ROADMAP
Actinide separation processes 2015
Authors: Pierre Joly (LGI Consulting), Eva Boo (LGI Consulting)

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This report provides an overview of the different actinide separation processes used in the partitioning and transmutation (P&T) of nuclear waste.

Indeed, “by partitioning (chemical separation) and transmutation (radionuclide conversion), it might be possible to reduce the long-lived component of the radioactive waste, thus easing the waste management problem. The objective of the European Union research and development effort on partitioning and transmutation is to study its practicability on an industrial scale.” (EURATOM, 2001)

The first chapter of the report introduces the development context of P&T as well as the logical sequence in which the European SACSESS project fits in. Reprocessing was initially developed for military purposes in order to recover the plutonium (Pu) in nuclear spent fuel for reuse in weapons. Although concern over this initial purpose still exists today, reusing these wastes as energy source to both decrease their environmental impact and increase their energy and economic value is now another preoccupation of nuclear scientists worldwide. The European Commission, by supporting projects such as SACSESS and others in the past (e.g. ACSEPT), is willing to analyse the potential creation of a complete P&T industrial line. During the past 60 years, many processes have been developed and/or studied to reprocess spent nuclear fuel. This report gives an overview of these processes, which may help political decision makers prioritise the most promising for P&T development.

The second chapter describes the methodology used to provide this overview. The mapping began with an overview of the pre-existing studies on the subject, followed by a set of interviews with the main scientific leaders on existing processes to target the most promising that are still evolving. A literature review on the main processes gave a good basis for the presentation of each partitioning process. Finally, the main experts in the field reviewed the processes.

The last chapter describes the partitioning processes identified to be the most promising. They are presented in two subgroups: aqueous separation processes and pyrochemical processes. Other processes exist, such as fluorination, but they are not considered in this report as they are not as promising.

For aqueous separation processes, the type of extraction performed is the differentiating characteristic. The processes co-extracting the actinides and the lanthanides are described first (TRUEX, DIAMEX, etc.). The processes partitioning minor actinides (DIDPA, SETFICS) are then covered, followed by the processes used to separate the actinides from lanthanides (SANEX processes, the CYANEX 301 process and the American processes). Finally, the processes allowing the separation of americium (Am) from curium (Cm), (EXAm), and the homogeneous partitioning processes (GANEX) are described.

For pyrochemical processes, the American and European electrorefinning processes, the European liquid-liquid reductive extraction in molten fluoride salts, the Russian Dimitrovgrad dry process and the Korean ACPF are detailed.

The mapping of these processes allows to compare current partitioning processes, including their status and their main advantages and disadvantages. It also allows preparing the next step, which is to identify the R&D needs for each process and prioritise them due to limited resources.

The roadmap that will be developed as part of the SACSESS project will support this approach and integrate the results from this technological mapping.
| **1c-SANEX** | One cycle SANEX | **HEDTA** | **N-(2-[4-carboxymethyl]amino[4-ethyl]-** | **N-(2-hydroxyethyl)glycine** |
| **ACPF** | Advanced spent fuel conditioning process | **HEDTA** | **N-(2-hydroxyethyl)ethylenediamine** | **N,N',N'-triacetic acid** |
| **ACSEPT** | Actinide recycling by separation and transmutation | **IFNEC** | **International framework for nuclear energy cooperation** | **Innovative SANEX** |
| **AHA** | Acetohydroxamic acid | **ITU** | **Institute for Transuranium Elements** | **Japan Atomic Energy Agency** |
| **ALSEP** | An-Ln separation | **JAERA** | **Japan Atomic Energy Research Institute** | **Korea Atomic Energy Research Institute** |
| **An** | Actinides | **KAERI** | **Lanthanides** | **Minor actinides** |
| **ANL** | Argonne National Laboratory | **MA** | **N-dodecane** | **Partitioning and Transmuting** |
| **ARTIST** | Amide-based Radio-resources Treatment with Interim Storage of Transuranics | **nDD** | **Oak Ridge National Laboratory** | **Platinum group metals** |
| **BAMA** | Branched-alkyl monoamide | **ORNL** | **Regular SANEX** | **Pacific Northwest National Laboratory** |
| **CA-BTP** | Bis-2,6-(5,6,7,8-tetrahydro-5,9,9-trimethyl-5,8-methano-1,2,4-benzotriazin-3-yl)pyridine | **P&T** | **Safety of actinide separation process** | **Plutonium Uranium Refining by Extraction** |
| **CDTA** | 2,2',2''-[(IR,2R)-1,2-cyclohexanediylidinitrilol]tetraacetic acid | **PGM** | **Selectiv actinide extraction** | **Solvent Extraction for Trivalent f-elements** |
| **CEA** | Commissariat à l’énergie atomique et aux énergies alternatives | **PNNL** | **Intra-group Separation in CMPO-complexant System** | **Trivalent Actinide-Lanthanide Separations by Phosphorus-reagent Extraction from Aqueous Komplexes** |
| **CHALMEX** | Chalmers GANEX | **SF** | **Sodium fast reactor** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** |
| **CIEMAT** | Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas | **SACCESS** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** |
| **CMPO** | N-octyl[phenyl]-N,N-diisobutylcarbamoylmethylphosphine oxide | **SANEX** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** |
| **Cyanex 301** | Bis(2,4,4-trimethylpentyl)dithio phosphonic acid | **SETFICS** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** |
| **CyMe4-BTBP** | 6'-bis(5,5,8,8-tetramethyl-5,6,7,8-tetrahydro-benzo[1,2,4]triazin-3-yl)2,2' bipyridine | **SF** | **Spent fuel** | **Spent fuel** |
| **D2EHA** | N,N-di(2-ethylhexyl)butanamide | **SF** | **Sodium fast reactor** | **Sodium fast reactor** |
| **DDP** | Dimitrovgrad dry process | **TALSPEAK** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** |
| **DEHBA** | N,N-di(2-ethylhexyl)isobutyramide | **TALSPEAK** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** | **Trivalent Actinide-Lanthanide Separation using Quicker Extractants and Aqueous Komplexes** |
| **DGA** | Diglycolamine | **TBP** | **Tidalkyl phosphate** | **Tidalkyl phosphate** |
| **DH2EHA** | N-N-dihexyl-2-ethylhexanamide | **TODGA** | **N,N,N',N' tetraoctyl diglycol amide** | **N,N,N',N' tetraoctyl diglycol amide** |
| **DHOA** | N,N-dihexyl octanamide | **TRPO** | **Trialkyl phosphate oxides** | **Trialkyl phosphate oxides** |
| **DIAMEX** | Diamide extraction | **TRU** | **Transuranic elements** | **Transuranic elements** |
| **DIDPA** | Di-isodecylphosphoric acid | **TRUEX** | **Transuranic extraction** | **Transuranic extraction** |
| **DMBDTMA** | Dimethyl-dibutyl-tetradecyl malonamide | **TRUEX** | **Transuranic extraction** | **Transuranic extraction** |
| **DMDOHEMA** | N,N,N'-didecyl-N,N'-dioctylhexyloxyethylmalonamide | **TRUEX & TALSPEAK** | **Transuranic extraction** | **Transuranic extraction** |
| **DOE** | Department of Energy | **TWE21** | **TWE21 2-(2-diocylamino)-2(oxoethoxy),N,N-dioctylpropanamide** | **TWE21 2-(2-diocylamino)-2(oxoethoxy),N,N-dioctylpropanamide** |
| **DTPA** | Diethylene triamine pentaacetic acid | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **EURO-GANEX** | European GANEX | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **EXAm** | Extraction of Am | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **FNR** | Fast nuclear reactor | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **FP** | Fission products | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **GANEX** | Grouped actinide extraction | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **GFR** | Gas cooled fast reactor | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **GNEP** | Global nuclear energy partnership | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **HAN** | Hydroxylammonium nitrate | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **HAW** | High activity waste | **UREX** | **Uranium extraction** | **Uranium extraction** |
| **HDEHP** | Bis-(2-ethylhexyl) phosporic acid | **UREX** | **Uranium extraction** | **Uranium extraction** |
1. INTRODUCTION
1.1 Overview and objectives

Nuclear energy generated about one third of the EU’s electricity, produced by more than 131 reactors in Europe (SNETP, 2013). The role of nuclear energy in the European energy mix is undeniable and contributes strongly to limiting greenhouse gas emissions.

However, the management of radioactive waste remains one of the most important issues arising from nuclear power production. The ability to increase the resource efficiency by managing waste and by decreasing its amount will be essential for the nuclear sector in the upcoming years. Among the different existing strategies, partitioning and transmutation (P&T) will allow a reduction of the amount, of the radiotoxicity and of the thermal power of these wastes and a more efficient use of nuclear natural resources. The enhancement of P&T techniques will lead to economic benefits for the nuclear industry as well as security and environmental benefits for all humankind.

The first task was to map the existing partitioning processes and cover their main characteristics, technological readiness levels and current and potential boundary conditions. This report is the outcome of this task.

It provides a complete cartography of the different and most promising partitioning processes at European level, including the main processes under development in various research centres. Processes developed in the USA, Russia, Japan and Korea are also presented, in less detail. It also presents an update of the mapping carried out in the FP6 PATEROS project.

These findings are a key input for the development of a first complete roadmap that will support decision makers’ choices between the numerous existing processes and enhance the positioning of the EU as a leader in the field.

The goal of the SACSESS project is to provide a structured framework to enhance the fuel cycle safety associated to P&T and to take a step further towards a future design of an advanced processing unit. For this, SACSESS is carrying out in-depth analysis on two main technology domains: aqueous processes and pyrochemical processes. In addition, it is performing transversal studies in global safety and process integration. This covers two areas:

- Global safety: identification of the weak points in existing processes (r-SANEX, i-SANEX, GANEX, 1c-SANEX, Pyro) by performing a safety analysis in order to implement, if relevant, an optimisation experimental programme.

- Roadmapping and assessment of the impact of European nuclear wastes aiming at:
  - Supporting the optimisation of European research in P&T with a first global picture of final industrial systems.
  - Preparing for industrialisation in the short term and setting up a common ground for discussions with potential industrial operators of P&T facilities.
  - Assessing the environmental impacts of the deployment of P&T systems.

1.2 Context description

The production of nuclear power entails the management of the entire nuclear fuel cycle: the front-end steps (exploration, mining, milling, U conversion, enrichment, and fuel fabrication), operations (transport, in-core fuel management, management of the reactors...) and the treatment of the spent fuels (back-end, interim storage, conditioning, reprocessing and MOX fabrication, or direct disposal).

Each year, the nuclear industry generates about 10 000 metric tons of nuclear used fuels (Nuclear Energy Institute, 2014). These wastes are highly toxic, particularly because of the presence of actinides (Figure 1).

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1“European Roadmap for the deployment of P&T in a regional context” - FP6 PATEROS project http://pateros.sckcen.be
There are two solutions to handle these highly polluting wastes:

- The current solution: direct disposal of spent nuclear fuel in a deep geologic repository.
- Reprocessing of spent nuclear fuel, recovering uranium and plutonium for fresh fuel production, and vitrifying the high-level waste for final disposal in a deep geologic repository. Alternatively, all TRU (Np, Pu, Am, Cm) could be recycled, which is the P&T strategy.

1.2.1 History

Historically the nuclear industry began reprocessing nuclear fuels in the early days of civil nuclear power utilisation. The initial purpose in 1943 was to separate and recover fissionable plutonium (Pu) from irradiated nuclear fuels for further use in nuclear weapons. In 1949, the University of Chicago developed the PUREX process, which allowed the recovery of the uranium (U) and the plutonium independently from each other.

This process recycled the reprocessed Pu into MOX nuclear fuel for thermal reactors, and reused the reprocessed U theoretically as fuel. At this time, minor actinides were not recycled, since there was no motivation for doing so.

However, today there are several reactor concepts (Generation IV reactors) that will be able to use them as fuel. Consequently, the interest in P&T practices has largely increased. During the last few decades, considerable scientific and technical efforts have been devoted to developing partitioning/reprocessing processes in the frame of domestic and international projects: SPIN (France), OMEGA (Japan), bilateral cooperation and EURATOM Framework Programmes.

Parallel to these programmes, in February 2006, the US Secretary of Energy Samuel Bodman proposed the creation of the Global Nuclear Energy Partnership (GNEP) aiming to form an international partnership to promote the use of nuclear power and close the nuclear fuel cycle in a way that reduces nuclear waste and the risk of nuclear proliferation. In 2010 the GNEP was renamed the International Framework for Nuclear Energy Cooperation (IFNEC). In the US, this decision was followed by large R&D investments for UREX+ (uranium extraction plus) systems.

1.2.2 European framework

As mentioned above, the EU is one of the leaders in the field of P&T and has developed a strong scientific network for enhancing research on P&T. Since the beginning of the 1990s, European research centres and universities have been working together in the framework of European projects to develop knowledge on actinides and P&T (see Figure 2).
Starting with FP2, a number of projects at European level performed research on P&T:

- Under FP2, two projects studied partitioning as part of the European call RADWASTOM-4C (Partition of high-level radioactive waste and High-level liquid waste partitioning by means of completely incinerable extractants).

- Under FP4, the IABAT project studied the possibility of transmutation in an accelerator-driven system and the EFTTRA project conducted transmutation experimentations on americium. Partitioning studies were performed in NEWPART.

- In FP5, transmutation studies were performed in the CONFIRM and the THORIUM CYCLE projects. Partitioning was studied in the PYROREP, PARTNEW and CALIXPART projects. The MUSE project developed analytical tools to calculate transmutation reactions, and the MASURCA project conducted experimentations on these reactions. In parallel, the TECLA project worked on all supporting activities for transmutation. The project ACTINET developed a network to study the actinides.

