and market conditions**

It remains difficult to place a value on RepU or to forecast precise prices for ERU fuel. It is clear that there are a number of additional costs that may be introduced, either to achieve the necessary over-enrichment to reach reactivity targets for the fuel, or to reflect processing issues. This report has discussed the modeling of these costs in Section 6.2. In addition, a checklist has been provided in Section 4.5, which can be used to ensure that most of the more significant potential cost issues have been identified and quantified. It is important to note that the cost of ERU is not particularly dependent on the natural uranium market price, which has shown increased volatility in recent years. The forecast renewed interest in nuclear power together with sustained demand for uranium is likely to maintain natural uranium prices at relatively high levels compared to prices that prevailed during the 1990s. This should encourage investment from the supply side in new facilities for processing RepU. We have seen in recent years increased investment in natural uranium supply, but we have not yet seen comparable demand for ERU fuel. Instead, investments in RepU processing facilities have been stimulated only recently.

## **7.2. CONCLUSIONS**

It can be seen that there is considerable experience in the recycle of RepU, however, the market for RepU processing services is not well developed. There are no insuperable problems associated with RepU processing or related to incore fuel performance. The trends towards higher burnups by reactor operators present new challenges. Nevertheless, the changing economic environment also presents new opportunities.

This report has identified the challenges and issues associated with the use of RepU; the TM in August 2007 has demonstrated that there is no shortage of interest in the industry to understand and address them. Key questions that need to be addressed by both utilities and suppliers include those listed in Section 4.5.

An interesting proposal made during the preparation of this report calls for the creation of an international forum at which all aspects of RepU use and facilitates should be discussed. This forum could present a platform for the suppliers of RepU processing services, RepU consumers and all stakeholders in the recycling of RepU to further develop a common understanding of the associated challenges and opportunities. This could create and promote some of the necessary conditions for a very large-scale use of RepU, and could develop and become self-sustaining.





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## ABBREVIATIONS AND ACRONYMS

ADU	ammonium di-uranate
AGR	advanced gas cooled reactor
ALARA	as low as reasonably achievable
ASTM	American Society for Testing and Materials
BLEU	blended low enriched uranium
BOC	beginning of cycle
CANFLEX	CANDU FLEXible fuelling
DU	depleted uranium
DUPIC	direct use of spent PWR fuel in CANDU
EFPD	equivalent full power days
ENU	enriched natural uranium
EOC	end of cycle
ERU	enriched reprocessed uranium
FBR	fast breeder reactor
GNEP	Global Nuclear Energy Partnership
MDU	Magnox depleted uranium
MOX	mixed (uranium-plutonium) oxide
NU	natural uranium
PUREX	plutonium and uranium recovery by extraction
RBMK	light water-cooled, graphite moderated reactor
SEU	slightly enriched uranium
SWU	separative work unit
SRU	scrap recovery unit
UNH	uranyl nitrate hexahydrate
UOC	uranium oxide concentrate
UO <sub>x</sub>	uranium oxide
WWER	water-cooled and water-moderated reactor

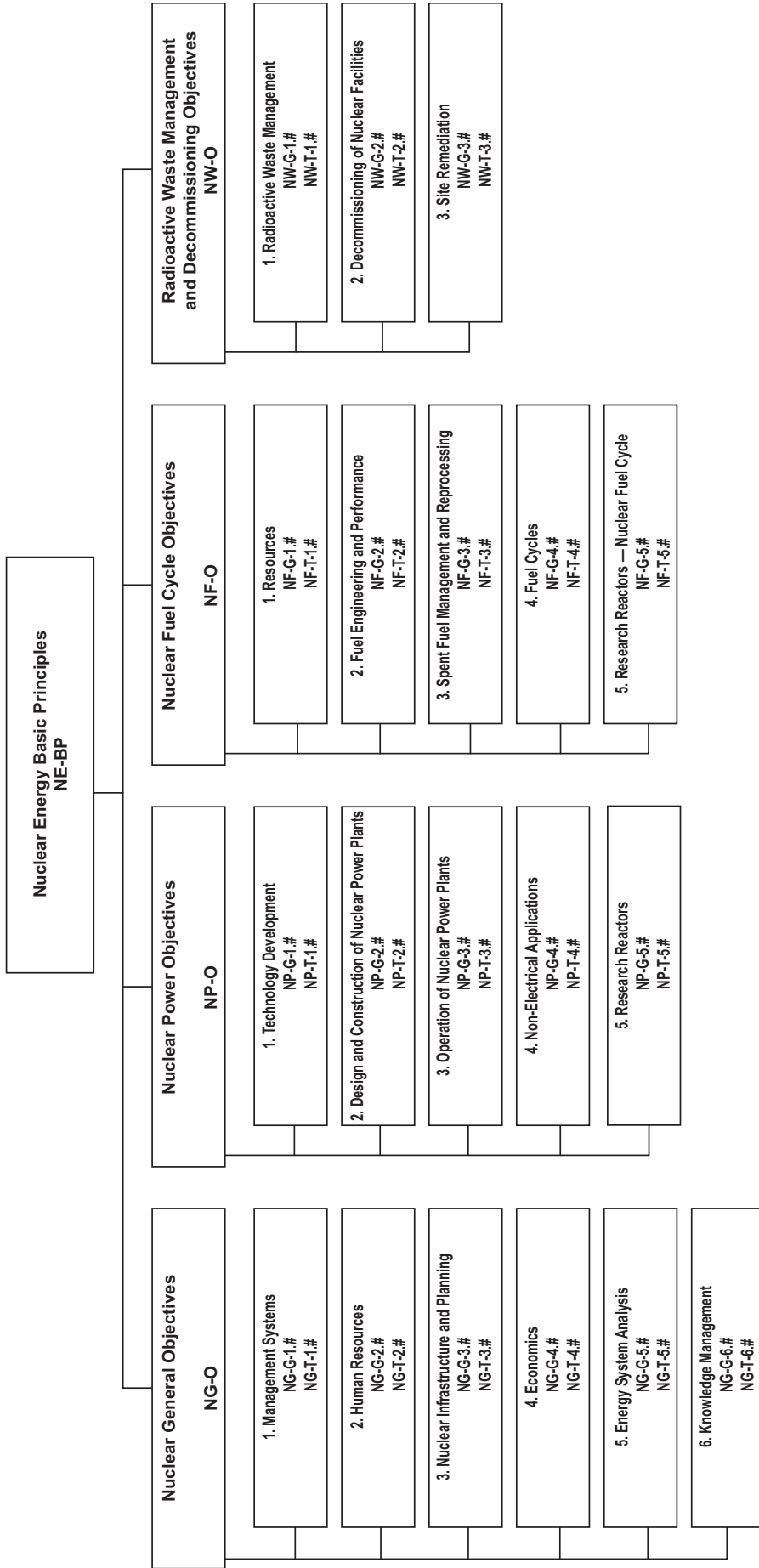


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