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Investigating the socio-technical boundary conditions of partitioning, conditioning and transmutation through (inter)national case studies

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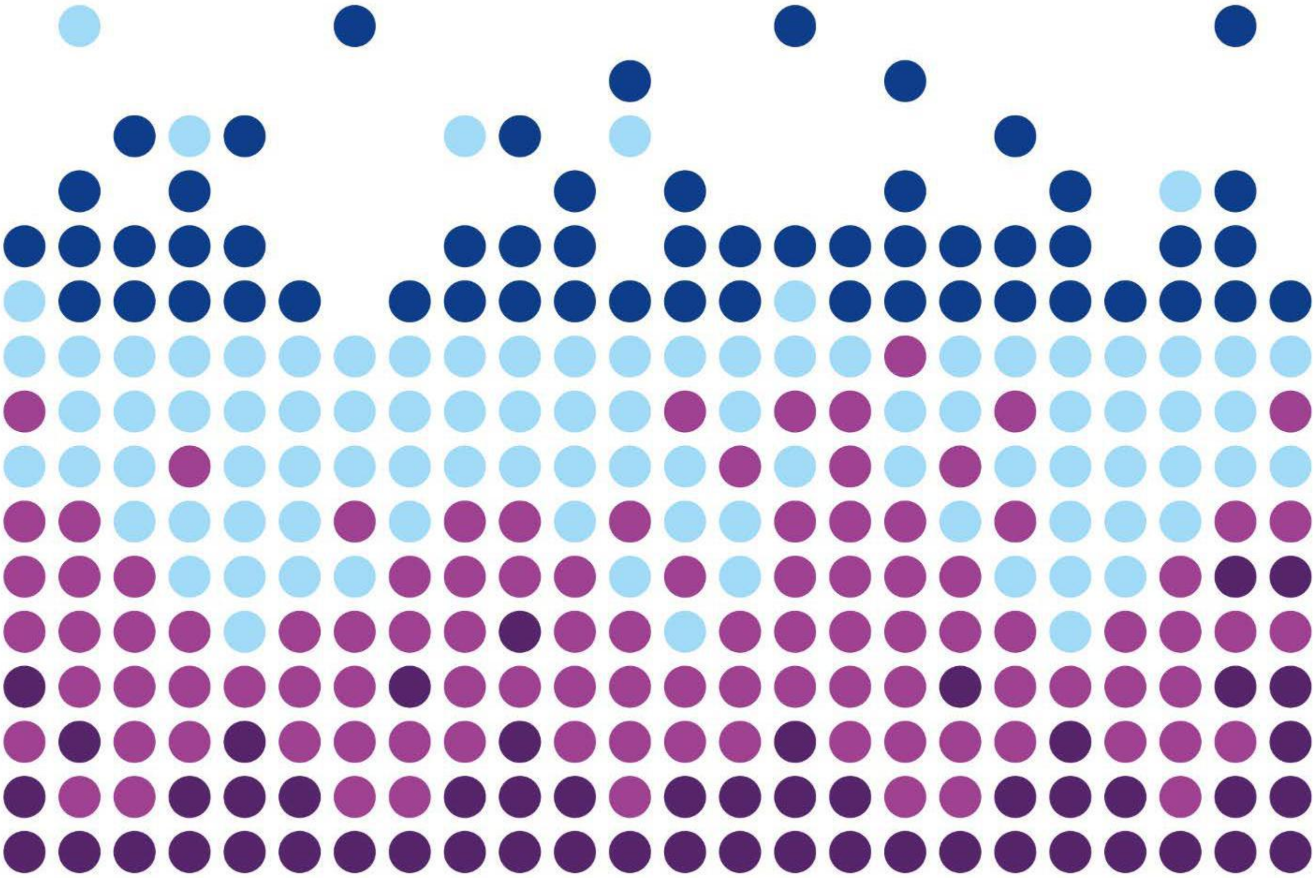

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SUMMARY

The ASOF project investigates the development of new, innovative processes for the separation (WP1), conversion (WP2) and conditioning (WP3) of spent nuclear fuel (SNF) in light of the optimization of final disposal concepts for nuclear radioactive waste in Belgium (WP4). This report focuses on the broader societal embeddedness of partitioning and conditioning and/or transmutation (P&C/T) in a web of socio-technical relations (including e.g. policy, economy, ethics, science).

The partitioning of SNF encompasses the broadening of existing reprocessing techniques to radionuclides beyond uranium and plutonium, with a particular focus on the separation of minor actinides, while transmutation then entails the conversion of partitioned long-lived elements into shorter lived or stable isotopes. By reducing the longevity, radiotoxicity and heat output of wastes, it is hoped that P&(C/)T can reduce the footprint of disposal facilities and simplify their design, which, it is hoped, would contribute to the societal acceptability of radioactive waste disposal. In this way, the impacts of P&C/T are not limited to the technical domain, but extend to broader society, which in turn sets boundary conditions to the development and potential implementation of P&C/T in terms of e.g. (inter)national policy frameworks, economic costs, ethical acceptability, or energy governance practices.

P&C/T has been presented as a solution to the 'wicked' problem of geological disposal, yet this report demonstrates how P&C/T in itself can be considered as a 'wicked' problem. Like geological disposal, P&C/T is "enmeshed in complicated political, social, environmental and economic aspects, while interests, values, preferences and financial considerations of [...] various actors and stakeholders diverge" (Brunnengräber, 2019: 337). Understanding this 'enmeshed' character of P&C/T requires an analytical frame, which is attentive to the close interconnections between and the co-production of society, science and technology.

As partitioning and (especially) transmutation currently still requires substantive R&D efforts and investments before industrial implementation can be demonstrated and achieved, a co-productionist focus on the topic also explores relations between P&C/T development and the imagined futures it entails. Reflecting on these relations, potential impacts and futures at a relatively early stage in the development of P&C/T, can also help to identify the societal needs and values, this technology answers and connects to.

This report explores some of the socio-technical interrelations P&C/T connects to by analysing six country cases: Finland, France, India, Japan, the UK and the US. Drawing on publicly available national and international policy documents, news articles and scientific publications, the report identifies socio-technical boundary conditions that can be used as a basis for reflections on other national contexts. The individual country case studies can be summarized as follows:

Finland currently looks to be the first country to implement geological disposal, and the expectation to start disposal in the 2020s. With developed plans for the direct disposal of SNF, the Finnish nuclear landscape provides little space for P&C/T to develop. Small scale involvement in international P&C/T research is maintained in the context of knowledge maintenance and a legal requirement to consider alternatives to GD.

France is one of few countries with significant domestic experience and expertise on reprocessing, and it has been active in developing experimental fast reactors. None of these are currently operational, while the latest project was stopped before the construction stage. These experiences raise questions about the future P&T development in France, with the CEA declaring they will not undertake similar projects in the foreseeable future.

India aims to implement a closed thorium fuel cycle through a three stage approach. India has experience with the partitioning of minor actinides and some fission products, and has been involved in fast reactor and ADS R&D. The future of P&T in India is hard to assess, although the country's aims of waste minimization and closing the nuclear fuel cycle can be seen as justifications for further development of P&C/T.

Japan has decided to diminish its dependence on nuclear energy in the wake of the Fukushima disaster, which also highlighted the risks of radioactive wastes, and has spurred on R&D on P&C/T to diminish the potential risks of HLW. However, the closure of several nuclear installations and potential plans to phase out nuclear by 2050 raise questions about the feasibility of P&T in Japan. Meanwhile Japanese attempts to develop domestic reprocessing capacity and to implement geological disposal have also experienced setbacks.

The United Kingdom is transitioning from a partially closed cycle to a once-through one following the cessation of reprocessing activities. It aims to implement geological disposal for disposing of high and intermediate level wastes. The UK has ruled out P&T as an option for radioactive waste management, because of its high costs compared to perceived benefits, and the unsuitability of the UK radioactive waste inventory for P&T, but it keeps a watching brief on the development of P&T.

The United States, following the cancellation of the Yucca Mountain geological disposal project, reassessed options for managing the back-end of the fuel cycle. The reassessment did not lead to reorienting and reclosing the fuel cycle after the 1970s decision to open it. This aligns with previous assessment of the feasibility of P&T, which held that in the US context, there are little arguments that would justify a strong push for P&T in the short-term, although R&D should continue.

Thematically analysing these above cases, the report identifies five dimensions that affect and are affected by the development of P&C/T, and as such set potential socio-technical boundary conditions for P&C/T. These dimensions are

1. Policy contexts and changes
2. Divisions of labour in managing the backend of the nuclear fuel cycle (who is focusing on which strategy, when, and where),
3. Material practices and infrastructures (e.g. reprocessing practices, disposal development, experiences with R&D on advanced reactors),
4. Nuclear markets and economies, and
5. Ethical considerations.

This list is not meant to be exhaustive nor can the different dimensions be strictly separated from each other. Rather, these dimensions are intricately connected, and evolutions in one will encompass evolutions in the other. Moreover, other country cases might identify alternative dimensions, or downplay those listed above. Thus the above list serves first and foremost as a foundation for further reflection. With regard to these five dimensions, the country cases highlight how:

- **Changes in international, regional and national** policies need to be taken into consideration on these different policy levels, since issues from proliferation, energy transitions, and domestic nuclear events are closely interrelated with each other and the (potential) development of P&C/T.
- **Existing divisions of labour** at the back-end of the nuclear fuel cycle add complexity to potential futures of P&C/T. These divisions of labour are situated at the organizational level (research bodies/implementing bodies), at a geographical level (international projects/national implementation), and at strategic level regarding radioactive waste management (geological disposal/geological disposal with P&C/T).
- Both **past and present material practices and infrastructures** at the back-end of the fuel cycle directly relate to P&C/T futures. Reprocessing infrastructures and experiments with fast reactors entail experiences and knowledge which might benefit (e.g. technical know-how) or impede (e.g. underperformance or accidents) future development of P&C/T, while vitrified waste closes the route for future P&C/T because of its material properties.

- **Evolutions of nuclear markets and economies** are essential for understanding the efforts directed to P&C/T. Low uranium prices or the costs of constructing and operating nuclear installations have diminished interest in the closed nuclear fuel cycle, especially among private market actors.
- **Ethical considerations** are closely intertwined with P&C/T development. Issues such as fair siting, current versus future costs/benefits, additional/diminished risks require explicit reflection and action before implementation.

Overall, this report provides grounds for further reflection on the socio-technical embeddedness of P&C/T. It highlights how P&C/T is not a story of linear scientific development, but rather of different speculative futures. Therefore, it is necessary to acknowledge and understand the ways in which P&C/T is entwined with different futures and future outcomes, but also how material-political pasts, presents and futures are interwoven along a range of mutually constitutive dimensions, which similarly need to be acknowledged and understood if responsible progress is to be made.

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LIST OF ABBREVIATIONS

ADS	Accelerator-driven system
ANDRA	Agence Nationale pour la gestion des Déchets RAdioactifs (FR)
ASDF	Actinide Separation Demonstration Facility
ASN	Autorité de Sûreté Nucléaire (FR)
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
CoRWM	Committee on Radioactive Waste Management (UK)
BARC	Bhabha Atomic Research Centre
BRC	Blue Ribbon Committee (US)
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (FR)
COEX	CO-EXtraction of uranium and plutonium
DAE	Department of Atomic Energy (IN)
DFR	Dounreay Fast Reactor
DIAMEX-SANEX	DIAMide EXtraction – Selective ActiNide EXtraction
DOE	Department of Energy (US)
EDF	Electricité de France (FR)
EXAm	Selective EXtraction of Americium
GANEX	Group ActiNide EXtraction
GDF	Geological Disposal Facility
GNEP	Global Nuclear Energy Partnership
FaCT	Fast Reactor Cycle Technology Development
FBR	Fast Breeder Reactor
FBTR	Fast Breeder Test Reactor
FP	Fission Product
FR	Fast Reactor
HLW	High Level Waste
IAEA	International Atomic Energy Agency
IGCAR	Indira Gandhi Centre for Atomic Research
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (FR)
JAEA	Japan Atomic Energy Agency
J-PARC	Japan Proton Accelerator Research Complex
KYT	Finnish Research Programme on Nuclear Waste Management
MA	Minor Actinide
MEE	Ministry of Employment and Economic Affairs (FIN)

METI	Ministry of Economy, Trade and Industry (JPN)
MOX	Mixed Oxide Fuel
NEA	Nuclear Energy Agency
NNL	National Nuclear Laboratory (UK)
NUMO	Nuclear Waste Management Organization of Japan
PFBR	Prototype Fast Breeder Reactor
PFR	Prototype Fast Reactor
PUREX	Plutonium Uranium Extraction
PWR	Pressurized Water Reactor
P&C	Partitioning and Conditioning
P&T	Partitioning and Transmutation
RRI	Responsible Research and Innovation
RWM	Radioactive Waste Management
RWMAC	Radioactive Waste Management Advisory Committee (UK)
SKB	Swedish Nuclear Fuel and Waste Management Co
SMP	Sellafield MOX Plant
SNF	Spent Nuclear Fuel
STS	Science and Technology Studies
STUK	Radiation and Nuclear Safety Authority (FIN)
TEF-P	Transmutation Physics Experimental Facility
TEF-T	Target Test Facility
tHM	tonnes of heavy metal
THOREX	Thorium Extraction
THORP	Thermal Oxide Reprocessing Plant
tU	tonnes of uranium
WNA	World Nuclear Association

LIST OF FIGURES

1. INTRODUCTION

The ASOF project, acronym of Advanced Separation for Optimal management of spent Fuel, targets the development of new, innovative processes for the separation (WP1), conversion (WP2) and conditioning (WP3) of spent nuclear fuel. The aim of the project is to initiate research within the Belgian national framework in view of a clear optimisation of the final disposal concepts for nuclear waste (WP4). The project is conceived and executed by the Belgian Nuclear Research Centre SCK CEN within the framework of the Energy Transition Fund, founded by the Federal Public Service Economy in order to stimulate and support research and development (R&D) on energy (transition).