- Under FP6, PATEROS developed a roadmap of P&T and EUROPART studied the partitioning of minor actinides. ACTINET 6 also studied actinide chemistry.

- Under FP7, the ACTINET-i3 project focused on actinide sciences (chemistry, materials, environment), and ACSEPT studied the partitioning of minor actinides. The CINCH and CINCH-II projects were also supported within FP7 EURATOM in order to mitigate the effects of the decline of number of staff in nuclear chemistry, by improving the European capacity of research by educating and training young scientists. ASGARD studied the advanced/novel nuclear fuels fabrication and their respective reprocessing issues for Generation IV reactors. TALISMAN led and coordinated a network of actinide facilities across Europe, but also managed a network between facilities and users that increases our knowledge for a safer management of actinides. It also enhanced the efforts made to support education and training issues by continuing the ACTINET Summer School series and travel grant attributions for attending international conferences. MAXSIMA, by supporting the development of the MYHRRA experimental reactor, will help the decision-making on nuclear waste management and transmutation.

Within this context, research on P&T processes is coordinated in a wide European approach and explains the logical sequence in which the SACSESS and ACSEPT projects were born. ACSEPT selected the most promising P&T processes. SACSESS is continuing its work and aims to find the best solutions for the treatment of nuclear spent fuels, as well as assess the feasibility of an industrial solution to achieve a closed fuel cycle.

1.3 Methodology

The following steps describe the methodology used:

Step 1 – Mapping of actinide separation processes

With the purpose of having a complete list of all actinide separation processes, regardless of their maturity, a preliminary desktop analysis was carried out in a first step, identifying the main processes. The most promising processes in the world were selected.

Step 2 – Review of the actinide separation processes selected

In addition to the desktop study, a literature review identified the main characteristics of each process, its status and the main stakeholders involved. The same structure, divided into four sections, was used to review all processes facilitating comparison between them:

1. Description of the process’ main objective: the type of process and the elements removed from the spent nuclear fuel.

2. Presentation of the companies involved in the creation and development of the process and the context in which the process was developed.

3. In-depth description of the process (e.g. the chemical species used to recover the actinides (An), the quantities of each species used, the flowsheets of the process, etc.).

4. Assessment of the process’ status, including explanations of the tests performed in the process.

During this step, the presentation of the results depends on the type of process:
- For aqueous separation processes, a table is included summarising the main information on the process and evaluating the technology readiness level (TRL) based on the TRL definition provided below and in Figure 3.

- For pyrochemical processes, an additional section addresses the management of the wastes generated during the process. Conclusions and an evaluation of the TRL of the processes are provided as well.

To define the TRLs used in this report, 3 subgroups were created:

**Proof of concept: Grouping the lowest TRLs: 1, 2 and 3.**

- TRL 1: The first ideas of the process are defined. For example, the presentation of a potential new extraction process of actinides using a specific kind of chemical species.
- TRL 2: It corresponds to the first investigations on the feasibility of the process.
- TRL 3: It is related to the computer simulation of the process, defining the fundamental data for the experimentation.

**Proof of principle: Grouping intermediate TRLs: 4, 5 and 6.**

- TRL 4: It corresponds to the first tests in the lab, the experimental validation of the process without HLW (cold test), and the theoretical validation with HLW using simulated feed.
- TRL 5: The first tests using HLW (hot test) have been implemented.
- TRL 6: The validation of the process using HLW at a bigger scale has been reached.

**Proof of performance: Grouping the most advanced TRLs: 7, 8 and 9.**

- TRL 7: It corresponds to the first demonstration of the process under operational environment, i.e. the development of an engineered process.
- TRL 8: It implies that the demonstration of the process at a pilot scale has been reached.
- TRL 9: The final stage has been reached, i.e. a well-established process is feasible at the industrial scale.
In order to compare the different chemical processes, 5 key performance indicators were defined for each process:

1. **Elements removed**: The elements recovered by the means of the process.
2. **Main solvent used**: The key chemical molecules of each process.
3. **Number of stages**: The number of stages in the tests performed for each process.
4. **Evolution of the waste volume**: The comparison of the volume before and after the process.
5. **The Technology Readiness Level**

For both the aqueous separation and the pyrochemical processes, this study also details the expertise of the main stakeholders involved and the processes they have been working on.

### Step 3 – Interviews and final update

This last step comprised a series of interviews with scientific experts within the SACSESS project with a view to update the status and main characteristics of each process.

### 1.4 Overview of the processes

Over the past decades, worldwide researchers gave birth to numerous processes. The most promising ones feature in this report and are presented in Figure 4. This illustration presents the different processes, the country/region of creation, the type (hydro or pyro) and the flow of the processes and the products obtained with each of them.
2. PARTITIONING PROCESSES
PARTITIONING PROCESSES

The history of reprocessing dates back to the 1940s. In the UK, metal fuel elements from the Magnox generation gas-cooled reactor were reprocessed at Sellafield for about 50 years. In the US, three civil reprocessing plants were built between 1966-1977. In France, 400t/yr were reprocessed at Marcoule until 1997, and since 1976, 1700 t/yr have been reprocessed at La Hague. In Asia, India has two 100t/yr oxide fuel plants operating at Tarapur and Japan has an 800t/yr plant at Rokkasho. Russia also has an old 400 t/yr oxide fuel reprocessing plant at Ozersk, and is currently building a 3000 t/yr plant at Zheleznogorsk (IAEA, 2007).

Today all commercial reprocessing plants use the hydrometallurgical PUREX process or upgraded versions of this process (UREX, COEX”, etc.). However, they will not be covered in this report as they are already at an industrial step.

During the last decades, the nuclear power countries around the world have been developing new, more efficient processes of P&T in order to find better molecules that are cleaner, more stable under radiation and easier to use. Hence, the history of P&T is full of tries and development activities, which have led to the present situation and to the numerous processes.

This report focuses on the processes under development in two main areas, aqueous separation and pyrochemistry.

2.1 Aqueous separation processes

Aqueous or hydrometallurgical processes separate the minor actinides from high-level waste by individual processes. Those developed in the past are mainly considered as extensions of the PUREX process.

In this section, the various processes that have been or are currently being developed are sorted and described by type of extraction performed, namely:

- Processes co-extracting trivalent An and Ln
- Processes partitioning the trivalent An
- Processes separating trivalent An from Ln
- Processes separating Am from Cm or from HLW
- Processes co-separating all TRU

2.1.1 Processes co-extracting trivalent actinides and lanthanides

Among the processes that co-extract trivalent actinides and lanthanides, the TRUEX (Transuranic Extraction) process, the DIAMEX process, the TRPO process and the ARTIST process are detailed here.

2.1.1.1 TRUEX

2.1.1.1.1 Main objective

The TRUEX process is a solvent extraction process based on PUREX and aims to extract the transuranic elements (namely Pu, U, americium (Am), and curium (Cm)) from nuclear fuel wastes in order to reduce the alpha activity of these wastes (Herbst, 1995). However, when used after a PUREX process it can be used instead of a DIAMEX process, i.e. to co-extract An(III) and Ln(III).

2.1.1.2 Country/developer

The Argonne National Laboratory (ANL, USA) is the author of the TRUEX process, which was published in 1995.

2.1.1.3 Description

TRUEX is a solvent-extraction process that removes and recovers transuranic material from acid waste solution. This is done by using a solution of 1.4M tributylphosphate (TBP, see Figure 6) and 0.2M n-octyl(phenyl)-N,N-diisobutylcarbamoylmethylphosphine oxide (CMPO, see Figure 5) diluted with n-dodecane (nDD).
As shown in Figure 7, the TRUEX process is a 20-stage process split into 5 main steps: extraction, scrubbing, Am stripping, Pu stripping and the solvent clean-up.

- In the extraction stages (1 to 6), the nuclear used fuel is blended with a solution composed of 1.4 M of TBP, 0.2 M of CMPO diluted in nDD.
- The scrubbing (stage 7) is then done by adding a 2.0 M Al(NO₃)₃ solution to the mix.
- The Am is then stripped (stages 8 to 14) by adding acidity with a 0.04 M HNO₃ solution to the bath.
- The Pu stripping (stages 15 to 18) is done by adding a 0.28 M (NH₄)₂C₂O₃ solution to the organic phase resulting of the previous steps.
- The two final stages are used to clean up the solvent by adding a 0.25 M Na₂CO₃ solution.

As a result, five solutions are generated during the process: the nonTRU raffinate, the americium strip, the plutonium strip, the carbonate wash and the acid rinse waste.

- The americium product stream, which contains Am(NO₃)₃ and HNO₃, is concentrated by evaporation and stored in a lead protected mine for future use.
- The plutonium product stream, which also contains the uranium, is processed by evaporating it to dryness, then calcining the solids in an oven at more than 600°C temperature to produce PuO₂.
- The sodium carbonate solutions are acidified by adding nitric acid, and then recycled to the TRUEX process by mixing them with the feed for the next bath.
- The acid rinse solution is combined with the acidified carbonate. Recycling these solutions is completed to recover the TRU content of this waste.

2.1.1.4 Status of the process

Experimentations with this process have led to good results (David B. Chamberlain, 1996). Seven runs were processed and about 350 L of waste were treated. However, about three times that volume of low-level wastes were generated. The alpha decontamination factor has shown to be in the range between 4900 and 65 500 with final alpha activity at about 5 nCi/mL.
Several needs were identified during these experimentations, in particular the solvent degradation due to alpha activity.

Despite this issue, the TRUEX process is ready to be industrialised, although recently developed processes seem to be more promising (e.g. ALSEP).

The TRUEX process was developed by the Argonne National Laboratory (USA) and is currently under study at the Bhabha atomic research centre (India).

The TRL of this process is estimated to be between 5 and 7 because the entire system has been demonstrated.

### Preliminary conclusions

The main information on the process is summarised in the following table:

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu, Am</td>
<td>TBP &amp; CMPO</td>
<td>20</td>
<td>x3</td>
<td>TRL 5-7</td>
</tr>
</tbody>
</table>

### DIAMEX

#### Main objective

The DIAMEX process (DIAMide Extraction) is a solvent extraction process that co-extracts trivalent actinides and trivalent lanthanides (Ln) from PUREX raffinate.

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**Figure 8: DMBDTDMA**

**Figure 9: HEDTA**

**Figure 10: DIAMEX process (Courson, et al., 1999)**
As shown in Figure 10, the DIAMEX process is a 16-stage process split into four main steps: extraction, two scrubbing steps and An/Ln stripping.

- The organic phase of the extraction process is a solution composed of 0.5 M DMDBTDMA in kerosene. The feed, which is the PUREX HLW, containing 3.5 M HNO₃, 0.1 M oxalic acid and 0.02 of N-(2-hydroxyethyl)-ethylenediamine-N,N’,N’-triacetic acid (HEDTA, see Figure 9) as masking agents, is introduced in stage 6.
- The solution is then scrubbed a first time with 3.5 M HNO₃ and 0.3 M oxalic acid solution in stages 8 to 10.
- The solution is scrubbed a second time with a 1 M HNO₃ solution in stages 11 and 12. These three previous steps remove the fission products (FP), which will stay in the aqueous phase. The organic phase is then used in the next step.
- The last step of the DIAMEX process is the stripping of An and Ln with a 0.1 M HNO₃ solution.

### 2.1.1.2.4 Status of the process

This process has been studied in depth and is today ready to be deployed in an industrial plant according to existing knowledge (Geist & Gompper, 2008).

The TRL of the DIAMEX process is estimated between 6 and 7 because it is ready to be deployed at engineering scale.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>An &amp; Ln</td>
<td>DMDBTDMA</td>
<td>16</td>
<td>No data</td>
<td>TRL 6-7</td>
</tr>
</tbody>
</table>

### 2.1.1.3 TRPO

#### 2.1.1.3.1 Main objective

The TRPO partition process is a solvent extraction process designed to follow the PUREX process and aiming to extract the transuranic elements (namely Pu, Am and Cm) from spent nuclear waste in order to reduce its alpha activity.

#### 2.1.1.3.2 Country/developer

The TRPO process was developed in the early 1980s at the Tsinghua University in China. It was also researched in India.

#### 2.1.1.3.3 Description

The TRPO process is a solvent extraction process that recovers transuranic material from PUREX raffinate (for the initial version) or from nuclear spent fuel (for the extended version). It is also used to co-extract An(III) and Ln(III) from a Purex raffinate. In order to do that, a mixture of trialkyl phoshpine oxides is used (TRPO or CYANEX 923 (Figure 11) dissolved at 30% in kerosene).

![Figure 11: Cyanex 923 (R = hexyl, octyl)](image)

---

2.1.1.2.5 Preliminary conclusions

The main information on the process is summarised in the following table.
The TRPO process is a 20-stage process split into six main steps: extraction, scrubbing, An(III) + Ln(III) stripping, a second scrubbing, Np + Pu stripping, and stripping of U:

- In the extraction stages (1 to 6), the PUREX raffinate is blended with a solution composed of TRPO or CYANEX 923 dissolved at 30% in kerosene.
- The first scrubbing stages (7 to 8) are done by adding a 1 M HNO₃ solution to the mix.
- The An(III) + Ln(III) is then stripped (stage 9 to 12) by adding a 5.5 M HNO₃ solution to the mix.
- The second scrubbing stages (13 to 14) are done by adding a 0.6 M oxalic acid solution to the mix.
- Then the Np + Pu are stripped (stage 15 to 18) by adding a 0.6 M oxalic acid solution to the mix.
- Finally, the U is stripped with a 5% Na₂CO₃ solution.

### Status of the process
The process was first developed by the Institute of Nuclear and New Energy Technology (INET) at the Tsinghua University of Beijing and is still under study. It has also been hot tested at ITU (Germany).

The TRL of this process is estimated between 4 and 5 because it has been tested at laboratory scale.

### Preliminary conclusions
The main information on the process is summarised in the following table.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>U, Pu, Np, and trivalent actinides</td>
<td>TRPO</td>
<td>22</td>
<td>Not tested yet</td>
<td>TRL 4-5</td>
</tr>
</tbody>
</table>

2.1.1.4 ARTIST

2.1.1.4.1 Main objective
After years developing the four-group process in the frame of the OMEGA project, the Japan Atomic Energy Research Institute (JAERI), which is today called Japan Atomic Energy Agency (JAEA), realised that the stripping of Am-Cm from the DIDPA solvent used needed a high concentration of nitric acid. However, it then required too many denitration steps, which made the process seem unrealistic.

Considering these points, researchers at JAERI chose to develop a new chemical process to treat the spent fuel (SF). The main concept of the ARTIST (Amide-based Radio-resources Treatment with Interim Storage of Transuranics) process is to recover and store all actinides, uranium and mixture of transuranic elements separately.
2.1.1.4.2 **Country/developer**
JAEA has been studying the ARTIST process since 2000.

2.1.1.4.3 **Description**
As shown in Figure 15, the ARTIST process is composed of 2 main steps: an **exclusive extraction of uranium** and a **total recovery of transuranic elements** (TRUs), and several optional processes.

- The first step is an exclusive extraction of the hexavalent U. The main difficulty of this step is to succeed in discriminating between tetravalent An and hexavalent ones. In order to do that, they use a branched-alkyl monoamide (BAMA). For now the molecules tested are N,N-di(2-ethylhexyl) butanamide (D2EHBA, see Figure 13), the N, N-dihexyl-2-ethylhexanamide (DH2EHA, see Figure 14). The result of this extraction is UO2.

- The second step is an integrated extraction of all the remaining transuranic elements. To do that, a solution of N,N,N’,N’ tetraoctyl diglycolic amide (TODGA, see Figure 16), N,N-dihexyl octanamide (DHOA, see Figure 17) in n-dodecane (nDD) is used.

- The first optional step of the process is the recovery of Pu from the TRU stream, using the DHOA process (DHOA & TBP).
- The second optional step is the separation of actinides and lanthanides from the TRU stream. The Japanese Agency is currently working on the development of N-donor ligand with high separation factor, stable, and a sufficient high lipophilicity.
- The third and last optional step is the extraction of bivalent strontium (Sr) from the TRU stream. To do that, TODGA-n-dodecane solvent is used.

![Figure 13: D2EHBA](image13.png)

![Figure 14: DH2EHA](image14.png)

![Figure 15: ARTIST process (Tachimori, et al., 2010)](image15.png)

![Figure 16: TODGA](image16.png)

![Figure 17: DHOA](image17.png)
2.1.1.4.4 Status of the process
The ARTIST process is still at an early stage of development, but seems to be promising and feasible. This process is currently only studied at JAEA.

The TRL of this process is estimated between 2 and 3 because the concept has been demonstrated.

2.1.1.3.5 Preliminary conclusions
The main information on the process is summarised in the table below.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>U, TRU, (Pu, Cs, Sr, An, Ln)</td>
<td>D2EHBA or DH2EHA, TODGA &amp; DHOA</td>
<td>Not defined yet</td>
<td>Not tested yet</td>
<td>TRL 2-3</td>
</tr>
</tbody>
</table>

2.1.2 Processes partitioning the trivalent actinides
Among the processes that partition minor actinides, the DIDPA process and the SETFICS process are covered in this section.

2.1.2.1 DIDPA

2.1.2.1.1 Main objective
JAERI developed a partitioning process to separate elements in high-level liquid wastes into four groups: transuranium elements, Tc-platinum group metals (PGM), Sr-Cs and the remaining other elements.

The DIDPA process is a solvent extraction process used to separate the TRU elements from nuclear waste in order to decrease its radiotoxicity.

2.1.2.1.2 Country/developer
The DIDPA process has been developed since 1985 at JAERI, now JAEA (Japan).

2.1.2.1.3 Description
The DIDPA process is a solvent extraction process aimed at extracting actinides and lanthanides from nuclear waste. It is based on the use of di-isodecylphosphoric acid (DIDPA, see Figure 18), and the use of pentetic acid (DTPA, see Figure 19) in the second cycle of extraction to be able to extract Am and Cm.

As shown in Figure 20, the DIDPA process is a two-cycle process. The first cycle comprises 5 main steps: extraction, scrubbing and three stripping.

- In the first step two solutions are blended with an H2O2 solution: the solvent solution, which is composed of a 0.5 M DIDPA and 0.1 M TBP solution, and the feed solution in a 0.5 M HNO₃ solution. It allows extracting all of the non-transuranic elements (Cs, Sr, Tc, and PGM) in the aqueous phase by raising the temperature.
- The organic phase is then scrubbed with a solution of 0.5 M HNO₃ and 1.0 M H₂O₂.
- Strip I is done by acidifying the solution with a 4 M HNO₃ solution and rising up of the temperature.
- Strip II is done by adding a 0.8 M H₂C₂O₄ solution to the organic phase of the strip I step. This step allows getting back the Np and Pu in the aqueous phase.
- Strip III is done by adding a 1.5 M Na₂CO₃ solution to the organic phase of the strip II step. That step allows getting back the U.
The aqueous phase of the Strip I step is then used in a second cycle, which is composed of 3 steps: extraction, and two stripping. First, the acidity of the solution is adjusted with a 0.5 M HNO3 solution.

- The first step of the second cycle is an extraction: DIDPA solvent is added to the solution.
- The Strip IV is done by adding a 0.05 M DTPA solution to the organic phase of the extraction II step. That step allows to get back Am-Cm together in the aqueous phase.

Strip V is done by acidifying the organic phase of the Strip IV step by adding a 4 M HNO3 solution. That step allows getting back Ln in the aqueous phase.

2.1.2.1.4 Status of the process
Experimentations with this process were performed in 2000 and the results were good. Several runs of the process were performed and about 12.5 L of waste were treated. However, they generated about five times that volume of low-level wastes. (Tachimori, et al., 2010). This process is currently under study at JAEA in Japan.

The TRL of this process is estimated between 5 and 6 because it has been completely tested.

2.1.2.1.5 Preliminary conclusions
The main information on the process is summarised in the table below.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Np-Pu, U, Am-Cm, Ln</td>
<td>DIDPA</td>
<td>16</td>
<td>X5</td>
<td>TRL 5-6</td>
</tr>
</tbody>
</table>

Figure 20: DIDPA process (Kubota, et al., s.d.)

2.1.2.2 SETFICS

2.1.2.2.1 Main objective
The Solvent Extraction for Trivalent f-elements Intra-group Separation in CMPO-complexant System (SETFICS) process could be considered as a modified TRUEX process, as it is based on the same CMPO solvent. SETFICS aims to recover An & Ln from a raffinate of SOFT PUREX in order to decrease the radiotoxicity of nuclear wastes.

2.1.2.2.2 Country/ developer
The SETFICS process has been under development since 1997 at JAEA (Japan).
2.1.2.2.3 Description

The SETFICS process aims to extract An & Ln from a raffinate of PUREX. As for the TRUEX process, it is based on the use of a solution composed of 1.4 M tributylphosphate (TBP, see Figure 22), 0.2 M n-octyl(phenyl)-N,N-diisobutylcarbamoyl-methylphosphine oxide (CMPO, see Figure 21) diluted by n-dodecane (nDD). However, unlike the TRUEX process, a solution of hydrophilic carboxylic acid (DTPA, see Figure 23) is also used.

As shown in Figure 24, the SETFICS process is a 70-stage process with four main steps: extraction and three stripping.

- In the first step, the solvent (composed of a solution of 0.2 M CMPO, 1.4 M TBP in n-dodecane) is blended with the feed in the seventh stage of the extraction step, and then scrubbed with two solutions, 10 M HNO₃ in stage 9, and a 0.1 M HNO₃ solution in stage 16. The organic phase is then used for the next steps; the aqueous phase composes the first final product of the process, the raffinate.
- In the second step, the solvent is introduced in stage 1 and is blended with the organic phase resulting of step one in the stage 6, then stripped with a hydroxylammonium nitrate solution (HAN) at pH 2.0 in stage 19. The organic phase is then used for the next steps; the aqueous phase composes the second final product of the process, the acid waste.
- In the third step, the solvent is introduced in stage 1 and is blended with the organic phase resulting of step two in stage 5, then stripped with a solution of 0.05 M DTPA and 1.5 M HAN at pH 2.2 in stage 19. The organic phase is then used for the next steps; the aqueous phase composes the third final product of the process, the trivalent An product.
- In the fourth step, the organic phase resulting of step 3 is stripped with a solution of 0.02 M HNO₃ introduced in stage 16. The used solvent in the organic phase is then recycled, and the aqueous phase composes the Ln waste.
2.1.2.2.4 Status of the process

In 2010, the process had never been tested with actual high activity wastes (HAW). The process remains only theoretical (Funasaka, et al., 2000) and is only studied at JAEA.

The TRL of this process is estimated between 3 and 4 because it has been tested at laboratory scale but not with actual HAW.

2.1.2.2.5 Preliminary conclusions

The main information on the process is summarised in the table below.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>An (III), Ln (III)</td>
<td>CMPO &amp; TBP</td>
<td>70</td>
<td>Not tested yet</td>
<td>TRL 3-4</td>
</tr>
</tbody>
</table>

2.1.3 Processes separating trivalent actinide from lanthanide

Among the processes that separate actinides from lanthanides, the three kinds of SANEX processes, the CYANEX 301, the TALSPEAK process, the TRUSPEAK process, the TRUSQUEAK process and the ALSEP process are described in this section.

2.1.3.1 SANEX

2.1.3.1.1 r-SANEX

2.1.3.1.1.1 Main objective

The r-SANEX (regular-Selective Actinide Extraction) is a solvent extraction process developed in the frame of the NEWPART, PARTNEW, EUROPART and ACSEPT European programmes. This process aims to selectively extract the trivalent actinides (Am and Cm) from a DIAMEX raffinate.

2.1.3.1.2 Country/developer

The r-SANEX process has been developed in the frame of European programmes since the early 2000s by many European research centres, namely ITU (Germany), the University of Reading (UREAD – UK), KIT (Germany), JULICH (Germany), CEA (France), and Chalmers University (Sweden).

2.1.3.1.3 Description

r-SANEX is a solvent extraction process aiming to extract MA (minor actinides) from a DIAMEX raffinate.

For this, the most recent version of the r-SANEX process uses a solvent consisting of 6,6'-bis(5,5,8,8-tetramethyl-5,6,7,8-tetrahydro-benzo[1,2,4]triazin-3-yl)-[2,2'-bipyridine (CyMe4-BTBP, see Figure 25), and N,N,N',N'-Tetraoctyl Diglycolamide (TODGA, Figure 26) in 1-octanol.

2.1.3.1.4 Country/developer

The r-SANEX process has been developed in the frame of European programmes since the early 2000s by many European research centres, namely ITU (Germany), the University of Reading (UREAD – UK), KIT (Germany), JULICH (Germany), CEA (France), and Chalmers University (Sweden).

2.1.3.1.5 Description

r-SANEX is a solvent extraction process aiming to extract MA (minor actinides) from a DIAMEX raffinate.

For this, the most recent version of the r-SANEX process uses a solvent consisting of 6,6'-bis(5,5,8,8-tetramethyl-5,6,7,8-tetrahydro-benzo[1,2,4]triazin-3-yl)-[2,2'-bipyridine (CyMe4-BTBP, see Figure 25), and N,N,N',N'-Tetraoctyl Diglycolamide (TODGA, Figure 26) in 1-octanol.

2.1.3.1.6 Country/developer

The r-SANEX process has been developed in the frame of European programmes since the early 2000s by many European research centres, namely ITU (Germany), the University of Reading (UREAD – UK), KIT (Germany), JULICH (Germany), CEA (France), and Chalmers University (Sweden).

2.1.3.1.7 Description

r-SANEX is a solvent extraction process aiming to extract MA (minor actinides) from a DIAMEX raffinate.

For this, the most recent version of the r-SANEX process uses a solvent consisting of 6,6'-bis(5,5,8,8-tetramethyl-5,6,7,8-tetrahydro-benzo[1,2,4]triazin-3-yl)-[2,2'-bipyridine (CyMe4-BTBP, see Figure 25), and N,N,N',N'-Tetraoctyl Diglycolamide (TODGA, Figure 26) in 1-octanol.

2.1.3.1.8 Country/developer

The r-SANEX process has been developed in the frame of European programmes since the early 2000s by many European research centres, namely ITU (Germany), the University of Reading (UREAD – UK), KIT (Germany), JULICH (Germany), CEA (France), and Chalmers University (Sweden).

2.1.3.1.9 Description

r-SANEX is a solvent extraction process aiming to extract MA (minor actinides) from a DIAMEX raffinate.

For this, the most recent version of the r-SANEX process uses a solvent consisting of 6,6'-bis(5,5,8,8-tetramethyl-5,6,7,8-tetrahydro-benzo[1,2,4]triazin-3-yl)-[2,2'-bipyridine (CyMe4-BTBP, see Figure 25), and N,N,N',N'-Tetraoctyl Diglycolamide (TODGA, Figure 26) in 1-octanol.