This report constitutes deliverable D4.**X** of WP4 and should be read as a companion to an earlier deliverable, D4.1, that examines the technoscientific "boundary conditions" for the potential realisation of partitioning and conditioning (P&C) and partitioning and transmutation (P&T) in Belgium, including factors such as the Belgian spent nuclear fuel inventory, Belgian waste classification systems, and the disposal concepts proposed by ONDRAF/NIRAS as a solution for long-term radioactive waste management (Weetjens et al., 2019). The present report expands this analysis by considering partitioning and conditioning and/or transmutation (P&C/T) as parts of a complex sociotechnical net of relationships that extends beyond the nuclear domain, most obviously to the fields of energy, climate and research policy, but that also encompasses existing (and potential) nuclear municipalities, national and regional, e.g. European, communities. The starting point of the report, then, is that P&C/T R&D, and their potential realisation, need to be understood as part of this web of actors and interactions, both influencing and being influenced by them.

This report explores the prospects of P&C/T in six nuclear countries: Finland, France, India, Japan, the UK, and the US. Each of these countries have, in different ways, been at the forefront of developing and/or implementing diverse nuclear technologies. The aim of the report is to illustrate some of the complexities and contingencies, in effect sociotechnical boundary conditions, which influence P&C/T, and that in turn are or might be influenced by P&C/T. Based on an analysis of the six cases, these conditions are situated in five interrelated dimensions: policy contexts, divisions of labour in the nuclear field, material practices and infrastructures, nuclear markets and economies, and ethical considerations. The influence of these different domains can be thought to either enable the further development of P&C/T, or to impede it. The presence and experience of reprocessing infrastructures, and policies committed to reprocessing or to closing the nuclear fuel cycle can be thought to belong to the enabling category, while past technical and infrastructural failures, low uranium prices, and policies favouring a once-through cycle and direct disposal can be seen as examples of the latter.

However, this division is not necessarily straightforward, as the close interrelations between the different domains create complexities. Countries with nuclear fuel reprocessing policies, might use existing reprocessing expertise and infrastructures related to the development of P&C/T. Conversely, vitrified wasteforms, that are unsuitable for partitioning, might be prohibitive to the development of P&C/T. Similarly, past technical incidents or unforeseen economic costs attached to reprocessing and other nuclear developments might make both politics and publics wary of future nuclear investments. As such, this report first and foremost serves as a tool to highlight the intricate connections between different societal domains and the development of P&C/T, thus illustrating how nuclear pasts and presents connect to different potential and speculative futures, rather than a linearly determined technological fate. In a next step, a forthcoming report will use the presented findings to analyse P&C/T in Belgium.

1.1 Organisation of the Report

This report is organised as follows.

Section 2 lays out the general background to the development of P&C/T, discussing the current state of nuclear power; P&C/T in the context of existing nuclear energy generation and fuel management practices; and the issue of RWM.

Section 3 presents the conceptual framework and methods underpinning data analysis.

Section 4 discusses the six country cases, focusing on the organisation of the nuclear industry; the current state of RWM; the prospects for and expected future developments regarding P&C/T in these countries; and a specific issue for each country case.

Section 5 brings these six cases together for closer analysis and discussion along five different dimensions: policy contexts, divisions of labour in the nuclear field, material practices and infrastructures, nuclear markets and economies, and ethical considerations .

Finally, section 6 lays out the conclusions of the report.

2. BACKGROUND

Nuclear energy became integrated in the energy mix in many countries in the second half of the 20th century. For some countries, nuclear energy provides an important source of baseline energy, but also an important component of climate change strategies as renewable energy (Grossi, 2020; NEA, 2020). However, for some commentators the sustainability of nuclear energy, and its viability as a component of the future energy mix is less evident. An often recurring element in such debates, is the long-term management of radioactive wastes (Kirk, 2020). Radioactive wastes are generated in all activities utilizing nuclear technology, yet the wastes produced in nuclear energy generation present particular problems. While they present a relatively small volume of the total radioactive waste accumulation, they are the most radioactive and longest lived of all radioactive wastes. In nuclear reactors, nuclear fuel is used to maintain a chain reaction. After spending some time in a reactor (i.e. a couple of years), this nuclear fuel is spent, and needs to be removed from the reactor. Spent nuclear fuel (SNF) consists mostly of unused uranium, but also of other radioactive isotopes, such as plutonium, strontium, caesium, technetium, and a range of non-radioactive isotopes. Because of the long half-lives of some of the isotopes contained in SNF, the internationally standardized aim of radioactive waste management is to contain and isolate SNF from the biosphere for a period of one million years. (OECD, 2013). Depending on country level policies SNF can be perceived as part of the radioactive waste inventory to be directly disposed of. Alternatively it can be reprocessed to extract uranium and plutonium from it (see next section). Both direct disposal and current reprocessing practices result in a need to deal with materials which pose a radiological risk for very long periods of time (from several hundreds of thousands of years up to a million and more) (Baetslé, Wakabayashi, and Sakurai, 1999).

Although proposals for the long-term management of SNF and HLW have existed for almost as long as civilian nuclear energy, radioactive waste management has taken a backseat in nuclear developments. It was not until the late 1970s that radioactive wastes emerged on the policy agenda in many European countries. Since then geological disposal, that was proposed as a potential solution to the waste issue by the US National Academy of Sciences in the 1950s (NAS, 1957) has become the favoured strategy for the long-term management of highly active, long-lived radioactive wastes. It enjoys broad technopolitical support, which is reflected in the 2011 EU Radioactive Waste Directive (EC, 2011) and the attempts of most nuclear countries to implement some sort of a geological disposal solution (IAEA, 2020).

Geological disposal includes the deposition of wastes in a disposal facility excavated several hundreds of metres underground in a suitable rock formation. Geological disposal facilities utilise a multi-barrier system where a number of engineered barriers together with the host rock are expected to isolate and contain radioactive wastes for the necessary timeframes (see Figure 1). The implementation of geological disposal, however, has proven to be a major challenge. Only a handful of countries, such as Finland and France, have made tangible advances towards the implementation of geological disposal, while others such as Japan, the UK and the US, have struggled with making headway with geological disposal. Other countries, such as India, seem to take a more waiting position for the implementation of geological disposal, and others, including Belgium, have yet to take a clear policy stance on the issue. However, the radioactive waste issue is something that needs to be addressed regardless of whether a country is committed to nuclear energy over the longer term (e.g. India) or whether it has decided to phase-out nuclear (e.g. Belgium, Germany).

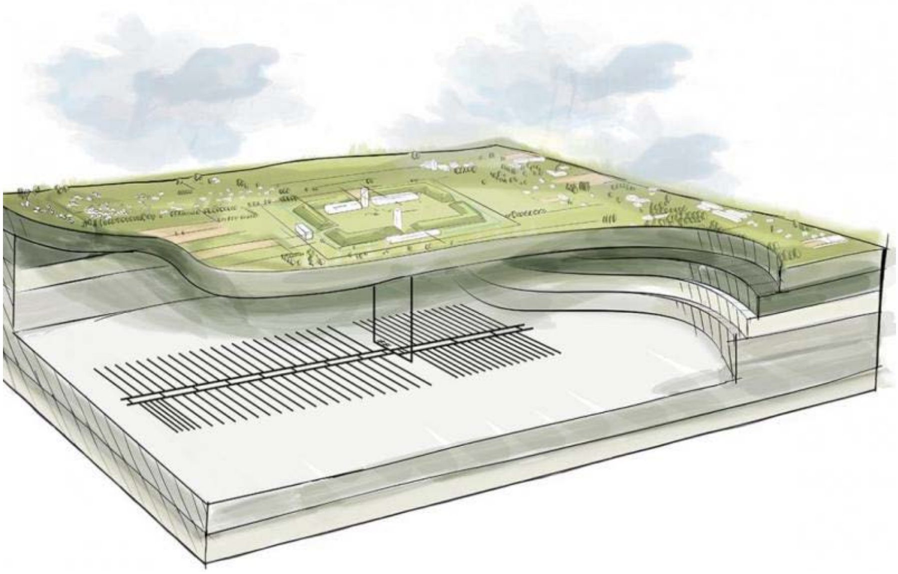

Figure 1: Reference concept for geological disposal by the Belgian radioactive waste manager (Source: ONDRAF/NIRAS)

Nuclear and policy actors have often raised public perception or acceptance as reasons for the overall lack of progress made with geological disposal (OECD, 2000; IAEA, 2020). In this context, P&C/T has been presented by some as a way to swing public opinion in favour of geological disposal (IAEA, 2004; Greneche et al., 2007). OECD-NEA, for instance, holds that "P&T has the potential to significantly improve public perception of the ability to effectively manage radioactive wastes by largely reducing the transuranic (TRU) waste masses to be stored and, consequently, to improve public acceptance of the geological repositories" (OECD-NEA, 2011: 10). In this way P&T is positioned as a complementary rather than an alternative technology to geological disposal (Schröder, 2017).

2.1 Fuel Cycles

Most countries operate what is known as a 'once-through' fuel cycle where SNF is stored and ultimately disposed. In such cases, SNF is considered as waste. A number of countries, however, consider SNF as a resource and reprocess it after it has been removed from the reactor. SNF still contains approximately 95 per cent of the original uranium, which alongside plutonium can be extracted from SNF and recycled as fuel. In such instances, the fuel cycle is referred to as 'closed'. See figure 2 for a schematic overview of these different fuel cycle options.

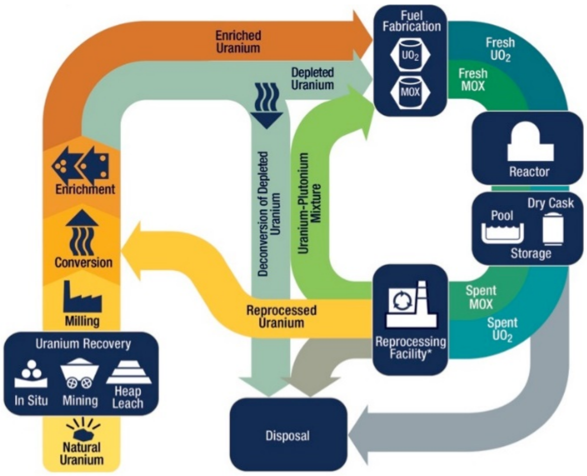

Figure 2: nuclear fuel cycles. Source: US NRC, 2018

The main reprocessing technique is PUREX (plutonium and uranium extraction), a hydrometallurgical process in which SNF elements are dissolved in concentrated nitric acid after which uranium and plutonium are chemically separated from other actinides and fission products through solvent extraction. The remaining liquid HLW is vitrified into a borosilicate glass wasteform, which is then stored to wait for disposal.

HLW contains minor actinides (MAs) and fission products that are highly radiotoxic, but also long-lived. The central MAs of concern include americium, curium and neptunium, of which especially the first two are major contributors to the decay heat, neutron output and radiotoxicity of HLW over the longer timeframes. For these reasons research on P&C/T focuses on these actinides.