As shown in Figure 28, the r-SANEX process is a 16-20-stage process with three main steps: extraction, scrub, and stripping.

- The first step of this process (stage 1-12) is extraction. The organic phase is composed of 15 mM CyMe4-BTBP, 5 mM TODGA in octanol. The feed introduced in stage 12 is a DIAMEX raffinate in a 1.3 M HNO3 solution. The older version of the r-SANEX used 15 mM CyMe4-BTBP, 0.25 M DMDOHEMA in octanol as solvent solution and the feed was in a 2 M HNO3 solution. However, since the SACSESS European project, an alternative to CyMe4-BTBP has been studied: the Bis-2,6-(5,6,7,8-tetrahydro-5,9,9-trimethyl-5,8-methano-1,2,4-benzotriazin-3-yl)pyridine (CA-BTP, see Figure 27).
• The second step (stage 12-16) is scrubbing with a 0.7 M HNO₃ solution. In the older version of the r-SANEX process, the scrubbing was done by a 0.5 M HNO₃ solution.

• The final step of the process (stages 7-20) is the stripping of the trivalent actinides using a 0.5 M glycolic acid solution, as the older version of the r-SANEX process.

This process recovers all of the trivalent actinides with good efficiency (> 99%).

2.1.3.1.1.4 Status of the process
This process is currently studied as part of the European SACSESS project. New solvents are being tested but some issues still need to be addressed such as the clean-up of solvent or the effects on the radiotoxicity of the waste.

2.1.3.1.1.5 Preliminary conclusions
The main information on the process is summarised in the table below.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>An(III), Ln(III)</td>
<td>DMDOHEMA/ CyMe₄-BTBP</td>
<td>20</td>
<td>Not studied yet</td>
<td>TRL 4-5</td>
</tr>
</tbody>
</table>

This process was studied at CHALMERS (Sweden) in the past and is currently under study at CTU (Czech Republic), IIC (Czech Republic), UNISTRA (France), JULICH (Germany), KIT (Germany), POLIMI (Italy), UNIPR (Italy), ICTCH (Poland), and ULANC (UK).

The TRL of this process is estimated between 4 and 5 because it has been tested at laboratory scale but some choices still need to be made and tests are still ongoing.
2.1.3.1.2 i-SANEX

2.1.3.1.2.1 Main objective

i-SANEX (innovative-Selective Actinide Extraction) is a solvent extraction process developed in the frame of the European ACSEPT project. This process aims to extract selectively the minor actinides (Am and Cm) directly from a PUREX raffinate, avoiding the DIAMEX step.

2.1.3.1.2.2 Country/developer

The i-SANEX process has been developed since 2008 in the frame of European programmes by many European research centres, namely ITU (Germany), KIT (Germany), JULICH (Germany), Uni Parma (Italy) and PoliMI (Italy).

2.1.3.1.2.3 Description

The i-SANEX process is a solvent extraction process aiming to extract MA from a PUREX raffinate. In order to do that, N,N,N',N'-Tetraoctyl Diglycolamide (TODGA, see Figure 30) is used as a solvent to co-extract An(III) and Ln(III) and 2,2',2'',2'''-[(1R,2R)-1,2-Cyclohexanediyldinitrilo] tetraacetic acid (CDTA, see Figure 31) is used in the feed to prevent the extraction of Zirconium (Zr) and Palladium (Pd).

In the second part of the process, SO₃-Ph-BTP (Figure 32) is used to selectively strip the remaining An (Wilden, et al., 2012).

As shown in Figure 33, the i-SANEX process is a 32-stage process with six main steps: extraction, two scrubs, a second extraction and two strips.

- In the first step, the solvent composed of 0.2 mol/L TODGA + 5% 1-octanol in TPH is introduced in stage 1. The feed is introduced in stage 4 in a 4.5 mol/L HNO₃ and 0.05 mol/L CDTA solution. This step allows extracting the Zr and Pd in the raffinate. Currently, other molecules are being tested in the framework of the SACSESS project: the 2-(2-(dioctylamino)-2-oxoethoxy),N,N-dioctyl-propanamide (TWE21, see Figure 34) instead of TODGA, and the N-{2-[Bis(carboxymethyl)amino] ethyl}-N-(2-hydroxyethyl)glycine(HEDTA, see Figure 35) instead of the CDTA.
2.1.3.1.2.4 Status of the process

This process is being studied in the European SACSESS project. New solvents are being tested and some issues are still to be addressed, such as the clean-up of solvent or the effects on the radiotoxicity of the waste (Magnusson, et al., 2012)(Galán, et al., 2014).

This process is currently under study at IIC (Poland) UNISTRA (France), JULICH (Germany), KIT (Germany) POLIMI (Italy), UNIPR (Italy), ICHTJ (Poland), CIEMAT (Spain), NNLI (UK), ULANC (UK) and UREADS (UK).

The TRL of this process is estimated between 4 and 5 because it has been tested at laboratory scale but some choices still have to be made and some tests are ongoing.
As shown in Figure 39, the 1c-SANEX process is a 32-stage process with five main steps: extraction, three scrubs and one strip.

- In the extraction step (stages 1-12), the solvent, which is composed of 0.015 M CyMe-BTBP, 0.005 M TODGA in TPH/1-octanol (40/60) solution, and the feed from PUREX acidified with a 3 M HNO₃ and 0.3 M oxalic acid solution.

- A scrubbing with a 1 M HNO₃ and 0.2 oxalic acid solution is then applied. It allows recovering the loaded solvent used in the next step in the organic phase and the raffinate in the aqueous phase, which contains most of the fission and activation products.

- Because the Pd is co-extracted with the trivalent actinides in the previous steps, another extraction has to be done. The two following scrubbing steps serve this purpose: the loaded solvent is refreshed with a new one, and blended with a 1 M HNO₃, 0.01 M L-cysteine solution. The aqueous phase, resulting of these two steps, now contains the Pd.

- In the final step, the organic phase from the previous steps is stripped with a 0.5 M glycolic acid solution at pH 4. It allows recovering An(III) in the aqueous phase.

2.1.3.1.3.4 Status of the process
This process is currently studied as part of the SACSESS project. New solvents are being tested and issues still need to be addressed, such as the clean-up of solvent and the effects on the radiotoxicity of the waste. (Wilden, et al., 2010), (Wilden, et al., 2013)
This process has been studied at JÜLICH (Germany) and is currently under study at CTU (Czech Republic), IIC, (Czech Republic), UNISTRA (France), KIT (Germany), POLIMI (Italy), at UNIPR (Italy), ICHTJ (Poland), and ULANC (UK). However, the 1c-SANEX process has never been hot tested.

The TRL of this process is estimated between 3 and 4 because it has been tested at laboratory scale but never hot tested, some choices still need to be made, and tests are still ongoing.

**2.1.3.2 CYANEX 301**

**2.1.3.2.1 Main objective**

The Cyanex 301 process is a solvent extraction process using the bis(2,4,4-trimethylpentyl)dithio phosphonic acid (Cyanex 301) as main solvent. It aims to selectively extract the An from a solution with low acidity.

**2.1.3.2.2 Country/developer**

The Cyanex 301 process has been developed by the Tsinghua University of Beijing (China) since 1995. However, the Argonne Laboratory (USA) has also worked on it when developing the UREX+ process.

**2.1.3.2.3 Description**

The Cyanex 301 process is a solvent extraction process aiming to selectively extract the actinides from a TRPO raffinate (CHEN, et al., 2012). The process is mainly based on bis(2,4,4-trimethylpentyl)dithio phosphonic acid (Cyanex 301, see Figure 40).

As shown in Figure 41, the CYANEX 301 process is a 3-step process: one extraction, one scrubbing and one stripping.

In the first step, the extraction (stages 1 to 7), the feed containing 241An and, Ln and 0.8 M NaOH (pH 3.5) is blended with the solvent solution (0.5 m Cyanex 301-keosene with a saponification of 2 mol %). The mix is then scrubbed (stages 8 to 10) with a 0.1 HNO3 solution at pH 3.5. The loaded organic phase is finally stripped (stages 11 to 14) with a 1.0 M HNO3 solution. It allows recovering the An (III) in the aqueous phase.
2.1.3.2.4 Status of the process
Hot tests were performed at Tsinghua University in 2012. However issues remain with this process, such as the fact that the extraction only worked at very low feed acidity (pH = 3) and the radiolytic stability of the extractant is limited (Touron, et al., 2008).

The TRL of this process is estimated between 4 and 5 because it has been successfully tested at laboratory scale.

2.1.3.2.5 Preliminary conclusions
The main information on the process is summarised in the table below.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>An (III) Cyanex 301</td>
<td>14</td>
<td>Not studied yet</td>
<td>TRl 4-5</td>
<td></td>
</tr>
</tbody>
</table>

As shown in Figure 45, the TALSPEAK process has three steps: two extractions steps and one stripping.

- In the first step, the raffinate from the UREX process is introduced with a 1 M of lactic acid solution in a bath. The two phases of the mix are composed of a 0.5 M HDEHP (DEHPA) solution in DIPB (Figure 45) for the organic phase and 1 M lactic acid, 0.1 M DTPA at pH 3.0 for the aqueous phase. The aqueous phase recovered at the end of this step contains the main FP wastes.

- The organic phase of step 1 is then introduced after being acidified at pH 1.5 in a mix. The two phases composing the mix are a 0.3 M HDEHP (DEHPA) solution in N-dodecane for the organic phase and 1 M lactic acid, 50 mM DTPA at pH 1.5 for the aqueous phase.

- In the final step (the stripping), the organic phase of step 2 is blended in a mix of two solutions: a 0.3 M HDEHP solution in N-dodecane for the organic phase and a 1 M HNO3 solution for the aqueous one. It allows recovering the trivalent actinides (Am & Cm) in the aqueous phase.
2.1.3.3.4 Status of the process
Many countries have significant experience with this process. However, some disadvantages have been noticed such as difficulties related to solvent clean-up, the need for adjusting the pH of the feed and the limited loading of metal ions in the solvent. The process seems to be ready for testing at a bigger scale.

This process has mainly been studied at ORNL, USA.

The TRL of this process is estimated between 4 and 5 because it has been fully tested at laboratory scale but the behaviour of some elements is still not well understood, and more tests need to be performed.

2.1.3.3.5 Preliminary conclusions
The main information on the process is summarised in the following table.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>An(III)</td>
<td>HDEHP (DEHPA)</td>
<td>Not known</td>
<td>Not tested yet</td>
<td>TRL 4-5</td>
</tr>
</tbody>
</table>

2.1.3.4 TRUSPEAK

2.1.3.4.1 Main objective
The TRUSPEAK process is a process combining the extractant from the TRUEX and TALSPEAK processes (TRUEX & TALSPEAK), and aiming to separate MA from nuclear fuel wastes. It is expected to offer an alternative to the American UREX+ processes.

2.1.3.4.2 Country/developer
The TRUSPEAK process was developed in the early 2000s at the Pacific Northwest National Laboratory (PNNL) and Argonne National Laboratory (USA).

2.1.3.4.3 Description
As a combination of the TALSPEAK and TRUEX processes, CMPO (Figure 46) and HDEHP (Figure 47) are mainly used as extracting agents.

![Figure 45: TALSPEAK process (Weaver & Kappelmann, 1964)](image1)

![Figure 46: CMPO](image2)

![Figure 47: DEHPA (HDEHP)](image3)
PARTITIONING PROCESSES

The initial concept was to combine a neutral donor extractant with an acidic one to yield a hybrid solvent system for separating MA from acidic HLW. Two main steps were considered:

- A first step, where the neutral extractant co-extracts MA & Ln, from HNO₃.
- A second step, where the acidic extractant selectively strips the MA with polyaminocarboxylate ligand.

The composition of the solvent has been established: it is 0.1 M CMPO and 1 M HDEHP in n-dodecane.

2.1.3.4 Status of the process
In 2009, the feasibility of the TRUSPEAK concept was established (Lumetta, et al., 2010). However, some issues have been brought to light: the minor actinide stripping is highly pH dependent, a synergic extraction behaviour of Am in the MA stripping regime limits the separation factor, and the MA and Ln distribution ratio values decreased with increasing [HNO₃] (Lumetta & Gelis, 2014).

This process is currently studied at ORNL (USA) and ANL (USA).

The TRL of this process is estimated between 2 and 3 because the concept has been demonstrated but no tests have been run.

2.1.3.5 Preliminary conclusions
The main information on the process is summarised in the table below.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>An(III)</td>
<td>CMPO &amp; HDEHP</td>
<td>Not yet established</td>
<td>Not studied yet</td>
<td>TRL 2-3</td>
</tr>
</tbody>
</table>

2.1.3.5 TRUSQUEAK

2.1.3.5.1 Main objective
The TRUSQUEAK process combines the extractant from the TRUEX and the TALSQUEAK processes (TRUEX & TALSQUEAK), and aims to separate MA from nuclear fuel wastes. It should offer an alternative to the American TRUSPEAK process.

2.1.3.5.2 Country/developer
The Pacific Northwest National Laboratory (PNNL) and the Argonne National Laboratory (USA) developed the TRUSQUEAK process in the early 2000s.

2.1.3.5.3 Description
As a combination of the TALSQUEAK and TRUEX processes, CMPO (Figure 48) and HEH[EHP] (Figure 49) are mainly used as extracting agent.

As for the TRUSPEAK process, the initial concept of TRUSQUEAK was to combine neutral donor extractant with acidic extractant to yield a hybrid solvent system for separating MA from acidic HLW.

Two main steps were considered:

- A first step, wherein the neutral extractant co-extracts MA & Ln from HNO₃.
- A second step, wherein the acidic extractant selectively strips the MA with polyaminocarboxylate ligand.

The composition of the solvent has been established: 0.2 M CMPO and 1 M HEH[EHP] in n-dodecane (Lumetta, et al., 2010).
2.1.3.5.4 Status of the process
Some improvements have been achieved when compared to the TRUSPEAK process:

- The MA and Ln extraction from HNO₃ is far better than in the TRUSPEAK process.
- The process is less dependent on the pH than in the TRUSPEAK process.
- In addition, there is less synergism in the distribution behaviour of Am in the MA stripping regime than in the TRUSPEAK process.

However, some issues remain:

- MA and Ln distribution ratio values for extraction from HNO₃ are modest (<10).
- These values decrease at [HNO₃] > 2 mol.L⁻¹.

This process is currently under study at PNNL (USA) and at ANL (USA).

The TRL of this process is estimated between 2 and 3 because the concept has been demonstrated, but no tests have been run.

2.1.3.5.5 Preliminary conclusions
The main information on the process is summarised in the following table.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>An(III)</td>
<td>CMPO &amp; HEH[EHP]</td>
<td>Not yet established</td>
<td>Not studied yet</td>
<td>TRL 2-3</td>
</tr>
</tbody>
</table>

2.1.3.6 ALSEP

2.1.3.6.1 Main objective
The ALSEP (Actinide-Lanthanide Separation) process is the last P&T process developed in the USA. This is a patented process that aims to directly separate the Am/Cm product from lanthanides from a raffinate of TBP cycle, as PUREX.

2.1.3.6.2 Country/developer
ALSEP is a patented process since January 2013 and belongs to the US Department of Energy (DOE).

2.1.3.6.3 Description
ALSEP is the third generation of processes developed by the US DOE. It uses a solvent composed of DGA (Diglycolamine Agent) extractant + HEH[EHP] (Figure 50). For now, two DGA extractants are being investigated: T2EHDGA (Figure 51) and TODGA (Guelis, 2013).

As shown in Figure 52, the ALSEP process is a 5-step process: one extraction, two scrubbing and two stripping.

- In the first step the solvent (HDEHP or HEH[EHP]/TEHDGA or TODGA in n-dodecane) is blended with the feed in HEDTA. The reference solvent presently tested is a 0.05 M T2EHDGA + 0.7 M HEH[EHP] solution. In this extraction region, the aqueous phase contains the raffinate with the main fission products.
- The organic phase of the extraction step is then scrubbed by an oxalic and HEDTA solution.
- The organic phase of the first scrubbing step is then scrubbed by a citric acid solution.
- Then the organic phase resulting of the two scrubbing phases is stripped with a DTPA (Figure 53)/citrate solution at pH 4. This step allows to selectively strip the Am/Cm in the aqueous phase.
• In the last step, the organic phase resulting from all the previous steps is stripped with another DTPA/citrate solution at pH 5. This step allows recovering the Ln in the aqueous phase and the spent solvent in the organic one.

2.1.3.6.4 Status of the process
ALSEP is the current process supported by the US DOE and was patented in 2013. Tests have been carried out but some issues remain such as the procedures of solvent washing. An ALSEP demonstration with alpha-active material is planned between 2015-2016. However, there are no plans for testing with actual spent fuel.

This process is currently under study at ANL (USA).

The TRL of this process is estimated between 2 and 3 because the concept has been demonstrated but no tests have been run.

2.1.3.6.5 Preliminary conclusions
The main information on the process is summarised in the following table.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am/Cm &amp; Ln</td>
<td>T2EHDGA/TODGA &amp; HEH[HEDTA]</td>
<td>Not yet established</td>
<td>Not studied yet</td>
<td>TRL 2-3</td>
</tr>
</tbody>
</table>

2.1.4 Processes separating americium from curium or from high-level waste

Among the processes that separate Am from Cm, the EXAm process is described in the following section. Other similar processes were tested LUCA (Modolo, et al., 2010), DIAMEX II or SESAME (Donnet, et al., 1997), but they produced a Cu pure flow. The EXAm process only produce Am pure flow.

2.1.4.1 EXAm

2.1.4.1.1 Main objective
The EXAm (Extraction of Americium) process is a solvent-extraction process that aims at recovering americium alone contained in the PUREX raffinate.
2.1.4.1.2 Country/developer
EXAm is a French process developed by the CEA in the framework of the 2006 Waste Management Act.

2.1.4.1.3 Description
The EXAm process (Rostainga, et al., 2012), (Vanel, et al., 2012) is a solvent-extraction process aiming to selectively extract the Americium from a PUREX raffinate. The process is mainly based on N, N'-dimethyl-N, N'-dioctylhexylethoxymalonamide (DMDOHEMA see Figure 54) and Bis-(2-Ethylhexyl) Phosphoric Acid (HDEHP, Figure 55) in HTP.

As shown in Figure 56, the EXAm process is a 6-step process: **one extraction, two scrubbing** and **three stripping**.

- In the first step of extraction, the feed diluted in HNO₃ with a concentration higher than 4 M and TEDGA (Figure 57) is blended with the extraction solvent composed of 0.6 M DMDOHEMA, 0.3 M HDEHP in HTP solution.

![Figure 57: TEDGA](image)

- In the second step, the mix of the previous step is scrubbed by a TEDGA and HNO₃ solution. The two first steps allow to remove most of the non-relevant fission products and of Cm, Eu, Sm, Gd, Y and Zr in the aqueous phase.
- The third step aims to remove Mo, Pd and Ru in the organic phase by stripping them with a NaOH solution and a buffer solution at pH 3.
- The resulting organic phase is then scrubbed of Ln allowing the stripping of Am by a HEDTA (Figure 58) + citric acid solution at pH 3.

![Figure 56: EXAm process (Rostaing, et al., 2012)](image)
• The remaining fission products in the organic phase (such as Ln and Fe) are then stripped by a 1 M HNO3 solution.

2.1.4.1.4 Status of the process
Hot testing of the entire process using a genuine PUREX raffinate was carried out in April 2010, and the feasibility of the EXAm concept was demonstrated.

This process is currently under study at CEA (France).

The TRL of this process is estimated between 4 and 5 because it has been successfully tested at laboratory scale.

2.1.3.5.5 Preliminary conclusions
The main information on the process is summarised in the following table.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am</td>
<td>DMDOHEMA + HDEHP in HTP</td>
<td>68</td>
<td>Not studied yet</td>
<td>TRL 4-5</td>
</tr>
</tbody>
</table>

2.1.5 Processes co-separating all transuranic elements

Among the processes that co-separate transuranic elements, the GANEX 1st cycle and the three GANEX 2nd cycle processes (CEA GANEX, EURO-GANEX, CHAMLEX are described in this section. These processes aim to provide fuels used in fast reactors.

2.1.5.1 GANEX 1st cycle

2.1.5.1.1 Main objective
The GANEX (Group Actinide Extraction) 1st cycle process is a solvent extraction process aiming to remove the bulk of uranium from high-level wastes (HLW).

2.1.5.1.2 Country/developer
The GANEX 1st cycle process has mainly been developed by CEA (Marcoule, France).

2.1.5.1.3 Description
The GANEX 1st cycle is a solvent extraction process mainly based on the DEHiBA (Figure 59) (Miguiditchian, et al., 2009) solvent (N,N-di-(ethyl-2-hexyl)isobutyramid).

As shown on Figure 60 the GANEX 1st cycle is a three-step process: one extraction, one scrubbing and one stripping.

• In the extraction step (stages 1 to 12), the feed in a 6 m HNO3 solution is blended with the Solvent solution (1 M DEHiBA in an industrial aliphatic solvent, HTP). The aqueous phase recovered at this step is the theoretical input of all the GANEX 2nd cycle processes.
• In the scrubbing step (stages 13 to 20), the organic phase is washed with a solution of N2H4 and HNO3.
• In the last step of this process (stages 21 to 28), the loaded solvent is blended with a stripping solution of 0.01 M HNO3, allowing to recover the uranium in the aqueous phase.
2.1.5.4 Status of the process
Hot tests were led by CEA in 2009. The results are promising and the process has produced enough GANEX 2nd cycle feed for testing it.

The TRL of this process is estimated to be between 6 and 7 because it has been successfully tested at laboratory scale and is ready to be incorporated to a complete GANEX process.

2.1.3.5.5 Preliminary conclusions
The main information on the process is summarised in the following table.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>U, GANEX 2nd cycle feed</td>
<td>DEHiBA 28</td>
<td>Not studied yet</td>
<td>TRL 6-7</td>
<td></td>
</tr>
</tbody>
</table>

2.1.5.2 GANEX 2nd cycle
The first cycle of the GANEX process is common to the following three processes: CEA GANEX, EURO-GANEX and CHALMEX.

2.1.5.2.1 CEA GANEX

2.1.5.2.1.1 Main objective
The GANEX 2nd cycle from the CEA is a solvent extraction process aiming at extracting all of the transuranic elements (Np, Pu, Am, Cm). The CEA GANEX process is mainly based on the DIAMEX-SANEX process. However, the solvents have been modified to take into account the presence of Np and Pu along with the trivalent MA.

2.1.5.2.1.2 Country/developer
The French CEA in Marcoule is the main developer of the CEA GANEX process.

2.1.5.2.1.3 Description
The CEA GANEX is a solvent extraction process aiming at extracting all the transuranic elements from the GANEX 1st cycle raffinate. In order to achieve this objective, the process uses a mix between DMDOHEMA (Figure 61) and HDEHP (Figure 62) as solvent.
As shown in Figure 63, the CEA GANEX is a 5-step process: one extraction, one scrubbing, the specific Mo, Tc stripping, the actinide stripping and the Ln, Y, Zr, Fe stripping.

- In the extraction step (stages 1 to 8), the feed solution (composed of the GANEX 1st cycle raffinate with 3-4 M of HNO₃) is blended with the solvent (composed of DMDOHEMA + HDEEHP in HTP).
- In the second step (stages 9 to 12), the previous mix is washed with a HNO₃ and a complexing agent solution. These two previous steps allow to remove all the non-extractible FPs, and to load the organic phase of all the extractible FPs.
- In the third step (stages 13 to 20), the molybdenum and the technetium are selectively stripped from a mix between the loaded organic phase of the previous steps and fresh solvent, with a carboxylic acid used to buffer the pH.
- In the fourth step (stages 21 to 40), the actinides are selectively stripped from a mix between the organic loaded phase of the previous step and fresh solvent by a mixture of an aqueous complexing agent and a reductive agent in buffered conditions. This step allows recovering the trivalent actinides (N, Pu, Am, Cm) in the aqueous phase.
- In the final step, the remaining extractible FPs and the lanthanides are stripped from the loaded organic phase of the previous step by the mixture of aqueous complexing agents in nitric acid.

2.1.5.2.1.4 Status of the process

In 2006 the GANEX 2nd cycle process was chosen as the solvent. Moreover, the CEA in Marcoule performed hot tests of this process in 2009 at laboratory scale (Miguirditchian, et al., 2009).

However the results on the An/Ln separation rate are much lower than expected due to a too long equilibrium reaching time.

This process has been studied at CEA (France), and is currently under study at CTU (Czech Republic), IIC (Czech Republic), JULICH (Germany), KIT (Germany), POLIMI (Italy), UNIPR (Italy), TWENTE (The Netherlands), ICHTJ (Poland), ULANC (UK) and UREADS (UK).

The TRL of this process is estimated to be between 4 and 5 because its feasibility has been demonstrated but is currently undergoing testing at laboratory scale.

2.1.5.2.1.5 Preliminary conclusions

The main information on the process is summarised in the following table.
2.1.5.2.2 CEA GANEX

2.1.5.2.2.1 Main objective
The EURO-GANEX (European GANEX) is a variation of the CEA GANEX developed within the European project ACSEPT. With the same purpose as the CEA GANEX, this process was developed in order to co-separate all transuranic elements from the GANEX 1st cycle.

2.1.5.2.2.2 Country/developer
EURO-GANEX was developed within the European collaborative project ACSEPT, and is being further developed in the follow-up project, SACSESS. This process was particularly studied at CEA (France), JULICH (Germany), KIT (Germany) and is currently under testing at UNISTRA (France), CIEMAT (Spain) and NNL (UK).

2.1.5.2.2.3 Description
The EURO-GANEX, as a variation of the CEA GANEX, is a solvent extraction process aiming to co-separate all transuranic elements. For this, a solvent consisting of TODGA (Figure 64) + DMDOHEMA (Figure 65) in kerosene is used.

* In the An + Ln extraction (stages 1 to 12), the solvent (composed of 0.2 M TODGA, 0.5 M DMDOHEMA diluted in Exxsol D80) is blended with the feed (composed of raffinate of GANEX 1st cycle, 5.9 M HNO3 and 0.055 M CDTA). In this step, the adding of CDTA (Figure 66) prevents the extraction of Pd and Zr.

* The mix of the previous phase is then washed with a 0.5 M HNO3 solution in the first stripping step (stages 13 to 16). The two previous steps allow the loading of the organic phase with the actinides and lanthanides.

* After these steps, the loaded solvent is blended with fresh solvent in the second extraction step (stages 17 to 22). This step is used to extract the lanthanides, which are back extracted with the actinides in the following step.

* In the first stripping step (stages 23 to 26), they blend the previous mix with the back extraction solution (composed of 0.055 M SO3-Ph-BTP (Figure 68), 1 M AHA (Figure 67) and 0.5 M HNO3). These two previous steps allow recovering the transuranic elements (Np, Pu, Am, Cm).