2.2 Partitioning & Conditioning/Transmutation

P&T does not do away with the need to implement disposal solutions. Rather, the main objectives of P&T include the reduction of the long-term radiological hazard posed by SNF and HLW by first separating long-lived actinides from short-lived ones, and then transforming the long-lived actinides into shorter-lived ones. By reducing the radiotoxicity and thermal load of wastes, it is hoped that the design of geological disposal facilities can be simplified and their size reduced.

P&T involves two distinct technologies. The IAEA (2004) has labelled partitioning as 'super-reprocessing', and it can be understood as the broadening of existing industrial reprocessing techniques to radionuclides beyond uranium and plutonium (Baetslé, 2001). Neptunium, for instance, could be separated from SNF in a modified PUREX process. However, this is not the case for americium and curium that require new processing stages, but also new and more complex installations (ibid.; IAEA, 2004).

Transmutation, in turn, requires the development of entirely new infrastructures and technologies whose viability needs to be demonstrated on the industrial scale (Merk et al., 2019). Therefore P&C, the partitioning and conditioning of long and short-lived nuclides, is considered as an interim step towards P&T.

2.3 Roads to P&C/T

P&T has been on the table as a potential option for fuel cycle management for decades. In the 1970s, P&T was assessed in terms of offering a route for HLW and SNF management, although at that time it was deemed an option for which little incentive existed (Ramspott et al., 1992). At the end of the 1980s and the start of the 1990s, however, P&T gained increased attention, with R&D projects starting both in Japan and Europe (see Section 4). Since then, P&T research has been funded under different European Framework Programmes (Greneche et al., 2007) that have focused on specific problems related to P&T or the integration of P&T into fast reactor research (Merk et al., 2019).

In terms of infrastructures, Fast Reactors (FR) and Accelerator Driven Systems (ADS) are considered to be the main technological options for the transmutation of MAs. The FR alternative, which has particularly been examined in France, would use FRs to burn MAs and plutonium as part of commercial energy generation, and in so doing minimise waste arisings (NEA, 2003). In this approach MAs can be either mixed into the FR fuel or can be loaded into the reactor core as dedicated targets. Both of these FR options have their limitations. In the first one the amount of MAs in the reactor is limited by a maximum concentration, while the number of target positions restricts how many MA targets can be loaded into the core. Moreover, increasing the concentration of MAs in the fuel mix can pose a threat to reactor safety, which means that a relatively large fleet of FRs would be required to transmute MAs (Abderrahim, 2015).

The accelerator-driven system (ADS), or the so called 'double-strata approach' has received attention for its potential to improve the flexibility and safety characteristics of transmutation systems (NEA, 2003). In this approach, which has been extensively researched in Japan, the existing reprocessing cycle is dedicated to commercial energy generation and plutonium recycling, and provides the first stratum. The second stratum is provided by the ADS that is dedicated to incinerating highly radiotoxic MAs and fission products. ADS couples a high-power proton accelerator to a spallation target that is surrounded by a subcritical reactor core, and because of reactor physics properties, it accommodates fuels that have higher MA content than FRs can (Abderrahim, 2015). However, it has also been argued that in comparison to FR, ADS still require significantly greater R&D efforts, adding an extra hindrance to any potential implementation of this technology in the short term (CEA, 2012).

2.4 Broader Socio-technical Contexts

Based on this short introduction it is evident that P&C/T can have significant impacts on the nuclear fuel cycle, and more particularly the management of its back-end. In this light, ASOF deliverable 4.1 provided an overview of technical boundary conditions set for the development of P&C/T in the Belgian context, focusing for example on the radiological and chemical inventory of SNF, and the current disposal concept designed by the Belgian waste management organisation. P&C/T however also can be expected to have impacts upon and boundary conditions set by broader society, for instance in relation to (inter)national policy contexts, economic costs, ethical acceptability, or energy governance.

Important considerations that need to be taken into account include the relationship between P&C/T, current RWM practices, (future) nuclear energy production, and the national and international organisation of the nuclear industry. For instance, it is pertinent to assess the relation between current national efforts to implement SNF and HLW disposal and the decades of R&D that P&C/T still requires. Are the timelines mutually exclusive? What might be stakes for waiting for the maturity of P&C – and T in particular? How do past and present RWM practices, such as reprocessing, shape the potential of P&C/T? Additionally, it is important to consider questions such as what prospects might P&T have in countries that have opted for diminishing their reliance on or even phasing out nuclear energy? Can P&C/T have a future in these countries or is P&C/T reliant on a (re)affirmed commitment to nuclear energy? Finally, it needs to be asked whether the national frameworks that currently dominate nuclear strategies and decision-making are tenable for the sizable investments needed by P&C/T.

By studying six different country cases, this report aims to identify the relations between P&C/T and broader socio-technical contexts characterized by historic developments, policy decisions, economic and international positions, ethical considerations, and imagined nuclear futures. In addition to the technical boundary conditions described in D4.1, an analysis of aforementioned relations will allow us to reflect also on broader societal boundary conditions, and how these impact upon and are impacted by the development of P&C/T.

3. ANALYTICAL FRAMEWORK

Understanding P&C/T in relation to and within its broader societal context, requires tools to uncover interactions between developments in science and technology and other societal domains. This section lays out an analytical framework which combines insights from different social scientific traditions, which focus on the interplay between science, technology and society, the human and the non-human, present actions and potential futures.

3.1 Wicked Problems

Governing the back-end of the nuclear fuel cycle, and in particular SNF and HLW, encompasses a multitude of ethical, social, political and technical issues, not in the least because of a temporal dimension that renders it contentious (van de Poel, 2011). The multi-millennial timeframes over which SNF and HLW might pose a risk to their surroundings, and the ensuing perceived need to contain and isolate these materials in geological disposal facilities, present a range of uncertainties which have been discussed and analysed both in the nuclear and social scientific communities (e.g. Bergmans and Schröder, 2012; Ewing, 2012).

Managing SNF and HLW presents a 'wicked' problem (Rittel and Webber, 1973). Wicked problems are considered as 'ill-defined, ambiguous and associated with strong moral, political and professional issues. Since they are strongly stakeholder dependent, there is often little consensus about what the problem is, let alone how to deal with it. Above all, wicked problems [...] are sets of complex, interacting issues evolving in a dynamic social context' (Ritchey, 2013). Brünnengraber (2019) identifies several characteristics of geological disposal, that qualifies it as a wicked problem. These include the importance of national contexts in determining RWM routes, changing narratives, systemic risks, vast timescales, interlinked layers with different levels of action (e.g. local, national, international), potentially conflicting actors, and democracy-related challenges to RWM.

By framing geological disposal as a 'wicked problem', social scientists seek to highlight how the technical disposal option is "enmeshed in complicated political, social, environmental and economic aspects, while interests, values, preferences and financial considerations of the various actors and stakeholders diverge extremely" (Brunnengräber, 2019: 337). P&C/T has been proposed by some as a potential aide in overcoming the challenge of implementing geological disposal, most particularly in relation to the timescales involved. However, rather than conceptualizing P&C/T as a 'straightforward solution' to the challenges in the implementation of geological disposal, this report approaches P&C/T as a 'wicked' problem in its own right. Therefore, the emphasis in Sections 4 and 5 will be on tracing and understanding the relations and challenges that impact the development and possible implementation of P&C/T, and conversely what potential impacts its development and implementation might have in (future) societies.

3.2 Co-production of Science, Technology and Society

This report is underpinned by an understanding of P&C/T not just as a technological innovation, but as a sociotechnical challenge. Thus, the analytical framework presented in this section highlights the 'co-production' of science, technology and society. An extensive academic tradition in the field of Science and Technology Studies (STS) has demonstrated the close interconnections between society ('the social') and science and technology ('the technical') (e.g. Fisher, 2007; Jasanoff, 2004; Latour, 2005). STS literature has posited that what happens in the 'technical' sphere is influenced by, and influences, what happens in the 'social' sphere. In effect, the two spheres cannot be understood or analysed in isolation of each other, and innovation should rather be understood as sociotechnical. Social science and humanities have established the influence of particular 'technopolitical regimes' (Hecht, 2009) and the role of 'sociotechnical imaginaries' (Jasanoff and Kim, 2009) in shaping the choice and development of nuclear technologies. The former concept refers to how "linked sets of people, engineering and industrial practices, technological artefacts, political program, and institutional ideologies [...] act together to govern technological development and pursue technopolitics" (Hecht, 2009: 16), while the latter describes "collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology” (Jasanoff, 2015: 4).

Likewise, scholars have established that the acceptability or desirability of nuclear power interacts with and is highly contingent on broader policy contexts, but also on cultural resources, such as national identities (Bickerstaff et al., 2008; Felt, 2015). In essence, social science and humanities researchers have shown that nuclear technology is not just a technical artefact, but also a political one. It is deeply embedded in, informed and shaped by, but also enacting political agendas, and imaginations of desirable futures. From this perspective, it is both relevant and timely to examine how P&C/T might shape and be shaped by nuclear and radioactive waste policies, histories and futures at a relatively ‘early’ stage of its development.

3.3 Responsible Research and Innovation

The co-production of science, technology and society is the central premise underlying Responsible Research and Innovation (RRI). On the European level, RRI has emerged as a framework for science, technology and innovation (STI) policy . It represents the latest development in a movement away from top-down government to a more democratic governance of STI (de Saille, 2015). RRI itself has a normative policy commitment to democratise STI and to produce ‘right impacts’ rooted in the European Treaty (von Schomberg, 2012). Who defines what these ‘right outcomes’ are, who and what benefits from them, however, are not straightforward questions, and recent social scientific literatures on the governance of STI seek to address these kinds of questions (among others). Overall, RRI pinpoints that ‘successful’ technological innovation requires close reflection of the societal needs and values it connects to, and of the kinds of impacts it might have (de Saille, 2015).

RRI is therefore interested in the governance and politics of STI. RRI can be described as a means for ‘taking care of the future through collective stewardship of science and innovation in the present’ (Owen, Stilgoe and Macnaghten, 2013: 1570). It has four key dimensions; *anticipation, reflection, inclusion* and *responsiveness*, which have emerged as important within public debates on science and technology (Macnaghten and Chilvers, 2014).

> *Reflection.* Reflexivity can be seen as an inherent part of responsible action by actors and institutions, and it equates to holding a mirror up to one’s activities, assumptions and commitments. It also includes an awareness of the limits of one’s knowledge and an acknowledgement that particular framings of problems or issues might not be universally shared.
>
> *Anticipation.* The negative effects of new technologies are often unexpected or unforeseen. Anticipation stimulates methodical consideration of the known, likely, plausible and possible effects of new technologies. It encourages consideration of ‘what if’ questions, while also seeking to enhance resilience and uncover new opportunities for innovation.
>
> *Responsiveness*. Responsiveness in innovation involves responding to new emerging knowledge, perspectives, views and norms. It signals a capacity for innovation processes to change direction or shape in response to public and stakeholder values, and changing circumstances.
>
> *Inclusion.* The waning of the authority of top-down policy-making has been associated with a rise in the inclusion of new voices in the governance of science and innovation as part of a search for legitimacy. Inclusive governance, public dialogues and participatory processes ‘open up’ (Stirling, 2008) framings of issues that both challenge ingrained assumptions and support reflection on the part of actors and institutions.

These four aspects of RRI are inherently tied to each other, but also to the notions of wicked problems and co-production. RRI’s processual focus can be seen as a way of addressing wicked problems through co-productive methods - with again emphasis on the interactions between science, technology and society. Together with the notions of RRI, co-production and wicked problems provide the framework for the subsequent analysis of the country cases discussed here. This report itself can be seen as a reflexive or an anticipatory exercise on contentious socio-technical challenges.

3.4 Data collection and analysis

The data analysed in this report is composed of scientific books and articles, public national and international science and policy documents, and news articles available in English (with a few exceptions, particularly in the French and Finnish cases). Documents were gathered using common internet search engines, website searches of national and international nuclear actors, and the snowballing method, in which one key document leads to the identification of other key documents (e.g. through references). There were notable differences in the availability of documents between different countries, which in part reflects their position on P&C/T, but also different political cultures (e.g. in terms of public transparency).

The collected documents were analysed using thematic analysis (Braun and Clarke, 2006), a process of identifying patterns or themes within qualitative data. The aim of the analysis was to identify important and interesting patterns in the data, which were used to explore P&C/T, and its relation to broader historic and current (nuclear) policies and practices. Emergent themes were considered in terms of boundary conditions which characterize the potential of P&C/T developments in particular national contexts; what potential do current and historic situations offer for P&C/T development, and which conditions would require changes if P&C/T were to be implemented. The analysis here is, thus, driven by the collected data. Emergent codes (e.g. current energy matrix, waste management practices, historic interest in reprocessing) were used in organising and interpreting the data (Glaser and Strauss, 1967).