* In the final step (stages 27 to 30), the lanthanides are back-extracted from the organic phase with a stripping solution of 0.5 M HNO3.
2.1.5.2.2.4 Status of the process

Hot tests of the EURO-GANEX were carried at ITU in 2014, and this kind of GANEX 2nd cycle was successfully demonstrated. Although TRU losses were observed, the research team believes that increasing the number of stages may minimise them (Malmbeck, et al., 2014).

Within SACSESS, TWE21 (Figure 70) is tested to replace TODGA and CA-BTP (Figure 71) for SO3-Ph-BTP.

2.1.5.2.2.5 Preliminary conclusions

The main information on the process is summarised in the following table.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Np+Pu+Am+Cm</td>
<td>DMDOHMA &amp; TODGA</td>
<td>30</td>
<td>Not studied yet</td>
<td>TRL 4-5</td>
</tr>
</tbody>
</table>

2.1.5.2.3 CHALMEX

2.1.5.2.3.1 Main objective

CHALMEX (Chalmers GANEX) is a variation of the CEA GANEX developed within the European project ACSEPT. Like the CEA GANEX, this process allows to co-separate all transuranic elements from GANEX 1st cycle.

2.1.5.2.3.2 Country/developer

The CHALMEX is a process that was developed within the European collaborative project ACSEPT, and is further

Figure 69: EURO-GANEX process (ACSEPT)

Figure 70: TWE21

Figure 71: CA-BTP

This process has been studied at CEA (France), JULICH (Germany), KIT (Germany) and is currently under testing at UNISTRA (France), CIEMAT (Spain) and NNL (UK).

The TRL of this process is estimated between 4 and 5 because its feasibility has been demonstrated and it has been hot tested at ITU, but is currently being tested at laboratory scale.
studied today in the SACSESS project by CHALMERS University (Sweden).

2.1.5.2.3.3 Description
CHALMEX, as a variation of the CEA GANEX, is a solvent extraction process aiming to co-separate all transuranic elements. For this, a solvent containing CyMe4-BTBP (Figure 72) + TBP (Figure 73) is used.

Due to well-known issues with TBP, another extractant, DEHBA, is also been investigated (Figure 74).

2.1.5.2.3.4 Status of the process
The theoretical feasibility of CHALMEX has been assessed. However, neither cold tests nor hot tests have been performed (ANEHEIM, 2012). Process calculations were done, and a mini hot test in tube was performed. The process is still under study at CHALMERS (Sweden).

The TRL of this process is estimated between 2 and 3 because its feasibility has been theoretically demonstrated but only mini tests have assessed its feasibility.

2.1.5.2.3.5 Preliminary conclusions
The main information on the process is summarised in the following table.

<table>
<thead>
<tr>
<th>Elements Removed</th>
<th>Main Solvent</th>
<th>Number of Stages</th>
<th>Evolution of the Volume of Wastes</th>
<th>TRL scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Np+Pu+ Am+Cm</td>
<td>CyMe4-BTBP &amp; TBP</td>
<td>Not yet known</td>
<td>Not studied yet</td>
<td>TRL 2-3</td>
</tr>
</tbody>
</table>

2.2 Pyroprocesses
The Electrolytic/electrometallurgical processing techniques or pyroprocesses were developed to separate nuclides from a radioactive waste stream. The main stakeholders working on these partitioning processes are the Argonne Laboratory (USA), the Korea Atomic Energy Research Institute (Korea), the Research Institute of Atomic Reactors (Russia) and more recently, partners of the European collaborative projects ACSEPT and SACSESS.

Pyroprocesses involve several stages including volatilisation; liquid-liquid extraction using immiscible metal-metal phases or metal-salt phases; electrolytic separation in molten salt; and fractional crystallisation. They are generally based on the use of either fused salts such as chlorides or fluorides (e.g. LiCl+KCl or LiF+CaF2) or fused metals such as cadmium, bismuth or aluminium. They are most readily applied to metal rather than oxide fuels, and are envisaged for fuels used in Generation IV reactors.

Among the processes in this chemistry field, the US and EU electrorefining, the liq-liq extraction in molten fluoride salts, the Dimitrovgrad Dry Process and the KAERI processes are covered in the following section.

However, due to the particularities of these processes and to their significant structure differences, no summary tables are provided.

2.2.1 US Electrorefining
The American researchers from ANL developed two versions of electrorefining: a first one aiming to recover only the uranium element, and a second that allows to recover all of the transuranic elements.
2.2.1.1 Main objective
This pyrochemical process was an innovative recycling method used in the US integral fast reactor programme. The overriding goals in the development of this pyroprocessing technology were to establish a process that is economically viable, resistant to the diversion of nuclear materials and proliferation of nuclear weapons, and efficiently operable with minimum generation of waste products.

2.2.1.2 Country/developer
The Argonne National Laboratory (USA) developed this pyrochemical electrorefining process in 1991.

2.2.1.3 Description
This pyrochemical process was designed to treat the IFR spent fuel. It allows recovering pure uranium at a solid mandrel cathode, and a mixture of plutonium, americium, neptunium, curium, uranium and some rare earth fission products at a liquid cadmium cathode suspended in the electrolyte salt.

The process begins with dismantling the irradiated fuel assembly and removing individual fuel rods. These fuel rods are sent to a chopper, where they are cut into short lengths (typically 6-7 mm). The chopped fuel rod segments are loaded into perforated steel baskets and placed in an electrorefiner.

A schematic diagram of the electrorefining part of the process is shown on Figure 75.

The operation of the electrorefiner is the key step of this process; it separates the actinides elements from the fission products present in the spent fuel.

In the IFR electrorefiner, virtually pure uranium is collected at a solid mandrel cathode, and a mixture of plutonium, americium, neptunium, curium, uranium, and some rare earth fission products is collected at a liquid cadmium cathode suspended in the electrolyte salt. The remaining fission products are collected in the salt and in the cadmium layer below the salt.

2.2.1.4 Status of the process
The ANL developed two versions of its electrorefining process, the uranium only recovery and the transuranic elements recovery.

- The first one was tested at pilot scale and seems ready to be industrialised. The TRL of this process is estimated between 8 and 9 because its feasibility has been demonstrated and it was tested at pilot scale.

- Despite the fact that second one has been claimed by the American researchers as demonstrated at laboratory and engineering scales, it only has been tested at the kilogramme scale. That why the TRL of this process is estimated to be between 5 and 6.

2.2.1.5 Waste stream & possible treatments
An integral part of the IFR pyroprocess development is the treatment and packaging of high-level waste materials arising from the pyroprocess operations, and the qualification of these wastes for disposal in a geologic repository.

A process has been developed to periodically remove the contaminated salt from the electrorefiner, separate most of the fission products, and return the purified salt in a form that is ready for continuing use.
To clean up the electrorefiner salt, the fission products are removed by ion exchange onto a column of Zeolite A. After the purification step, the column material and the contained fission products are converted to a mineral waste form for disposal (ACKERMAN, et al., 1997).

**2.2.1.6 Preliminary conclusions**

As mentioned above, these processes were well studied in the US and have the great advantage to be included in a complete fuel cycle. However, the US DOE seems to support more the ALSEP process today.

**2.2.2 EU Electrorefining**

**2.2.2.1 Main objective**

This pyrochemical process, designed to reprocess metal fuel, is based on separation through electrorefining on an aluminium cathode in molten chloride.

**2.2.2.2 Country/developer**

The Electrorefining process, based on the one advanced by ANL (USA), was developed within the European collaborative projects EUROPART and ACSEPT. This process is now being studied in the SACSESS project.

**2.2.2.3 Description**

The electrorefining process builds on the one proposed by the Argonne National Laboratory to reprocess oxide fuel. The flowsheet was simplified for use with metal fuel, for which a prior reduction step is not necessary. The process is based entirely on electrolytic techniques without any reductive salt/metal extraction step. It comprises several consecutive stages: electrorefining followed by electrolysis on a solid aluminium cathode to obtain satisfactory actinide recovery and actinide/FP decontamination performance.

As shown in Figure 76, the electrorefining process is complex and gathers many steps:

- The first step of this process, adapted from the Argonne National Laboratory process, is the mechanical treatment of the metal fuel (which will be decomposed in U, TRU, FP for the rest of the process description). This step allows to remove some gaseous elements like Xe, Kr, He, H3, I.
- In a second step, the remaining oxide fuels are subjected to an electrolytic reduction with LiCl.
- Then the salts are removed from the bath. In addition, the anode is partially dissolved with gaseous Cl2.
- Then the previous products are subjected to the electrorefining in molten LiCl-KCl on a cathode made of Al. This step of the process produces an alloy of Actinide and aluminium and a mix of LiCl-KCl + AnCl3 + FPClx.
- The second mix is then treated by an exhaustive electrolysis in order to recover the remaining Actinides in an An-Al alloy from LiCl-KCl + FPClx.
- After these steps, the salts are cleansed from the FPs, producing wastes, which will be stored in ceramic tanks into zeolite and glass frits form.
- The An-Al alloy is, on the other hand, subjected to chlorination on an Al cathode with Cl2. During the chlorination reactions, the aluminium cathode is fully oxidised to AlCl3. This step produces AlCl3, AnClx and after condensation UCl6.
- The actinides are then recovered from AnClx using a pyrohydrolysis in steam as AnOx.
- The U elements are also recovered from UCl6 using the same process of pyrohydrolysis in water stream as UO2.
- One more step treats AlCl3 by pyrohydrolysis in steam, producing AlO3, which will be stored in ceramic wastes.

**2.2.2.4 Status of the process**

Partners in the EUROPART and ACSEPT European projects have developed a general process flowsheet to reprocess oxide fuel based on the one proposed by the Argonne National Laboratory.

Today this work is continuing and further steps are taken in the SACSESS project, by studying the monitoring of the molten salt system, the clean-up of the salts by exhaustive electrolysis and the ceramic matrix.

However, no tests of the entire process have been carried out.

This process is currently under study at ITU (Germany), CEA (France), CNRS (France), ENEA (Italy), POLIMI (Italy), PSI (Switzerland), NNL (UK), UNIMAN (UK), and CRIEPI (Japan).

**The TRL of this process is estimated between 2 and 3 because its feasibility has been demonstrated but some steps remain to be tested.**
2.2.2.5 Waste stream & possible treatments

As shown in Figure 76, many types of wastes are generated during this process:

- Metal waste, which depends on the nature of the fuel elements (fast nuclear reactor, gas cooled fast reactor, etc.). It consists of structural elements that are normally dismantled before the fuel reaches the pyrochemical stage of the process, as well as hull segments together with FP comprising the platinum-group metals + Mo. After removal of the salt, the hulls are conditioned through melting.

- The glass-ceramic matrix: according to the studies conducted within the ACSEPT project, the contamination level of these wastes can be expected to be low, but this cannot be affirmed with certainty for now. Some tests and measurements have to be conducted.

- Finally, within this process, a large amount of chlorine gas is also generated. However, it seems that the entire amount produced can be recycled.

2.2.1.6 Preliminary conclusions

As mentioned above, most of the steps of this process are well-known and have been tested over the past fifty years. However, some steps are still being tested in the European project SACSESS, and the entire process still has to be tested (Boussier & Bourg, 2007).
Figure 76: Electrorefining process (ACSEPT)
2.2.3 Liq-liq reductive extraction in molten fluoride salts

2.2.3.1 Main objective
The liquid-liquid reductive extraction in molten fluoride salts is a pyrochemical process aiming to separate the actinides from the lanthanides with LiF-AlF₃ in nuclear spent fuel.

2.2.3.2 Country/developer
The liq-liq reductive extraction in molten fluoride salts was extensively studied by CEA both as an institutional programme and as part of European projects (e.g. ACSEPT and SACSESS).

2.2.3.3 Description
This process was developed by the CEA Marcoule (France) when the distribution of actinides and lanthanides in molten fluoride/liquid metal media was studied. The results obtained with plutonium, americium, cerium and samarium in the (LiF-AlF₃)/(Al-Cu) medium revealed the potential of the system for separating the actinides from the lanthanides (Conocar, et al., 2005). Consequently, they developed a process based on these components.

The flowsheet planned for the Liq-Liq process is shown in Figure 77:

- In this process, the nuclear spent fuel is first subjected to thermal treatment at 1100°C in order remove Cs and Rb contained in it. Today, the CEA plans to use a voloxidation to replace the thermal treatment.
- In a second step, the elements remaining are subjected to a fluorination at 450-500°C, which removes the Zr in the ZrF₄ form.
- The reductive extraction then takes place. This step is divided into two sub-steps at 830°C: a first step, the digestion, in which the components are introduced (the output of the two previous steps, the salt (LiF-AlF₃) and some Zn), and a second step in which the extraction is performed with an Al cathode. These steps allow separating the actinides from the FPs.
- The FPs are then subjected to vitrification for disposal.
- The next step has been set up to back extract the actinides at 700 °C. In order to achieve that, a chloride salt (NaAlCl₄) is used.
- The An are then precipitated thanks to gas into AnO₂.

![Figure 77: Liq-liq reductive extraction in molten fluoride salts/liquid process](image-url)
2.2.3.4 Status of the process
This process, mainly developed by CEA, has not been entirely tested. The scientific feasibility has been demonstrated within the European ACSEPT project, and some parts of the process are currently being studied in SACSESS, namely the modelling of the thermodynamic behaviour of LiF-ALF₃, the dissolution limits of the components and the stability of the various steps.