After initial analysis of the level of individual country cases, a cross-country perspective was adopted to identify codes and themes in order to cluster together different national situations and experiences. Following this, the codes and themes were examined and those that fitted together were organised into broader themes in an iterative process. The analysis and discussion presented below in Sections 4 and 5 is not exhaustive, but rather it aims to identify key themes and 'sensitizing' concepts to spur further discussion and reflection of P&C/T.

4 COUNTRY CASES

This section presents the six country cases, Finland, France, India, Japan, the UK and the US, in alphabetical order. Each case study explores the organisation of the nuclear industry, the current state of RWM, and the prospects for and expected future developments regarding P&C/T in that particular country case. Each case concludes with a country specific concern that can be considered relevant in P&C/T discussions. Findings from this section will be discussed in section 5.

4.1 FINLAND

4.1.1 Nuclear Landscape

Finland has four operational nuclear reactors at two plants, Olkiluoto on the western coast and Loviisa on the southern coast, that produced approximately 33% of the country's energy mix in 2017 (IAEA, 2019). The Olkiluoto plant is operated by Teollisuuden Voima (TVO), which is owned by a consortium of industrial and regional energy companies, while the Loviisa plant is operated by the state-owned Fortum. TVO is constructing a third reactor at Olkiluoto, whereas a new utility company, Fennovoima, has submitted a construction licence application for Finland's sixth nuclear reactor to be built in Pyhäjoki.

Finland operates a once-through fuel cycle. With regards to the frontend of the fuel cycle Finland is reliant on international collaboration, as there is no domestic uranium resource or fuel treatment and enrichment facilities. Uranium to Finnish plants is mainly sourced from Russia, Australia, Canada, China and Niger, whereas fuel enrichment is undertaken in Russia and Western Europe. However, in February 2020 a Finnish mining company, Terrafame Oy, was granted a licence by the Finnish Government to begin the extraction and treatment of uranium in the northeast of the country (MEE, 2020).

The backend of the fuel cycle is domestically managed. The reactors currently in operation are expected to produce approximately 4,000 tU of SNF during their lifetimes, and the third reactor under construction in Olkiluoto is forecasted to produce around 2,500 tU of SNF (IAEA, 2019). SNF from these reactors will be disposed of in a geological disposal facility (GDF) located in Olkiluoto. Fennovoima estimates that its reactor will generate between 1,200 and 1,800 tU during its lifespan. The company is also planning to manage its SNF through geological disposal, and it expects to have a disposal site chosen during the 2040s and to begin disposal operations in the 2090s, at the earliest (Fennovoima, 2016).

4.1.2 RWM and P&T

The Finnish policy for SNF is direct disposal. This is predicated by Finnish nuclear legislation stating that any radioactive waste produced in Finland will be treated and permanently disposed of in the country (MEE, 2011). The legislation effectively also prevents both the importation and exportation of any material considered radioactive waste from and to Finland. This in turn can have further repercussions regarding Finnish readiness and willingness to engage with P&T in the future.

Finnish SNF disposal plans are based on the so called KBS-3 multi-barrier concept developed by SKB in Sweden. The Finnish geological disposal facility (GDF), currently under construction, is situated approximately 450 metres underground in granitic bedrock on the island of Olkiluoto, near the power plant. The plans for the long-term management of SNF were laid out in the early 1980s. While the initial aim was to dispose of SNF permanently abroad by sending it for reprocessing, geological disposal was investigated from the beginning as an option for long-term SNF management. The process to find a site began in the 1980s and by the late 1990s Olkiluoto and Loviisa remained the two sites under consideration. Olkiluoto was chosen as the disposal site after the Finnish Parliament ratified the site selection in 2001. In 2004 the excavation of an underground rock characterisation and research facility, Onkalo, commenced. In 2012 the Finnish RWM organisation, Posiva applied for a construction licence for the GDF, and was granted it in 2015. Posiva is currently preparing an operational licence application for the GDF, and expects to commence disposal operations in the 2020s.

Against this backdrop P&T is unlikely to play a role in Finnish RWM. Even if the legislative side is overlooked, the Finnish nuclear establishment has been reluctant regarding the potential implementation of P&T. According to the Finnish Nuclear Radiation and Safety Authority (STUK) for P&T to be viable in the future nuclear technology on the whole needs to develop both qualitatively and quantitatively. Posiva on the other hand sees P&T as a 'technically impractical solution' to RWM, and also lists an 'increased risk of exposure to workers and, based on present experience with reprocessing', the replacement of a homogeneous, very long-lived waste inventory with a more diverse one composed of waste likely to be a chemically heterogeneous mixture of isotopes with a wider range of half-lives, which in turn would complicate disposal operations (Posiva, 2012).

Due to the advanced state of the Finnish disposal project, P&T is currently expected to play a marginal role at best in Finnish RWM (Juutilainen and Häkkinen, 2015). Nonetheless, retrievability, the technical possibility of retrieving wastes from the GDF post-disposal, is, to an extent, included in the Finnish disposal plans, although it is not a legal requirement as it is in France for instance, which leaves a technical caveat for the inclusion of P&T in the Finnish RWM strategy in the future. In fact, the potential development and viability of P&T in the future is a main, if not the main, justification for the inclusion of retrievability in the Finnish disposal concept (STUK, 2015).

While Finnish RWM is strictly geared towards the implementation of GD, Finnish nuclear legislation stipulates that research needs to be carried out into RWM methods alternative to geological disposal. Since Finland does not have a national nuclear research centre, this research is carried out within the remit of the Finnish Research Programme on Nuclear Waste Management (*Kansallinen ydinjätetutkimus*, KYT) by universities and VTT Technical Research Centre of Finland.

4.1.3 Knowledge Maintenance

KYT is based on the Finnish Nuclear Energy Act (990/1987) and the programme's aim is to ensure that the Finnish authorities have access to sufficient and comprehensive nuclear expertise that are needed for comparing RWM methods and strategies (KYT, 2020). The purpose of KYT is knowledge production and maintenance, and it offers expertise to counterweight and complement Posiva's RWM expertise and geological disposal through an examination of alternative technologies including P&T (Juutilainen, 2013). KYT is partially funded from the Nuclear Waste Fund into which the nuclear operators deposit a certain sum annually (aside from research the Fund covers all activities related to the backend of the nuclear fuel cycle).

Finnish involvement in international and/or European P&T research is justified by a need to have knowledge of the state of the art RWM technologies aside from geological disposal (MEE, 2018). This 'strategic knowledge' is considered important in case current RWM plans cannot, for some reason, be realised (Rasilainen, 2006). KYT enables Finnish involvement, even if limited, in international P&T research. Involvement in international R&D is considered important for networking purposes, for ensuring access to European projects in the future, and for guaranteeing the generation and maintenance of national nuclear expertise in the midst of, and following, a generational change in the nuclear sector (MEE, 2011; MEE, 2015).

Thus, in the Finnish case P&T has been ruled outside the current RWM strategy. Although retrievability is both justified by and leaves a caveat for the utilisation of P&T, Finnish engagement with P&T is more about the vitality of the national nuclear sector than it is about 'seriously' considering the role of P&T as part of Finnish nuclear futures.

4.2 FRANCE

4.2.1 Nuclear Landscape

France currently has 56 nuclear power reactors in operation, which in 2019 provided 70.6% of the total French electricity generation (IAEA, 2020). As such, it currently is the country with the highest share of nuclear in its energy matrix worldwide (World Nuclear Association, 2020). In 2015, however, the French national government decided to reduce the share of nuclear to 50% by 2025, a goal which currently has been postponed to 2035 (IAEA, 2020; World Nuclear Association, 2020c). Two reactors have been decommissioned in 2020 (both at Fessenheim), while a new reactor is under construction at the Flamanville NPP (IAEA, 2020). All nuclear energy reactors are operated by Electricité de France (EDF), a multinational company in which the French state has a majority stake. Other key actors in the French nuclear field are the French nuclear safety authority ASN (Autorité de Sûreté Nucléaire), the Institute for Radiological Protection and Nuclear Safety IRSN (Institut de Radioprotection et de Sûreté Nucléaire), the research and development centre CEA (Commissariat à l'énergie atomique et aux énergies alternatives), the radioactive waste management organization ANDRA (Agence nationale pour la gestion des déchets radioactifs), and the nuclear fuel cycle company Orano. As with EDF, also a majority share of this latter actor is owned by the French state.

For many decades now, France is striving for a closed fuel cycle, being one of few countries to domestically reprocess its spent nuclear fuel. Currently, this reprocessing strategy diminishes the use of uranium by around 12%, as fission products and minor actinides are vitrified and stored after separation, and retrieved uranium and plutonium can be re-used once in PWRs (Carré and Delbecq, 2009). Historically, many countries from across Europe and beyond have relied upon French reprocessing activities for their spent fuel. However, over time, the number of countries which France can count as customers for its reprocessing services has dwindled, meaning that nowadays the large majority of spent fuel sent to French reprocessing facilities comes from its domestic nuclear reactors (Schneider and Marignac, 2008; World Nuclear Association, 2020d). These reprocessing activities take place at two sites: at the La Hague plant, spent fuel is reprocessed, while in the MELOX facility at the Marcoule site, MOX fuel is manufactured from the extracted uranium and plutonium (Krikorian, 2019). At the end of 2019, the La Hague plant has, since its initiation, reprocessed approximately 36 502 tonnes of spent fuel from light water reactors, of which 71% originated from French reactors (Orano, 2019). While French nuclear reactors create around 1200 tonnes of spent fuel each year, EDF –which operates these reactors- does not designate all spent fuel for reprocessing (yet). In this way, a strategic reserve is built, in order to provide plutonium required for GenIV nuclear reactors (WNA, 2020d).

4.2.2 RWM and P&T

At the end of 2018, the French radioactive waste inventory included 3880m^3 of high-level waste, mostly originating from reprocessing activities (ANDRA, 2020a). Given France's reprocessing policy, spent fuel as such is not considered a final waste according to French regulation (OECD NEA, 2016). The main legal framework for managing these (and other) radioactive materials and wastes is provided by Act No. 91-1381 of 30 December 1991 (also known as the Bataille Law) and by Planning Act No. 2006-739 of 28 June 2006 concerning the sustainable management of radioactive materials and waste (OECD NEA, 2011b).

The 1991 Bataille Law followed a turbulent period, in which negative public attitudes toward radioactive waste –and in particular the siting of an underground laboratory- lead the French government to set a one year moratorium on the topic and to submit the issue to the French parliamentary office for evaluation of scientific and technological options (CEA, 2016). The recommendations made by this parliamentary office were mostly translated in the Bataille Law, which inter alia laid down three main objectives for R&D over a 15 year period: 1) deep geological repositories, 2) long-term storage, and 3) partitioning and transmutation. Furthermore, it established new procedures for public information and debate. Subsequently, the 2006 act inter alia declared that deep geological disposal is the reference solution for high-level waste in France, and that a plan for the management of radioactive materials and waste should be drafted and updated every three years (ASN, 2006). Furthermore, in Act 2016-1015 of 25 July 2016, the procedures for a *reversible* deep geological repository are specified, defining the concept of reversibility as "the possibility offered to successive generations either to continue with the construction and then operation of successive tranches of a repository, or to reassess the choices previously made and change the management solutions" (ASN, 2017: 175). In terms of siting, the 2006 law stipulates a trajectory for opening the proposed geological repository at Bure, a commune in the Meuse department which was identified as a potential site for a GD in the 1990s (ASN, 2006). Bure already hosts ANDRA's Underground Research Laboratory, which researches the disposal of high-level waste in deep clay undergrounds. While awaiting the realization of this geological disposal project - referred to as Cigéo (centre industriel de stockage géologique) - high-level wastes are currently stored at Orano's La Hague and Marcoule sites. In the latest available national plan for the management of radioactive materials and waste (2016-2018), it is mentioned how reception of the first radioactive waste packages in the deep geological disposal is scheduled for around 2030, while the ANDRA website forecasts 2035 for this milestone (ANDRA, 2020b).

It is also noteworthy that France has a considerate history of public involvement in radioactive waste management, seeing "the existence of a democratic dialogue at all levels" as "one of the cornerstones of the radioactive materials and waste management policy" (ASN, 2017: 50). This is translated in initiatives both at the local level, with local information committees (CLIs) around each nuclear installation, and at the national level, with national public debates on the issue (see e.g. https://pngmdr.debatpublic.fr/).

As stated, the 1991 Bataille Law prescribed that R&D efforts should also be directed to the exploration of partitioning and transmutation in the back-end of the French nuclear fuel cycle, a focus which was reconfirmed in the 2006 law. In this latter act it was more specifically stated that by 2012, an assessment should be made of the industrial prospects of P&T, and that there should be an aim towards opening a first prototype installation before the end of 2020 (ASN, 2006). Overall, given this legal imperative, France has a rather substantial history in exploring and developing the P&T option. For example, a panel of international experts reviewing a CEA report on P&T R&D in the period 1991 – 2005 notes how with regard to liquid-liquid extraction of minor actinides, France has done "some excellent innovative work" putting it "at the forefront of international efforts" (OECD NEA, 2006: 14). Over the years, the CEA had developed a range of actinide partitioning processes, such as the GANEX (Group ActiNide EXtraction) process, the DIAMEX-SANEX (DIAMide EXtraction – Selective ActiNide EXtraction) process, the COEX (CO-EXtraction of uranium and plutonium) process, and the EXAm (Selective EXtraction of Americium) process (IRSN, 2019). In a summary of its 2012 assessment of P&T, the CEA hence posited that "the feasibility of minor actinide separation has been demonstrated in the laboratory for all the options under consideration today. There are no theoretical obstacles to extrapolating these processes to commercial scale" (CEA, 2012: 24). While the report also highlights progress in research on transmutation (e.g. demonstrating the feasibility of americium transmutation on a very small scale), it recognizes that important steps are still ongoing/need to be taken, and that transmutation on an industrial scale can also have certain downsides (e.g. regarding the operation of the material cycle) or uncertainties (e.g. regarding safety and industrial risk), besides its positive effects on radioactive waste properties (CEA, 2012).

Overall, the 2012 CEA report, and French R&D more generally, seem to attach more benefits to fast neutron reactors in a P&T strategy, as compared to dedicated infrastructures with an accelerator-driven system (CEA, 2012). This latter option however has also been researched, e.g. by the National Center for Scientific Research CNRS (IAEA, 2015). Regarding fast neutron reactors, effort has been mostly dedicated to the development and implementation of sodium-cooled fast reactors. Historically, France has operated three experimental sodium-cooled fast reactors. The first was Rapsodie, which went critical in 1967, five years after construction started, and operated until 1983. In 1973, Phénix, a second experimental fast reactor, became operational. While until the end of the 1980s, Phénix had a good operational record, later on it was troubled by several incidents, and was finally shut down in 2009 (Schneider, 2009). Also in the 1970s, plans were made to establish a first commercially sized fast breeder reactor; Superphénix. These plans met with fierce opposition, and in 1976 thousands of protesters occupied the site on which the reactor was to be built, followed by heavy protests a year later (Schneider, 2009). Superphénix went critical in 1985, but was plagued by incidents and continued opposition, which eventually led to its permanent closure in 1997. At the start of the 21st century, a new initiative was launched: the construction of an Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID). Projected to be constructed at the Marcoule nuclear site, the design studies for ASTRID started in 2010, and commissioning was foreseen in the 2020s (Varaine et al., 2018a). In its 2012 report, the CEA identified ASTRID as "the indispensable step before a possible industrial deployment [of 4th generation, sodium-cooled fast reactors]", and highlighted R&D on transmutation as one of the pillars of the ASTRID project. However, in 2019, the project was cancelled, after spending 738 million euros in the period up to 2017 (Le Monde, 2019).

4.2.3 After ASTRID

Despite the fact that ASTRID was one of the major French nuclear projects in the past decade, there is surprisingly little official communication to be found on its cancellation, and the reasons or justifications underlying this decision in 2019. On the website of the CEA, which was the main organizational actor in the development of ASTRID, no particular explanation or interpretation of the 2019 decision can be found, and also the website of the nuclear regulator (ASN) provides no clarification in this regard. A 2019 report by the "Commission nationale d'évaluation des recherches et études relatives à la gestion des matières et des déchets radioactifs" connects the cancellation of ASTRID to a wider trend of postponing the foreseen deployment of fast reactors in France (CNE, 2019). In different press articles on the subject, it is reported that the CEA sees the 'current energy market situation' at the root of this decision (Reuters, 2019). In particular, low uranium prices get the blame (Le Figaro, 2019). One article also argues a lack of political support as reflected in the decision to reduce the share of nuclear in France's energy matrix to 50%, and identifies a growing French uncertainty after Japan cancelled its Monju fast reactor (Power Mag, 2019).

Irrespective of why the decision has been taken, the CEA has declared that they will not undertake similar projects in the short- to midterm, in fact stating that the industrial development of Gen IV reactors will not happen before the second half of the 21st century (Reuters, 2020). The cancellation of ASTRID has sparked concerns regarding the potential loss of knowledge and experience (Berniolles, 2019; CNE, 2019; Rodriguez et al., 2020), meaning a potential setback in obtaining the goal of closing the nuclear fuel cycle, which is now set in the long term. While France has clearly shown interest and dedication in the development of P&T as an option for the back-end of its fuel cycle, its past experiences also demonstrate the complexity of translating imagined futures into actual practice.

4.3 INDIA

4.3.1 Nuclear Landscape

Soon after its independence in 1947, India expressed clear nuclear ambitions, with the development of its atomic energy act and atomic energy commission in 1948, and the establishment of its first nuclear research facility (the Atomic Energy Establishment, nowadays known as the Bhabha Atomic Research Centre (BARC)) and Department of Atomic Energy (DAE) in 1954 (IAEA, 2016). Currently nuclear energy only amounts to about 3% of India's energy matrix (IAEA, 2016), but expectations are that the share of nuclear will grow in the future, in order to face the country's growing population and energy demand (World Nuclear Association, 2020e). The country currently has 22 nuclear power reactors in operation, amounting to a total of 6780 MW, and another 7 reactors under construction (DAE, 2019; World Nuclear Association, 2020e). All 22 reactors are operated by Nuclear Power Corporation of India Limited (NPCIL), a public sector enterprise owned by the Government of India (IAEA, 2016).

The Indian nuclear fuel chain cannot be understood without reference to its unique three-stage approach to nuclear energy. This three stage approach has been developed in the 1950s as the 'Thorium Utilization for Sustainable Power Programme', and is based on utilizing India's vast thorium reserves (in contrast to its limited uranium reserves) (see e.g. Brookhaven National Laboratory, 2011; IAEA, 2016; Ram Mohan and Aggarwal, 2009). This approach encompasses the following steps: 1) the use of natural uranium-fuelled pressurized heavy water reactors (PHWs) and the reprocessing of SNF for plutonium extraction (needed for the second stage), 2) the use of fast breeder reactors which are plutonium (and natural uranium) fuelled, and which convert thorium to build the inventory of uranium-233 (needed for the 3rd stage, as thorium itself is not fissile), 3) the use of advanced heavy water reactors, based on a thorium cycle, and producing more uranium-233. Although steps have been taken regarding piloting facilities and testing techniques for stage 2 and 3, on an industrial level, only the first stage has been attained and implemented for the moment.

Regarding phase two, the Indira Gandhi Centre for Atomic Research (IGCAR) in Kalpakkam conducts R&D on fast breeder reactors and the connected fuel cycle technologies (DAE, 2019). In this light, a Fast Breeder Test Reactor (FBTR) has reached its first criticality in 1985, and a 500 MWe Prototype Fast Breeder Reactor (PFBR) is under development at Kalpakkam (DAE, 2019). The third phase, which relies on the development of Advanced Heavy Water Reactors fuelled by thorium, has as its most concrete realizations the ongoing development of a 300 MWe Advanced Heavy Water Reactor by BARC, and the continued operation of a uranium-233 fuelled research reactor, the Kalpakkam Mini Reactor (KAMINI) (DAE, 2019).

4.3.2 RWM and P&T

The Indian approach heavily relies on the reprocessing of SNF in its different envisioned stages (Raj et al., 2006; Natarajan, 2017). Facilities for SNF reprocessing have been set up at Trombay, Tarapur and Kalpakkam. Reprocessing activities in the first stage are primarily directed at the separation and build-up of a plutonium inventory, intended for fuel fabrication in the second stage (Raj et al., 2006). In the second stage, the FBTR commissioned in 1985 uses mixed carbide fuel (70% plutonium and 30% uranium). Because of the increased plutonium content, the PUREX process was adapted, and a test plant has been commissioned in 2003 (the CORAL facility at IGCAR), a Demonstration Fast Reactor Fuel Reprocessing Facility is constructed and a fast reactor fuel cycle facility is designed (Natarajan, 2017). India's current R&D on the second phase of its staged approach, has also resulted in the production of irradiated thorium. Using a THOREX process, Uranium 233 has been separated from this irradiated thorium by BARC and IGCAR (Natarajan, 2017).

All of these reprocessing processes, besides providing resources for future nuclear fuel, also result in various forms of radioactive waste. Overall, the Indian RWM strategy is based on three pillars: 1) delay and decay of short lived radionuclides, 2) concentration and containment of radioactivity as much as practicable, and 3) dilution and dispersion of low-level activity to the environment (AERB, 2007; Ram Mohan and Aggarwal, 2009;

Raj et al., 2006; Wattal, 2013). The handling of radioactive waste is regulated by the 1987 Atomic Energy (Safe Disposal Of Radioactive Wastes) Rules. India's RWM strategy requires that near-surface disposals are constructed and operated at each nuclear site, serving the disposal of low-and intermediate level (solid) waste (Raj et al. 2006; Wattal, 2013). HLW is contained through vitrification in a glass matrix at one of India's vitrification facilities in Trombay, Tarapur or Kalpakkam (Kaushik, 2014). This vitrified waste is currently stored, waiting for its long-term disposal in a GDF.

While India's aim to dispose of HLW in deep geological facilities puts it in line with the international consensus on HLW management, the actual efforts directed at realizing this long-term strategy seem to be scattered and their current status is difficult to assess. In a 2015 interview, the director of the Nuclear Recycle Group of the BARC, P.K. Wattal, for example mentions how "the need for a deep geological repository would arise only after 30-40 years [because of the cooling period of vitrified waste]", while at the same time pointing out how R&D is actually ongoing regarding host rock characterization (Paliwal, 2015). The websites of the major Indian nuclear organizations (DAE, AERB, BARC, IGCAR) provide little to no information on the current status of India's development of a GDF, at least not to an English speaking public. Some articles do mention efforts towards siting and soil characterization (Misra, 2011; Ram Mohan and Aggarwal, 2009; Raj et al., 2006), with crystalline rock apparently being favoured (Ram Mohan and Aggarwal, 2009). A 2011 article by a BARC researcher mentions how "preliminary conceptual design and layout of a geological repository with a capacity of 10000 overpacks spread over about four square kilometre area have been developed" (Misra, 2011: 482). Also the plan to construct an underground research facility is mentioned (Misra, 2011; NDA, 2013; Raj et al., 2006), although to the best of our knowledge, this has not yet been realized today.

In the context of India's reprocessing strategy, the country has developed experience with partitioning of uranium and plutonium from SNF. The partitioning of other actinides and of fission products is also being researched, and in some cases practiced on an engineering scale. In Tarapur, BARC operates an Actinide Separation Demonstration Facility (ASDF), focused on the partitioning of minor actinides (Manohar, 2016), and in Trombay, a Solvent Extraction Facility has been in operation since 2015 (Patel et al., 2016). The latter is designed to extract uranium (first cycle), and the fission products caesium (second cycle), and strontium, and minor actinides/lanthanides (third cycle) (Patel et al., 2016). Interestingly, separation of some of these elements is not only conducted with the goal of conditioning or transmutation and subsequent disposal, but also with a striving to search for other applications. In 2015, for example, India has started with extracting Cs-137 from liquid HLW, and vitrifying it in 'glass pencils' which are used as a source for blood irradiation machines (Patel et al, 2016; Yadav and Aggarwal, 2019). While partitioning of MAs and some FPs is thus pursued, and offers an essential step towards transmutation, the position of transmutation in the Indian system is again difficult to assess.

Different sources mention the extensive R&D being conducted on P&T in the Indian case. The above facilities provide ample proof in this direction (IAEA, 2010; Natarajan, 2017; Raj, 2005; Raj et al., 2006), as well as research on fast reactors and accelerator driven systems, both potential infrastructural routes towards transmutation (Kale; 2020; Raj, 2005; Singh, 2017). However, the extent to which P&T is actually perceived as a future part of the Indian fuel cycle is less clear. As closing the fuel cycle is the main impetus of India's three stage approach, waste minimization and sustainability of the nuclear power programme can be seen as logical aims, and both can be connected to the development and implementation of P&T (Kale, 2020; Raj, 2005). But as with geological disposal, or RWM more generally, there is little information available (at least in English) on the current status of P&T with regard to its position in the Indian management of the back-end of the fuel cycle.