CNRS (France) and UJV (Czech Republic) are currently working on this process.

The TRL of this process is estimated to be between 3 and 4 because its feasibility has been demonstrated but some steps remain to be tested.

2.2.3.5 Waste stream & possible treatments
As shown in Figure 77, the wastes generated during the process are:

- The metal waste: which depends on the nature of the fuel elements (fast neutron reactor, gas cooled fast reactor, etc.). It consists of structural elements that are normally dismantled before the fuel reaches the pyrochemical stage of the process, as well as hull segments together with FP comprising the platinum-group metals + Mo. After removal of the salt, the hulls are conditioned by melting.

- The FPs: which are designated to be disposed. According to the studies conducted in ACSEPT, the contamination level of these wastes can be expected to be low, but for now this cannot be affirmed with certainty. Some tests and measurements still need to be conducted.

2.2.3.6 Preliminary conclusions
As mentioned above, most steps of this process are well known and have been tested. However, some steps are still being tested as part of the SACSESS project, some points remain to be investigated and the entire process still has to be tested.

2.2.4 Dimitrovgrad dry Process (DDP)

2.2.4.1 Main objective
The Dimitrovgrad dry process (DDP) was developed and demonstrated for the reprocessing of fast reactor oxide fuel. In this process, which is essentially an electro-winning process, spent oxide fuel is de-cladded and fragmented. The DDP can allow the electro-refining of MOX fuel either for recovering UO₂ alone or with UO₂-PuO₂ (+NpO₂), according to the gaseous conditions applied in the electrolyser.

2.2.4.2 Country/developer
The DDP is a Russian process developed in the early 1970s at the Research Institute for Atomic Reactors (Russia).

2.2.4.3 Description
The DDP is a pyrochemical process aiming to treat MOX spent fuel to recover the U, Pu, and Np elements. As shown in Figure 78, DDP is mainly composed of electro-winning steps:

- The first step of DDP is a chlorination of the nuclear spent fuel at 700°C. The MOX fuel is deposited in a pyrographite bath with NaCl-KCl into gaseous Cl₂ is injected.
- The mix is then subjected to a preliminary electrolysis at 680°C. By adding Ar(Cl₂), it allows to recover Np and U on the cathode under the UO₂ and NpO₂ form. The cathode is then removed.
- In the third step, the Pu is precipitated and crystallised at 680°C. To do that, Cl₂ + O₂ + Ar are added to the bath. The Pu precipitated under PuO₂ form and some UO₂⁺ stay in the bath.
- A second electrolysis is then performed at 700°C. Cl₂ + O₂ + Ar are still added to the bath. UO₂ is recovered on the cathode.
- The final step is a melted purification at 700°C, allowing recovery of all the remaining wastes by adding Na₃PO₄.

2.2.4.4 Status of the process
This process has produced more than 3.6 tonnes of UO₂ fuels and 2 tonnes of UO₂-PuO₂ fuels since the 1970s, for Russian fast reactors BOR60, BN350 and BN600. Thus, the process is operational. However, it has been used to fabricate fresh fuel from pure uranium and plutonium but was never really used at high scale in reprocessing starting with spent fuel.
The TRL of this process is estimated between 8 and 9 because it has been used in Russian reactors.

2.2.4.5 Waste stream & possible treatments
In Russia, the wastes produced during DDP are handled; the main ones are vitrified and stored.

2.2.4.6 Preliminary conclusions
The DDP process is one of the most developed P&T processes. However, it does not allow the recovery of all of the actinides that are present in the nuclear spent fuel.

The DOVITA process, which is an evolution of DDP with modifications in its parameters, may allow this recovery. However, the feasibility of this process is still under study.

2.2.5 Kaeri process ACPF

2.2.5.1 Main objective
ACPF (advanced spent fuel conditioning process) is a process developed to reduce the radiation toxicity and amount of wastes in nuclear spent fuel in order to store it easily. This technology involves the electrolytic reduction of uranium oxide in a high temperature LiCl-Li2O molten salt bath.

2.2.5.2 Country/developer
The Korean atomic energy research institute (KAERI) conceived this process in 1997 (YOU, et al., 2009).

2.2.5.3 Description
The ACPF process aims to decrease the amount and the radiotoxicity of nuclear spent fuel waste by extracting some of the major actinides. An overview of the process is shown in Figure 79.

As shown in Figure 79, the ACPF process (Lee, et al., 2011) is decomposed as follows:

- First the PWR spent fuel (SF) is disassembled and decladded. This step allows to get rid of the metallic hull, which is then treated separately.
- The remaining elements are then subjected to a voloxidation. By adding air to the fuel oxide, this step performed at 500°C allows to remove I2, Kr, Xe, and to recover U3O8 + (TRU +FP).
- The next step is an electrolytic reduction by adding molten LiCl with some Li2O used as the electrolyte. The product of the electrorefining process is a reduced metal mixture, which contains molten salt after reaction. This is transferred to the cathode processor to distill off the molten salt. Distilled salt is moved to waste salt treatment process where impurities such as Sr are removed. The purified salt is recycled to electro-reduction process. The reduced metal is conveyed to electrorefining process.
Finally, an electro-winning step recovers TRUs and rare earth elements together with residual uranium. Liquid Cd is used as a cathode. Recovered elements in liquid Cd are treated in the distillation system to separate Cd. Then, they transferred to the sodium cooled fast reactor (SFR) fuel fabrication process.

**2.2.5.4 Status of the process**

Cold tests were performed at KAERI in 2009. The feasibility of the process has been demonstrated and tested.

The TRL of this process is estimated between 3 and 4 because its feasibility has been demonstrated and cold tested at laboratory scale.

**2.2.5.5 Waste stream & possible treatments**

During the ACPF process some wastes are released:
- During voloxidation: a large amount of gas form fission products such as Kr, Xe, I and H.
- During metallisation: volatile fission products such as Ru, Tc, Mo, Se and Rb
- During smelting: a large amount of volatile fission product such as Ru, Tc, Mo, Se, and Rb

The following treatments have been developed to handle these wastes:
- Crystallisation is used to recover pure LiCl salt from contaminated salt of electro reduction system.
- The second waste salt of LiCl-KCl is treated by blowing oxygen, leading to solid precipitates. After settlement for a while and cooling, this becomes a solid rod with different layers. The upper layer is cut and recycled to electro-refining the system. The lower layer is distilled since it contains salt and distilled salt is returned to electrorefining system. The precipitates are solidified to yield a final waste form.

**2.2.5.6 Preliminary conclusions**

The process is ready for industrialisation and has the advantage of being fully integrated into a closed fuel cycle that is complementary with the SFR fuel fabrication process.
3. CONCLUSIONS
3.1 Process versions multiplication

During the last decades, the will of the nuclear scientific world to achieve a closed fuel cycle has led to numerous and various processes of partitioning. Figure 80 presents the different processes that reprocess nuclear spent fuels over time.

Moreover, for most of the processes, several molecules are or have been tested, which directly leads to more process versions. For example, with the i-SANEX process, two solvents are investigated, TODGA and TWE21, and two molecules preventing the extraction of Zr and Pd are investigated, CDTA and HEDTA.

3.2 Preliminary conclusions on processes

Since the early 1980s, the scientific workforce has mainly studied the processes from two scientific fields, the aqueous separation and the pyrochemical processes. In the aqueous separation field, processes are commonly structured regarding the type of extraction they perform.

3.2.1 Hydroprocesses

Four processes co-extracting the actinides and the lanthanides are described in this report:

- The American **TRUEX** process, developed by the Argonne National Laboratory in the 1990s, has been demonstrated and tested. It is currently under study at Bhabha atomic research centre in India. It is ready to be industrialised despite some issues that remain to be studied. The estimated TRL for this process is between five and seven. However, the process is not expected to be industrialised soon because the US DOE is no longer supporting it.
- The French **DIAMEX** process, developed by CEA in the late 1990s, has been demonstrated and tested. Recent progress shows that the process is ready to be industrialised. The estimated TRL for this process is between six and seven. The combination with the r-SANEX process is under study and provides a complete P&T solution.
- The Chinese **TRPO** process, developed by Tsinghua University, has been demonstrated, and tested at ITU. It is still under study in China. Some improvements still have to be achieved to be able to industrialise this process. The estimated TRL for this process is between four and five.
- The concept of the Japanese **ARTIST** process, developed by JAERI (today JAEA) in the frame of the OMEGA project in the early 2000s, has been demonstrated but not yet tested. The estimated TRL for this process is between two and three. The process seems promising and it will certainly be one of the priority processes to be developed.

Two processes partitioning the minor actinides are described in this report:

- The **DIDPA** process, developed by JAERI in the 1980s, has been demonstrated and hot tested. JAEA is carrying out complementary studies on this process. The estimated TRL is between five and six.
- The Japanese **SETFICS** process, developed by JAEA in the late 1990s, has been demonstrated but never tested with HAW (only cold tested for now). It is still under study at JAEA. The estimated TRL for this process is between three and four.

Eight processes separating actinides from lanthanides:

- ITU, UREADS, KIT, JULICH and CEA developed the European **r-SANEX** process in the frame of European projects in the early 2000s. As one of the processes studied in SACSESS, it has been demonstrated and tested, but some issues have to be studied further, such as the solvent stability under radiation. The estimated TRL for this process is between four and five.
- ITU, UREADS, KIT, JULICH and CIEMAT developed the European **i-SANEX** process in the frame of European projects in the early 2000s. As one of the processes studied in SACSESS, it has been demonstrated and tested, but some issues have to be studied further, such as the solvent stability under radiation. The estimated TRL for this process is between four and five.
- ITU, UREADS, KIT, JULICH and CIEMAT developed the European **lc-SANEX** in the frame of European projects in the early 2000s.
CONCLUSIONS

As one of the processes studied in SACSESS, it has been demonstrated and tested, but some issues have to be studied further, such as the solvent stability under radiation. The estimated TRL for this process is between three and four.

- The Chinese **Cyanex 301** process developed by Beijing University and studied at ANL in the framework of the development of their UREX+ process has been demonstrated and hot tested. It is still under study at Tsinghua University, and is not ready to be industrialised for now. The estimated TRL for this process is between four and five.

- The American **TALSPEAK** process, developed by ORNL in the late 1960s, has been demonstrated and hot tested in several countries; it is ready to be industrialised but some drawbacks still under study are slowing down its development. The estimated TRL for this process is between four and five.

- The American **TRUSPEAK** process developed at PNNL in the early 2000s has been demonstrated, but not tested. It is still under study at ORNL and at ANL. The estimated TRL for this process is between two and three.

- The American **TRUSQUEAK** process developed by ANL in the 2000s has been demonstrated but not tested. It is still under study at PNNL and at ANL. The estimated TRL for this process is between two and three.

- The American **ALSEP** process patented by the US DOE in 2013 has been demonstrated but not tested. It is still under study at ANL. This is the process supported by the US DOE, a demonstrator is planned to be built in 2015-2016. The estimated TRL for this process is between two and three.

One process separating Am from Cm:

- The French **EXAm** process developed in the 2000s by CEA has been demonstrated and hot tested. It is still under complementary study at CEA, and is not ready to be industrialised for the time being. The estimated TRL for this process is between four and five.

Four processes with homogenic partitioning the transuranic elements:

- The French **GANEX 1st cycle** process was developed by CEA in the 2000s. It is the first step of all the GANEX cycles. It has been demonstrated and hot tested. Some improvements still have to be achieved for industrialisation. The estimated TRL for this process is between six and seven.

- The CEA developed the **CEA-GANEX** or **GANEX 2nd cycle** process in the 2000s. It has been demonstrated and is undergoing tests. The estimated TRL for this process is between four and five.

- The European **EURO-GANEX**, developed in the frame of the ACSEPT project in the 2000s, has been demonstrated and tested. It is currently under study in the SACSESS project. The estimated TRL scale for this process is between four and five.

- The Swedish **CHALMEX** process, developed in ACSEPT in the 2000s, has been demonstrated. It is currently under study in SACSESS. The estimated TRL scale for this process is between two and three.
Figure 81: Hydroprocesses overview (LGI, 2014)
3.2.2 Pyroprocesses

In the pyrochemical field, five processes are described in this document:

- **The US Electrorefining** was developed by the ANL since the 1980s. There are two versions of it. The first one, which only recovers the uranium and the second one allowing the recovering of all the transuranic elements. They all have been tested at pilot scale, but the second one only at the kilogramme scale. The estimated TRLs, for these processes are respectively between seven and eight and between five and six.

- **The European Electrorefining** process was developed in the EUROPART and ACSEPT projects in the 2000s. This is an adaptation of an ANL developed process. It is still under study in SACSESS, but its feasibility has been demonstrated. It has never been entirely tested. The estimated TRL for this process is between two and three.

- The European **Liquid-liquid extraction in molten fluoride salts** was developed in the EUROPART and ACSEPT projects in the 2000s. It is still under study in SACSESS, but its feasibility has been demonstrated. It has never been entirely tested. The estimated TRL for this process is between two and three.

- **The Russian Dimitrovgrad dry process** was developed by RIAR in the 1970s. It is operational and producing fuel for the BOR60, BN350 and BN600 Soviet reactors. The estimated TRL for this process is between eight and nine.

- The Korean **ACPF** process developed by KAERI in the 1990s has been hot tested and demonstrated. It is ready to be industrialised. However, it is still under study to fix remaining issues. The estimated TRL for this process is between four and six.

Partitioning processes are a worldwide initiative with the European Union at the forefront. As further developed in the annex of this report, the different stakeholders of partitioning processes are divided into four regions (see in Figure 82): the USA, the European Union, Russia and Asia (namely China, Korea, Japan, and India).