4.3.3 Self-sufficiency

India's three stage approach and connected efforts at closing the nuclear fuel cycle underline the importance of 'self-reliance' for understanding past and potential future developments in the Indian nuclear field. India's emphasis on self-reliance can partly be attributed to its vast thorium reserves, as mentioned above. But also its position in the international nuclear landscape is an important factor: in 1974, the Indian government conducted nuclear tests which were largely condemned by the international community. In the aftermath of these nuclear tests, the Nuclear Supplier's Group was established as a multilateral to install an extra control on exports of nuclear materials. As India was excluded from this supplier's group, the country found itself in a situation of international nuclear isolation, hence pushing its need for self-reliance and 'indigenously' developed technologies and infrastructures (Ram Mohan and Aggarwal, 2009).

However, over the past decade, India's position in the international nuclear landscape has known some important changes, potentially also impacting on the necessity of its three-stage approach. In 2008, the Nuclear Supplier's Group, granted a waiver to India, lifting some of its previous exclusions from international nuclear trade and exchange (Ram Mohan and Aggarwal, 2009). More precisely, this waiver allowed India to conduct nuclear trade with supplier countries, making it possible to import uranium, but also e.g. reactor technologies (Kumar, 2014). It has been noted how this may lead policymakers to re-evaluate the use of reprocessing, and the goal of 'closing' the nuclear fuel cycle more generally (Kumar, 2014; Ram Mohan and Aggarwal, 2009).

4.4 JAPAN

4.4.1 Nuclear Landscape

Japan has 54 reactors, all of which were closed for safety checks in the immediate aftermath of the Fukushima triple disaster in March 2011. By March 2020 nine were back online, while further six had passed regulatory checks. Another 18 reactors are at various stages of the Nuclear Regulation Authority's (NRA) review process and it remains uncertain whether they will be connected to the grid again (IAE, 2020; WNA, 2020a). Currently nuclear accounts for about 3% of the total electricity generated, compared to its 30% share of the total mix before Fukushima (WNA, 2020a). The nuclear industry in Japan is privately operated. Nuclear is considered by the Japanese Government as an important source of base-load energy in the long-term, and it aims to bring the share of nuclear back up to 20-22% of the total by 2030 despite announcing its aim to reduce the country's dependency on nuclear power (IEA, 2020; METI, 2018).

Japan, as a resource poor country, operates a closed nuclear fuel cycle, and it is the only state without nuclear weapons capability to reprocess SNF (Ogawa and Schiffer, 2007). Its basic nuclear policy has been to recycle uranium and utilise plutonium as MOX in order to reduce its dependency on uranium imports from countries such as Australia, Canada and Kazakhstan (METI, 2018; von Hippel and Hayes, 2018; WNA, 2020a). Historically, Japan sent SNF for reprocessing at La Hague in France and Sellafield in the UK. SNF shipments to France began in the 1970s and to the UK in the 1980s on the premise that HLW resulting from reprocessing would be returned to Japan for disposal. A total of twelve HLW shipments were undertaken from France, and they ceased in 2007, while shipments from the UK commenced in 2010. By 2014 four out of the eleven anticipated shipments had been completed (WNA, 2020a). The returned HLW is stored in the Rokkasho interim storage facility that opened in 1995. Rokkasho is also a site for a reprocessing plant that was expected to start operations in 2008, but the beginning of which has been postponed for 2021, for technical challenges, but also because of Fukushima. Aside from mining, Japan has a complete fuel chain from enrichment to reprocessing (IAEA, 2020b).

4.4.2 RWM and P&T

Japan currently stores about 18,000 tons of SNF, which, combined with the already reprocessed SNF, represent radioactive waste equivalent to about 25,000 canisters of vitrified waste (Japan Times, 2017). Japan's favoured policy for the long-term management of HLW is geological disposal. As in most nuclear countries, the implementation of geological disposal has proved out to be a major challenge, and the search for a disposal site has not moved beyond research and development (CSIS, 2014). The Japanese RWM organisation, NUMO, charged with the implementation of geological disposal nonetheless expects a site to be selected around the mid-2020s and a GDF to become operational approximately a decade later (WNA, 2020a). Meanwhile, the management of SNF is a key concern, as storage facilities are nearing their maximum capacity as SNF awaits for reprocessing (von Hippel and Hayes, 2018). Meanwhile, the Science Council of Japan has recommended that R&D on transmutation technologies will be prioritised to reduce the risks of HLW (Oigawa, 2015; Sasa, 2015).

Japan has been one of the most active countries in the development of P&T. It collaborates with Belgium on the ADS and with France on FRs, which for long were its priority (SCK CEN, 2017; Varaine et al., 2018b). R&D into P&T commenced in Japan under the OMEGA program in 1988. Initially the programme focused on maximising the energy that could be extracted from uranium, but more recently the emphasis has been on the ability to deal with plutonium and MAs in a flexible way (Oigawa, 2015). The Japan Atomic Energy Agency (JAEA) carried out a feasibility study on the commercialisation of fast breeder reactors (FBR) from 1999 to 2005. FBRs have been considered as a means to deal with Japan's plutonium stock, and a Fast Reactor Cycle Technology Development (FaCT) programme was launched in 2006 to advance the commercialisation of fast reactor cycle technology, but it was halted in the aftermath of Fukushima (IAEA, 2020b). In 2014 Japan committed to support the development of ASTRID in France. However, following the 2018 French decision to scale down ASTRID to reduce construction costs, Toshiba announced Japan might have to build its own demonstration reactor, as the scaled down ASTRID is a step back for Japan's FBR development (WNA, 2020a).

In 2013, a Government working party recommended that ADS should be moved from research to demonstration stage, and that a dedicated transmutation fuel and its cycle, the so called 'double-strata approach' should also be supported (ibid.). In line with the recommendations, the Japanese Government promotes the development of transmutation technologies to reduce the volume and radiotoxicity of radioactive wastes (METI, 2018).

JAEA operates J-PARC (Japan Proton Accelerator Research Complex), which is composed of Transmutation Physics Experimental Facility (TEF-P) to investigate the physical properties of subcritical reactors and to accumulate operational experience of the ADS. JAEA wants to complement TEF-P with an ADS Target Test Facility (TEF-T) to research and develop a spallation target and related materials with a high-power proton beam (Oigawa, 2018**;** Sasa, 2015). JAEA's P&T strategy extends beyond MAs, plutonium and uranium, as it looks to separate, for instance, platinum group metals for potential reuse, although it admits that these might just be destined for disposal (Oigawa, 2018). In 2019 the JAEA reported on developing a so called "SELECT Process" for the separation of highly toxic radionuclides from HLW with a high efficiency, and it expects the process to mark a step forward in the practical use of P&T leading to toxicity and volume reduction of HLW (JAEA, 2019).

4.4.3 Fukushima Effect

Japanese nuclear industry and its future cannot be discussed without reference to the so called Fukushima effect (Hindmarsh and Priestley, 2016), as the accident severely disrupted the Japanese nuclear industry. It brought nuclear energy generation momentarily to a complete standstill, eroded public trust in the nuclear industry, led to the development and establishment of new regulatory practices and processes, and affected the development and potential implementation of advanced fuel cycles (IAEA, 2020b). On one hand, Fukushima brought RWM, its importance and challenges related to it, to public attention, and it also increased interest in P&T technologies, as a way of managing or mitigating the long-term hazards of radioactive waste (METI, 2018). On the other hand, it contributed to the closure of Japan's FR prototypes, Monju ja Joyo (JAEA, 2019). Monju was shut down by the Japanese Government in 2016 partly because of technical issues and partly, because of difficulties of retrofitting the reactor according to new regulations post-Fukushima (ibid.).

Moreover, although the Japanese Government considers nuclear as an important baseload energy source, its aim to reduce the country's dependency on nuclear and consideration of a possible nuclear phase out around 2050 (IAEA, 2020b; METI, 2018) raise questions about the viability of the P&T alternative as part of Japan's long-term RWM strategy, as P&T requires a long-term commitment on nuclear energy to make it feasible on an industrial scale. Perhaps unsurprisingly then, the Japanese Government advocates a flexible approach to nuclear policy on the account of 'various uncertainties, including the technological trend, energy supply-demand balance and the international situation' (METI, 2018).

4.5 UNITED KINGDOM

4.5.1 Nuclear Landscape

The UK has 15 operational nuclear reactors that accounted for 19% of the country's total energy mix in 2017. 31 reactors have already been closed and seven are set to be shut down in the next decade. Currently one new reactor is under construction (at Hinkley Point C nuclear power station in Somerset), although proposals to construct reactors at the existing nuclear sites at Sizewell, Bradwell, Wylfa and Oldbury exist. Plans to develop nuclear new build in Moorside near Sellafield were frozen in 2017 due to the developer Toshiba's financial difficulties, yet in the summer of 2020 plans to construct small modular reactors (SMRs) at the site were put forward (NIA, 2020; BBC; 2020). The UK nuclear industry was privatised in 1996 with the exclusion of Magnox reactors that remained under state control until 2015, when the last one of them was closed down (Young, 2003; NDA and Magnox Ltd, 2019).

Apart from uranium mining and uranium ore purification, the UK until recently had an independent nuclear fuel cycle capability ranging from uranium conversion, enrichment and fuel manufacture to SNF reprocessing, transport, RWM and decommissioning (IAEA, 2018). The UK has more than 50 years of experience of reprocessing. The Sellafield MOX plant (SMP) and Thermal Oxide Reprocessing Plant (THORP) operated on the Sellafield site in Cumbria for 1964-2020 and 1992-2018 respectively (Leafe, 2017). The decision to close SMP followed the loss of Japanese reprocessing contracts in the wake of Fukushima, while THORP never reached its reprocessing targets and operated at a financial loss (NDA, 2011a; Forwood, 2018).

The decision to cease reprocessing operations means that the UK is transitioning from a partially closed fuel cycle to a once-through cycle. This in turn impacts RWM as SNF is/may be designated as waste. According to current UK plans, SNF from the youngest UK reactor at Sizewell (a Pressurised Water Reactor connected to the grid in 1995) and SNF from potential nuclear new build reactors is to be disposed of as waste in a future geological disposal facility. However, the UK's National Nuclear Laboratory (NNL) observes that a nuclear expansion might generate such significant volumes of high burnup SNF that its management in an open cycle might prove difficult (NNL, 2015; see below).

4.5.2 RWM and P&T

In 2006, the UK Committee on Radioactive Waste Management (CoRWM) recommended geological disposal as the UK's long-term RWM strategy. During its deliberative process, CoRWM considered all RWM options that had been given serious consideration by the international scientific community, including P&T. It, however, ruled out the P&T option, because it did not present a 'complete waste management option', but also because it lacked a proof of concept, and the cost of P&T was judged to be disproportionate to the benefits it could offer (CoRWM, 2006, 2018). CoRWM did nonetheless consider recommending that the UK Government keep a 'watching brief' on P&T.

The UK Government committed to GD as a policy first in a 2008 White Paper and again in 2014 (BERR, 2008; DECC, 2014), and P&T was not mentioned in either of the policy documents. In fact, bodies such as the NNL and the Government's Radioactive Waste Management Advisory Committee (RWMAC) have asserted that P&T is not practicable, realistic or justifiable for the UK nuclear waste inventory (RWMAC, 2003; NNL, 2014).

The UK's radioactive waste inventory is updated every three years with the last update having taken place in 2019 (NDA, 2020). The Inventory contains information about existing radioactive wastes that already exist or are expected to arise in the future, but it also contains information about radioactive materials (such as, plutonium) that currently are not classed as waste, but may be classed as such in the future if no further use can be found for them. The waste inventory is composed of very low level waste – 2,690,000m^3 total volume of packaged waste; low level waste (LLW) – 1,280,000m^3 total volume of packaged waste; intermediate level waste (ILW) –

500,000m^3 total volume of packaged waste; and high level waste (HLW) – 1,500m^3 total volume of packaged waste.

The UK's reprocessing HLW is vitrified in borosilicate glass. Vitrified waste packages have been designed suitable for storage and disposal, and extracting MAs is not considered a viable option. Even if it was, it is considered that the associated costs would likely be prohibitive and the logistics very difficult (King, 2003; NNL, 2014). P&T is thus considered unsuitable for the UK HLW, but it has also been rejected as a treatment for cementitious ILW, because in these wasteforms radionuclides are dispersed through too large a volume. This effectively means that the costs of P&T would be high and even larger waste volumes could potentially be generated by the process (Al-Kahili et al., 2003). Even if P&T proved a technically and economically feasible option, it is assumed that its overall impact on the safety would be negligible. The UK's reference concept for geological disposal assumes that waste packages are emplaced in alkaline backfill, which would ensure that MA species are relatively immobile. Therefore, benefits gained from P&T are considered very limited (NNL, 2015). It is expected that the waste carrying capacity of the UK GDF is mainly determined by decay heat output, in which case P&T might provide means for reducing decay heat. Yet, it has been argued that this strategy would be relevant only in a scenario with a large nuclear programme where minimising the number of geological disposal facilities is a major consideration (ibid.). Likewise, the RWMAC (2003) holds that P&T cannot be introduced in isolation from a renewed commitment to nuclear power and reprocessing plants, as partitioning would require continued use of reprocessing plants and (almost certainly) investment in new reactors.

4.5.3 Plutonium Management

The UK stores 140 tonnes of plutonium, including foreign, mostly, but not exclusively Japanese-owned, plutonium that has resulted from historical reprocessing contracts. Initially, plutonium separation in the UK was driven by weapons needs, but from the 1960s onwards also by a concern over the availability of uranium. Plutonium was envisioned as fuel for FRs that the UK was developing, and the SNF from UK's Magnox reactors was explicitly designed to be reprocessed, and thus to potentially support a future plutonium economy (Hyatt, 2020). FRs were considered to provide a solution to the UK's long-term energy challenge, as they could produce nuclear materials for new fuel. In the 1950s, the Dounreay Fast Reactor (DFR) was developed in Scotland. It was an experimental reactor, and due to its 'relative success' it was followed with a more advanced FR, also at Dounreay, known as the Prototype Fast Reactor. (PFR) Following the commissioning of the PFR in 1974, the DFR stopped operating in 1977 (NDA, 2011b). The PFR, in turn, was closed in 1994 when the UK Government abandoned the development of FRs as commercially unviable, but continued reprocessing until 2020, leaving the UK with the largest plutonium stock in the world (NDA, 2019b).

The UK Institute of Mechanical Engineers (IMechE) has advocated a 'three-tier' approach to the management of the UK's plutonium stock. It holds that plutonium of sufficiently high grade should be reused as MOX fuel, while a lower-grade material should be recycled in a FR and poor quality plutonium should be prepared for disposal in a GDF (IMechE, 2013). The UK Government, however, has preferred a two-tier approach to plutonium management. It holds that for nuclear security reasons, converting plutonium into MOX reuse is a preferable, but also the most credible and technologically mature option (DECC, 2011). While the Government recognises that some plutonium needs to be disposed of as it cannot be converted to MOX, it does not consider FRs as a realistic strategy, as there is 'no guarantee that commercial fast reactors will be available for several decades' (ibid.). On the other hand, the fast reactor option could extract useful energy from plutonium, contributing to the UK's energy security, but it could also reduce the volume and toxicity of wastes needing long-term management (NDA, 2019b). Therefore, and in part due to the long timeframes it takes to implement any plutonium management strategy, the UK Government and the Nuclear Decommissioning Authority (NDA) continue to monitor progress regarding the development of FRs elsewhere (DECC, 2011; NDA, 2019b).

Additionally, commentators have observed that the MOX alternative has its uncertainties, at least in the UK context. While plutonium has been reused as MOX in commercial light water reactors (LWRs) both in Japan and France, the UK's experiences of MOX fuel manufacture did not achieve the design throughput, and thus the production of MOX on a commercial scale remains to be convincingly demonstrated in the UK context (Hyatt, 2020; IMechE, 2013). Moreover, none of the current nuclear reactors in the UK is licensed to use MOX fuel (IMEchE, 2013), and more crucially, no reactor operator has signalled any interest in using MOX, as uranium supply is expected to meet demands for the foreseeable future, meaning that while MOX might be technically feasible, there currently is very low economic incentive for plutonium reuse as MOX in LWRs (Hyatt, 2020).

It has been argued that decisions about plutonium management need to take into consideration potential interdependencies with potential nuclear new build projects, geological disposal plans and questions about national security (ibid.). Thus, while the UK Government prefers the MOX-option, its commitment to it is lukewarm, since 'only when the Government is confident that its preferred option could be implemented safely and securely, that is affordable, deliverable, and offers value for money, will it be in a position to proceed with a new MOX plant' (DECC, 2011: 4).

4.6 UNITED STATES

4.6.1 Nuclear Landscape

Currently, the United States has 96 operating nuclear reactors, accounting for 20% of US electricity production (Energy Information Administration, 2020a). 17 nuclear reactors are no longer operating, and in various stages of decommissioning, while the newest reactor –the Watts Bar Unit 2 in Tennessee- came online in 2016 (ibid.). As more reactors are planned to be decommissioned in the (near) future, the share of nuclear in the US energy mix is expected to diminish in the coming years (Cho, 2020). At the same time, several initiatives have been taken to revive (private) interest in nuclear, with the 2020 launch of a $230 million 'Advanced Reactor Demonstration Program (ARDP) by the DOE as a recent example (DOE, 2020).

US nuclear energy production adheres to a once-through nuclear fuel cycle. While the US played a pioneering role in developing reprocessing methods, principally in the context of nuclear weapon production (Simpson and Law, 2018), President Ford declared an official ban on funding for commercial reprocessing in 1976 (CRS, 2008). This ban was primarily justified by reference to the proliferation risk of reprocessing, and was affirmed in 1977 by President Carter (ibid.). While President Reagan lifted the ban on commercial reprocessing in 1981, it has not been practiced since, inter alia due to economic cost (Hamilton et al., 2012). A total of three civil reprocessing plants have been built in the US, of which only one has actually operated; a reprocessing plant in West Valley, New York, which successfully operated between 1966 and 1972. The other two were situated in Morris, Illinois and Barnwell, South Carolina, but the former was declared inoperable in 1974, and the latter was abandoned after the announcement of aforementioned ban in 1977 (Silverio and Lamas, 2010). Due to government-operated reprocessing in the military and defence context since the 1940s, the USA however does have reprocessing operational experience (World Nuclear Association, 2018).

Also notable is a significant change in US uranium sourcing. Historically, the US had a strong focus on domestic uranium mining, facilitated through incentives (e.g. long-term price guarantees) and trade policies (e.g. import barriers). However, these incentives and trade barriers came to a halt, and currently the majority of uranium is imported (Energy Administration Information, 2020b). In 1980, the heyday of domestic mining, a total of 43,7 million pounds of uranium concentrate originated in the US, versus 3.6 million pounds being imported. In 2018, however, only 1.16 million pounds were sourced domestically, while 90% was imported, mostly from Canada (24%), Kazakhstan (20%), Australia (18%) and Russia (13%) (ibid.).

4.6.2 RWM and P&T

Up to 2016, the total amount of SNF generated by the US nuclear power industry amounted to approximately 77 900 MTHM (Metric Tons Heavy Metals) (US DOE, 2017). As no facility for final disposal of SNF is in operation yet (see below), SNF is currently stored onsite of –both operating and terminated- nuclear power plants, mostly in wet storage, with a smaller fraction already moved to dry cask storage. In addition, a fraction of the US SNF is currently stored at 4 sites operated by the DOE (mostly non-commercial SNF), and at a storage installation owned by GE Hitachi Nuclear Energy in Morris, Illinois (ibid.). It is estimated that every year, 2 000 MTHM is added to the US commercial SNF inventory (GAO, 2012). This raises important concerns regarding the capacity for storage of SNF, and the potential security threats and safety risks related to interim storage (ibid.). These concerns remain high on the agenda, as the search for a long-term disposal solution continues.

This search for a long-term disposal solution has an extensive history. A 1957 report by the National Academy of Sciences was one of the first to put geological disposal forward as a preferable option for managing HLW (Hess et al., 1957). In the next decades, recognizing the growing need for a repository for HLW and SNF, especially given the ban on commercial reprocessing introduced in the 1970s (see above), recommendations were formulated on establishing multiple potential repository sites. In 1982, this was put into law by the introduction of the nuclear waste policy act (NWPA), which stipulated a route towards a permanent disposal of

SNF, and other high-level radioactive waste, by assigning the Department of Energy (DOE) with the task to investigate potential sites for a geological disposal of the US HLW and SNF. It aimed at establishing "a fair and technically sound process for selecting repository locations" (Hamilton et al., 2012, 20). It aimed to distribute responsibility among different locations, by setting the capacity limit for a first repository on 70 000 metric tons of HLW and SNF (at least until a second repository would be opened). In 1987 amendments were added to the 1982 NWPA, explicitly moving away from its initial focus on multiple sites, and instead stipulating that Yucca Mountain (Nevada) was to be the only site to be further researched and considered as a location for a repository (MacFarlane and Ewing, 2017). This focus on one site was controversial from the beginning, especially among Nevada residents, and after more than 2 decades of research – and spending over 14 billion dollars - the Obama administration decided to no longer fund the Yucca Mountain project from 2011 onwards (Newman, 2012).

This elimination of the Yucca Mountain program meant an explicit rethinking of potential roads for America's nuclear fuel cycle. A Blue Ribbon Commission on America's Nuclear Future was formed, which needed "to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and recommend a new strategy" (Hamilton et al., 2012, preamble). This decision stressed the importance of managing the United States' SNF and other high-level radioactive waste not only in terms of a historic burden, but in the broader frame of potential roads ahead for nuclear in the US. Some of the major recommendations made by this Blue Ribbon Commission are; a consent-based approach on future siting of deep geological repositories, continued efforts regarding the realization of these geological repositories, while simultaneously developing one or more consolidated storage facilities, and supporting the advancement of nuclear energy technology and workforce. But while this latter focus on advancing nuclear technology emphasized the need for continued support for RD&D on advanced reactor and fuel cycle technologies, the commission also highlighted "*that it would be premature for the United States to commit, as a matter of policy, to "closing" the nuclear fuel cycle given the large uncertainties that exist about the merits and commercial viability of different fuel cycles and technology options*" (Hamilton et al., 2012, xii, emphasis in original). Any serious commitments towards SNF reprocessing, or advanced techniques such as P&T, were backgrounded in the Commission's final report, by questioning its potential added value to the management of the back-end of the nuclear fuel cycle.

This does not mean that P&T has not been researched in the US. Already in the 1957 report mentioned above, the authors note how "separation of the Cs [caesum] and Sr [strontium] isotopes from waste […] would of course greatly simplify the general problem of waste disposal. Research on the feasibility of such separation should be pushed." (Hess et al., 1957: 5). Since the 1960s R&D efforts have been directed at exploring and understanding the potential of P&T. This has also resulted in various research efforts concerning the overall feasibility and desirability of P&T from a broader perspective, taking into account aspects such as cost, policy and/or risk. An early example of such an assessment can be found in a 1980 report by the Oak Ridge National Laboratory on the feasibility of and incentives for P&T. As the final report of a 3-year research effort, this document questions the potential of P&T in the US context, highlighting that although its major aspects seem technologically feasible, there seems little to gain in terms of cost or safety of a fuel cycle including P&T versus a fuel cycle which does not include P&T (although the used reference fuel cycle does include reprocessing of SNF). Also, the report notes how P&T is clearly in conflict with US policy on the nuclear fuel cycle (which in 1980 still officially bans the option of commercial reprocessing), and contradicts moves towards a geological disposal as P&T makes "the disposition of existing waste and fuel inventories uncertain since irretrievable commitment of actinides to a repository might defeat the purposes of P-T and thus impede waste management until P-T [is] implemented" (Croff et al., 1980, xv).

A 1992 report by the Lawrence Livermore National Laboratory reaches largely similar conclusions, focusing particularly on the potential impact of P&T on the US geological disposal of SNF and HLW (Ramspott et al., 1992). This report emphasizes that there is little or no added value of P&T over the current (1992) US plans for disposal of SNF when taking into account economic costs, repository and waste inventory issues, policy frameworks, institutional issues, public acceptance and licensing. It repeatedly points towards the need for a large-scale and orchestrated implementation of P&T infrastructures and technologies in order for it to offer potential benefits to the back-end of the US fuel cycle, which it assesses as highly complex and therefore not likely to be achieved (Ramspott et al., 1992). Finally, an extensive 1996 report by the National Research Council on technologies of separation and transmutation concludes that the US should stick to its once-through fuel cycle, not in the least because economic cost rationales, highlighting that in case the future uranium prices would significantly rise, the P&T option should be reconsidered (National Research Council, 1996). Although none of the reports cited above perceive P&T as a clearly feasible option in the foreseeable future, they also indicate a continued need for R&D on this route.