The European Union is one of the leaders in the field of P&T. The EU has developed a strong scientific network for enhancing research on P&T. Indeed, since the beginning of the 1990s, European research centres and universities have been working together in the framework of European projects to develop knowledge on actinides and P&T.

No joint actions have been performed in the USA, Russia or Asia. However, extensive research has been carried out in these countries with interesting results:

- In Russia, researchers have been mainly focusing on pyroprocesses in the past decades, and have developed many processes, including the DDP mentioned in this report. However, they have not developed a solution to retreat the minor actinides from the nuclear spent fuels.

- In Asia, researchers have been studying many kinds of processes but their network is not as well-organised as in Europe.

- In the USA, researchers have developed their own processes to take care of their own wastes, but mostly in the field of actinide/lanthanide separation.
3.3 Research needs identification and roadmapping

Because of the multitude of processes, decision makers in the nuclear field need to select the most promising processes to develop further and to optimise the resources. This is the purpose of the next study planned in the SACSESS project. This report will directly feed the first draft of the roadmap with the identified existing processes. The objective of the roadmap will be to evaluate the needs of R&D, assess technology maturity (technology readiness levels), match the processes with appropriate fuel cycles identifying the molecules they use, evaluate the easiness to produce these molecules, etc.

Based on the mapping of processes in this report and their qualitative structuring in the roadmap, the research and industrial community will get a comprehensive view on the state-of-the-art and further research needs in the field. It will support decision makers and the research community to orientate efficiently their research efforts and strategies in the short-, medium- and long-term.
4. ANNEX: ACTORS OF P&T
This annex provides additional information with a complete overview of the different stakeholders of P&T worldwide and highlights the existing relationships between them.

4.1 In Europe
This section identifies the European stakeholders currently working on P&T in the SACSESS project or in other past projects.

4.1.1 The SACSESS consortium

In Czech Republic:
The Czech Republic has six nuclear reactors generating about one third of its electricity. The government commitment to the future of nuclear energy is strong and plans to increase the country’s nuclear capacity.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTU</td>
<td>Ceske Vysoke Uceni Technicke V Praze</td>
<td>Aqueous</td>
<td>r-SANEX, 1c-SANEX, GANEX</td>
<td>-</td>
</tr>
<tr>
<td>IIC</td>
<td>Institute of Inorganic chemistry Academy of sciences of Czech Republic</td>
<td>Aqueous</td>
<td>r-SANEX, i-SANEX, 1c-SANEX, CEA-GANEX</td>
<td>-</td>
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<tr>
<td>UJV</td>
<td>Ustav Jaderneho Vyzkumu Rez A.S</td>
<td>Pyrochemical</td>
<td>Liquid-liquid extraction</td>
<td>Fluorisation</td>
</tr>
</tbody>
</table>

In France:
France has 56 nuclear reactors generating about 75% of its electricity. It is the world leader in electricity exports thanks to its nuclear production. It has always been very active in developing nuclear technology (reactors, reprocessing, etc.) and is currently building its first Generation III reactor. It already has a reprocessing plant and about 17% of its electricity comes from recycled nuclear fuel. However, since the last presidential election, France seems to want to step back from nuclear by cutting down its nuclear-produced electricity to 50% by 2030.

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<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
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<tr>
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<td>Commissariat à l’énergie atomique et aux énergies alternatives</td>
<td>Aqueous, Pyrochemical</td>
<td>EXA, Electrorefining</td>
<td>DIAMEX, CEA-GANEX, Liquid-liquid extraction, SESAME, CALIXCROWN, PALADIN, BTPs, TMAHDPTZ+octanoïc acid, EURO-GANEX, COEX™, UREX</td>
</tr>
<tr>
<td>CNRS</td>
<td>Centre national de la recherche scientifique</td>
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<td>Electrorefining, Liquid-liquid extraction</td>
<td>-</td>
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<tr>
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<td>Université de Strasbourg</td>
<td>Aqueous, Pyrochemical</td>
<td>EURO GANEX, r-SANEX / 1c-SANEX, i-SANEX</td>
<td>Liquid-liquid extraction</td>
</tr>
</tbody>
</table>
**In Germany:**
Until March 2011, one quarter of the electricity produced in Germany came from nuclear energy, using 17 reactors. However, they have shut down most of nuclear reactors since then, and all will be shut down until 2022. Nevertheless, it has a strong commitment to research on reprocessing.

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<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
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<td>r-SANEX</td>
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<td></td>
<td>CEA-GANEX</td>
<td>TRPO</td>
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<tr>
<td>ITU</td>
<td>JRC-Joint Research centre- European Commission</td>
<td>Aqueous Pyrochemical</td>
<td>Electrorefining</td>
<td>TRPO</td>
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</tbody>
</table>

**In Italy:**
Since the Chernobyl event, Italy has shut down its four reactors but about 10 % of its imported electricity comes from nuclear.

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<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
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<tr>
<td>ENEA</td>
<td>Agenzia nazionale per le nuovo tecnologie l'energia e lo sviluppo economico sostenibile</td>
<td>Pyrochemical</td>
<td>Electrorefining</td>
<td>-</td>
</tr>
<tr>
<td>POLIMI</td>
<td>Politecnico di Milano</td>
<td>Aqueous Pyrochemical</td>
<td>i-SANEX</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>r-SANEX</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1c-SANEX</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CEA-GANEX</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electrorefining</td>
<td></td>
</tr>
<tr>
<td>UNIPR</td>
<td>Universita degli studi di parma</td>
<td>Aqueous</td>
<td>i-SANEX</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>r-SANEX</td>
<td></td>
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<tr>
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<td></td>
<td>1c-SANEX</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CEA-GANEX</td>
<td></td>
</tr>
</tbody>
</table>

**In The Netherlands:**
The Netherlands has one reactor generating about 4% of its electricity and is Europe’s largest provider of medical radioisotopes. They may build another reactor in the next years, but this remains very uncertain.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>TWENTE</td>
<td>University of Twente</td>
<td>Aqueous</td>
<td>CEA-GANEX</td>
<td>-</td>
</tr>
</tbody>
</table>
In Poland:
Poland has no nuclear reactor for now but is planning to have one in 2025.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICHTJ</td>
<td>Instytut Chemii i Techniki Jarowej</td>
<td>Aqueous</td>
<td>i-SANEX, r-SANEX, 1c-SANEX, CEA-GANEX</td>
<td>-</td>
</tr>
</tbody>
</table>

In Spain:
Spain has seven nuclear reactors generating one fifth of its electricity. The future of nuclear energy in Spain has been uncertain but has firmed up as the cost of subsidising renewables is becoming unaffordable.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
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<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIEMAT</td>
<td>Centro de investigaciones energéticas, medioambientales y tecnológicas</td>
<td>Aqueous</td>
<td>i-SANEX, EURO-GANEX</td>
<td>-</td>
</tr>
</tbody>
</table>

In Sweden:
Sweden has 10 nuclear reactors generating about 40% of its electricity. Its position on nuclear is complicated; it has planned to increase the renewables share in its energy mix but has not planned to shut down nuclear reactors.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHALMERS</td>
<td>CHALMERS TEKNISKA HÖGSKOLA AB</td>
<td>Aqueous</td>
<td>CHALMEX</td>
<td>r-SANEX, CTH</td>
</tr>
</tbody>
</table>

In Switzerland:
Switzerland has 5 nuclear reactors generating about 40% of its electricity. It plans to phase out nuclear power by 2034. However, it contributes to research on reprocessing.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSI</td>
<td>Paul Scherrer Institut</td>
<td>Pyrochemical</td>
<td>Electrefining</td>
<td>-</td>
</tr>
</tbody>
</table>
In the United Kingdom:
The UK has 16 reactors generating about 18% of its electricity. Because the end of their lifetime is approaching, the British government is assuming that there will be a requirement of 60 GWe of net new generating capacity by 2025, of which 35 GWe is to come from renewables and 25 GWe from nuclear. The UK has major reprocessing plants and fuel cycle capacity.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>NNL</td>
<td>National Nuclear Laboratory</td>
<td>Aqueous Pyrochemical</td>
<td>i-SANEX EURO-GANEX Electrorefining</td>
<td>EURO-GANEX</td>
</tr>
<tr>
<td>UEDIN</td>
<td>The University of Edinburgh</td>
<td>Aqueous Pyrochemical</td>
<td>Liquid-liquid extraction</td>
<td>-</td>
</tr>
<tr>
<td>ULANC</td>
<td>Lancaster University</td>
<td>Aqueous</td>
<td>i-SANEX r-SANEX 1c-SANEX CEA-GANEX</td>
<td>-</td>
</tr>
<tr>
<td>UNIMAN</td>
<td>The University of Manchester</td>
<td>Pyrochemical</td>
<td>Electrorefining</td>
<td>-</td>
</tr>
<tr>
<td>UREADS</td>
<td>University of Reading</td>
<td>Aqueous</td>
<td>i-SANEX CEA-GANEX</td>
<td>1c-SANEX</td>
</tr>
</tbody>
</table>

4.1.2 Other stakeholders

In France:
In addition to its significant research capacity, France counts one of the world’s industrial leader in the nuclear sector, which is also involved in the reprocessing sector as shown in the table below.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREVA</td>
<td>-</td>
<td>Aqueous</td>
<td>-</td>
<td>COEX™ PUREX</td>
</tr>
</tbody>
</table>
A global overview of the European nuclear situation is presented in Figure 84.

Figure 84: European P&T stakeholders from SACSESS consortium (I.GI, 2014)
4.2 Worldwide

This section identifies the non-European stakeholders currently working on P&T in the SACSESS project or in other past projects.

4.2.1 SACSESS stakeholders

In Japan:
Japan is the only non-European country to have a partner in the SACSESS consortium.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRIEPI</td>
<td>Central Research Institute of electric power industry</td>
<td>Pyrochemical</td>
<td>Electrorefining</td>
<td>-</td>
</tr>
</tbody>
</table>

4.2.1 Other stakeholders

In China:
20 nuclear reactors are in operation in China, 28 are under construction and more are planned to be built. China’s policy targets closed fuel cycle, thus, it is performing research on reprocessing.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>THU</td>
<td>Tsinghua University</td>
<td>Aqueous</td>
<td>TRPO Cyanex 301</td>
<td>-</td>
</tr>
</tbody>
</table>

In India:
India has 20 nuclear reactor in operation and plans to build more. It has been working significantly on the Thorium fuel cycle and on reprocessing.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHABHA</td>
<td>Bhabha Atomic Research Centre</td>
<td>Aqueous</td>
<td>TRUEX TBPs</td>
<td>-</td>
</tr>
</tbody>
</table>

In Japan:
Japan’s 48 reactors have been stopped since the Fukushima disaster. Japan has a full fuel cycle setup, including enrichment and reprocessing of used fuel for recycling, and is carrying out research on reprocessing.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAEA</td>
<td>Japan Atomic Energy Agency</td>
<td>Aqueous</td>
<td>ARTIST DIDPA SETFICS NEXT</td>
<td>Super-DIREX</td>
</tr>
<tr>
<td>-</td>
<td>Mitsubishi</td>
<td>Aqueous</td>
<td></td>
<td>Super-DIREX</td>
</tr>
</tbody>
</table>

ACTORS OF P&T
**In South Korea:**
South Korea is a growing nuclear exporter, recently winning a contract to build four nuclear reactors in the United Arab Emirates. South Korea has 23 reactors generating one third of its electricity - this number is expected to increase.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAERI</td>
<td>Korean atomic energy research institute</td>
<td>Pyrochemical</td>
<td>ACPF</td>
<td>DUPIC</td>
</tr>
</tbody>
</table>

**In Russia:**
Russia is the first country in the world to have built a nuclear reactor in 1954. Today it has 32 nuclear reactors and it plans to build 11 more.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>RIAR</td>
<td>Research Institute for Atomic Reactors</td>
<td>Pyrochemical</td>
<td>Dovita</td>
<td>DDP</td>
</tr>
</tbody>
</table>

**In the US:**
The USA is the world’s largest producer of nuclear power, accounting for more than 30% of worldwide nuclear generation of electricity. 100 units are operable today and five are under construction. Following a 30-year period during which few new reactors were built, it is expected that six new units may come on line by 2020, four of those resulting from 16 licence applications made since mid-2007 to build 24 new nuclear reactors.

<table>
<thead>
<tr>
<th>Stakeholder acronym</th>
<th>Name of the stakeholder</th>
<th>Type of process</th>
<th>Process under study</th>
<th>Process studied in the past</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANL</td>
<td>Argonne National Laboratory</td>
<td>Aqueous, Pyrochemical</td>
<td>ALSEP, TRUSPEAK, TRUSQUEAK</td>
<td>TRUEX, UREX+, Pyro A, Pyro B</td>
</tr>
<tr>
<td>-</td>
<td>Energy Solutions</td>
<td>Aqueous</td>
<td></td>
<td>NUEX</td>
</tr>
<tr>
<td>ORNL</td>
<td>Oak Ridge National Laboratory</td>
<td>Aqueous</td>
<td>TRUSPEAK</td>
<td>TALSPEAK, UREX+</td>
</tr>
<tr>
<td>PNNL</td>
<td>Pacific Northwest National Laboratory</td>
<td>Aqueous</td>
<td>TRUSQUEAK</td>
<td>-</td>
</tr>
</tbody>
</table>

A global overview of the European nuclear situation is presented in Figure 86.
Figure 85: Nuclear panorama (LGI, 2014)
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