4.6.3 A Dynamic Policy Context

Despite a general lack of interest in developing and implementing P&T in the short- to midterm, some routes for advancing and enabling P&T can be discerned in different policy initiatives. At the start of the 21st century for example, some significant initiatives were taken to reform the back-end of the fuel cycle. From 2002 onwards the DOE "conduct[s] a program of SNF reprocessing research and development (R&D), in part to consider alternative SNF management options" (National Research Council, 2008, 47). This program is known as the 'Advanced Fuel Cycle Initiative'. In 2006, this advanced fuel cycle initiative was encompassed in the 'Global Nuclear Energy Partnership (GNEP)' launched by president Bush. The GNEP focused both on the domestic development of nuclear energy in the US and on a global scale, the latter through a partnership focused on proliferation resistant exchange of technology and nuclear fuel production/reprocessing.

On the domestic level, GNEP aimed at developing and deploying technologies for recycling SNF (without separating plutonium) in order to reduce radioactive waste, while also developing and deploying advanced nuclear reactors (Lindemeyer, 2009). As such, it envisioned a future of commercial reprocessing, thus breaking with decades of no commercial reprocessing on American soil. After the inauguration of President Obama in 2009, however, the GNEP radically changed its domestic component, and domestic commercial reprocessing was (again) out of the picture. Most recently, under the Trump administration sounds were heard on a reappearing interest in the reprocessing of spent nuclear fuel, with for example congress providing funding for conceptual design studies for a sodium-cooled fast-neutron Versatile Test Reactor (VTR) at the Idaho National Laboratory (von Hippel, 2020). Overall, the above evolutions demonstrate the constant opening and closing of the door for spent fuel reprocessing – and connected advanced developments such as P&T - as administrations and policies change.

5. DISCUSSION

The previous section presented profiles for six countries that can be considered as pioneers in nuclear technology in different ways. It outlined the ways in which P&C/T might or might not sit in their current RWM strategies and expectations for nuclear power more broadly. The country cases were used to identify some cross-cutting themes or societal dimensions that can affect – and thus need to be reflected on – actions and discussions regarding the development of P&C/T. The list of societal dimensions (changing policy contexts, divisions of labour in the back-end of the fuel cycle, material practices and infrastructures, nuclear markets, and ethical considerations) presented below is by no means exhaustive or complete. Rather its aim is to provide a starting point for reflection of potential P&C/T futures. Crucially, adhering to the co-productionist analytical framework of this report (Section 3), it must be noted that while the dimensions here are presented as distinct entities for clarity, in practice these different dimensions are closely entwined. Rather than existing in isolation, they influence each other and co-evolve. As such, the dimensions presented below should be read as interdependent constituents of P&C/T development.

5.1 Changing Policy Contexts

International considerations. The nuclear industry is inherently international, and changes or shifts in the international sphere influence country level developments. Good examples of these include Japan that feels the need to develop domestic reprocessing capacity in part due to the UK's decision to close THORP. Likewise, the US decision to cease reprocessing activities were influenced by concerns over international non-proliferation risks. Meanwhile, India's push towards a closed thorium cycle was spurred on by its 'isolation' in the international nuclear scene. As India is increasingly included in the international nuclear community, its need and motivation to pursue a closed cycle might waver. Finally, it is worth noting that the general push towards closed cycles in the early days of nuclear development was in part fuelled by international concerns over the scarcity of global uranium resources, which in the following decades waned as more uranium resources were found, and prices dropped.

Regional considerations. In the European context, one of the more significant changes that was not touched upon in the previous section, but deserves a mention, is the EU's recent rebuttal of nuclear as 'green energy'. In its 2020 Green Deal, the EU lays out its strategy to transform the EU into an **'**economy where there are no net emissions of greenhouse gases in 2050, where the environment and health of citizens are protected, and where economic growth is decoupled from resource use' (EC, 2020). The Deal excludes nuclear from Europe's green transition. What exactly this means for P&C/T R&D is not yet clear, however it can be speculated that justifying nuclear projects in the European context becomes harder. Currently, EU law holds that the construction of nuclear facilities needs to be justified, as it needs to be shown that the benefits of nuclear projects are greater than their drawbacks. How the EU's decision to divest from nuclear affects the justification and evaluation processes remains to be seen.

National considerations. Closely entwined with the international and regional levels is the national one. Here key considerations affecting potential P&C/T futures include events such as the Fukushima triple disaster, the 'failure' of ASTRID in France, and the closure of THORP in the UK. Following Fukushima, Japanese nuclear aspirations both to reduce dependency on nuclear power and to reduce radioactive waste hazards through P&C/T contradict each other, and it remains to be seen which aspiration prevails and with what consequences. The French failure to implement ASTRID in turn raises questions for the (near term) infrastructural developments required for P&C/T implementation, while the closure of THORP might lead to a loss of expertise and practical knowhow that might regionally or internationally be beneficial for the development and demonstration of P&C/T.

5.2 Division of Labour in the Back-end of the Fuel Cycle

Research and implementing bodies. One notable issue that emerges in most cases here is that the actors who implement RWM solutions (mainly geological disposal) and those who conduct R&D on possible (alternative) solutions are different. For instance, in Finland the implementing body is responsible only for the development and realization of geological disposal, while in France, geological disposal is the responsibility of the waste management organization while P&C/T is legally framed as an RWM alternative to be researched by CEA. In this way, P&C/T exists at the periphery of current RWM paradigms, while it is also considered to require substantial effort and time to reach the same level of maturity as geological disposal. Therefore, questions arise to what extent these options are complementary or exclusionary. Can P&C/T reach industrial maturity in time to influence geological disposal or should the development of geological disposal be halted until the potential of P&C/T has fully been explored (Andrén, 2012)? If P&C/T is a desired addition to geological disposal, it would be worth considering how resources between different technical actors are divided or at least to establish stronger interactions between those implementing geological disposal and those researching P&C/T.

P&C/T in RWM. Related to the above observations what also needs to be considered is the anticipated or desired role for P&C/T in radioactive waste management. Since P&C/T still requires geological disposal, while geological disposal does not necessarily need P&C/T, it needs to be reflected whether P&C/T is a 'plan B' in case current plans for geological disposal would – against common expectations - turn out to be unattainable. Or whether it should be fully incorporated in a plan A and accompany geological disposal from the beginning. The latter option would require that developments made towards the realization of geological disposal, including the definition of disposal inventories, are reconsidered and opened again for evaluation. From this, further questions emerge. How long can or should all options be kept open? How might the implementation of P&C/T affect societal acceptability and desirability of geological disposal?

Geographical responsibilities. Equally important are questions of where. It seems to be broadly accepted that P&C/T is feasible only as a multi-national project (e.g. Sections 4.1 and 4.5), therefore questions emerge as to who assumes the responsibilities, potential risks and benefits of hosting a P&C/T facility in their territory or community. The experience with Superphénix in France illustrates it cannot be expected that local stakeholders want to carry the burden of these risks. Likewise, a recent German report on P&C/T states that, at least in the German case, societal acceptability of P&T can be expected to be higher the less financial, social and environmental costs P&T imposes on Germany (acatech, 2014). Additionally, while most countries seem willing to keep a 'watching brief' on P&C/T development, indicating potential future interest in utilizing P&C/T, the costs of P&C/T R&D are carried by few countries. Similarly, expertise on P&C/T is already concentrated. Especially when P&C/T would move from the R&D stage to (industrial) implementation, these observations raise the issue of which countries will actually be able and willing to host the necessary infrastructures, and whether benefits will be reaped at the national or international level.

5.3 Material Practices and Infrastructures

Reprocessing. As was discussed in Section 2, partitioning is 'advanced reprocessing' that expands the separation portfolio from uranium and plutonium to include MAs. In this sense, countries (e.g. France, the UK, and India) that have historically reprocessed SNF could be in an advantageous position, as they could extend existing infrastructures and radioactive waste management practices to include the separation of MAs. However, the UK and Japanese cases in this report demonstrate that even 'conventional' reprocessing is not without its economic and technical challenges. It can be argued that the UK's decision to cease reprocessing and Japan's struggle to realize reprocessing domestically raise questions about technological and infrastructural feasibility of P&C/T.

Vitrification. Reprocessing has led to the creation of vitrified HLW. Meaning in essence that reprocessing has created waste streams that are unsuitable for P&C/T. What emerges here, then, is a paradox, as those countries that might have more suitable infrastructures and higher capabilities to undertake P&C/T also have waste inventories that are not suitable for further processing. From this perspective, countries reluctant to consider P&C/T, such as Finland that is disposing of SNF directly, might benefit from P&C/T more in the long run than would countries that have both actively reprocessed SNF and are currently also actively engaged in P&C/T, such as Japan.

Past efforts with FRs. What needs to be borne in mind is that regarding the development and even operation of fast reactors there is already notable experience. Yet, so far FRs have not proven feasible in the long-term. The abandonment of Superphénix in France, Dounreay in the UK and Monju in Japan speak of the challenges related to FR systems. The three cases seem to demonstrate the economic realities, technical problems and the risk of accidents that have affected the development of FRs together with, for instance, proliferation concerns. Dounreay, for instance was closed down, because it turned out to be more expensive than expected when uranium was thought to be in scarce supply; Superphénix was shutdown among other things, because its average capacity factor was below 7% during its eleven years of operation; Monju in turn was closed down after two accidents. Likewise Dounreay experienced a number of accidents, and the site has been badly contaminated. It needs to be asked then what kind of, but also whose, interests and desires the development and realization of FRs in particular seek to address?

5.4 Nuclear Markets and Economies

Price of uranium. The price of uranium has been mentioned already a couple of times in the above discussions, but it is still worthwhile mentioning the role it, and in particular fears over uranium scarcity, played in the early development of both reprocessing technologies and FR systems. It is also worth noting that its lack of access to international uranium reserves has been one of the motivators for India's efforts to develop a thorium cycle. The early fears about the accessibility of uranium never materialized and the contemporary consensus is that a once-through fuel cycle, rather than a closed cycle, is the economically more feasible and sensible alternative (Bunn et al., 2003). How this affects the development of P&C/T is worth to be reflected on, for while some actors (e.g. WNA, 2018) frame P&C/T as a radioactive waste management technology, the IAEA (2004), but also others (Guidez and Boullis, 2015) additionally highlight how P&C/T can enhance and bolster the sustainability of nuclear energy generation in the future – thus raising questions what the aim of P&C/T development is (see Conclusion).

Keeping to budgets (and schedules). Another broader consideration that needs to be taken into account are the increasing challenges of big nuclear projects to adhere both to their budgets and schedules. Historical experience has demonstrated that the development, implementation, and operation of nuclear infrastructures often turns out to be more costly than initially expected. In Japan, for example, the development of the Rokkasho reprocessing plant already costs three times more than initially budgeted (NHK World Japan, 2020), and Monju failed to create little economic return on its almost 10 billion dollar construction costs as a consequence of its accidents (AFP, 2014). Similarly, THORP in the UK failed to generate the profit that was envisioned, while reactor projects in Finland (Olkiluoto) and France (Flamanville) are both significantly behind schedule and over budget. With perhaps the exception of Monju, these projects are (or were) based on existing technologies. Discrepancies between estimated and actual costs of nuclear infrastructures might make actors wary of engaging in new projects. These issues are intricately linked to the organization of national nuclear landscapes.

Ownership. Where nuclear infrastructures are largely developed, operated and owned by private actors following market logics (e.g. the US), economic issues might be a greater barrier to further development than in countries that have a state-owned and operated nuclear field (e.g. India).

5.5 Ethical Considerations

Intergenerational considerations. The rationale underlying P&C/T development can be seen as a largely ethical one. P&C/T is framed in official discourses as decreasing the long-term risks of geological disposal, and reducing the multi-millennial threat of radioactive wastes by, for instance, transforming MAs into less long-lived forms. Simultaneously, the viability of P&C/T is dependent on further commitment to nuclear energy generation for at least another century, and might also encompass new risks e.g. in terms of increased transports of nuclear materials (Taebi and Kadak, 2010). Therefore, the ethical 'acceptability' and basis of P&C/T needs to be weighed from more than just a geological disposal perspective. Additional questions emerge around the issue of consent. In social scientific and ethical literature on geological disposal, the question whether present generations can choose technological paths for future generations has been discussed at some length (e.g. Andrén, 2012; Shrader-Frechette, 2000). One view in these discussions has been that the present generation should not lock future generations to the geological disposal alternative, not at least in its current passive safety conceptualization. Similar discussions need to be conducted in relation to P&C/T. Is it ethically acceptable to incorporate P&C/T as part of the disposal solution if it simultaneously means the generation of more radioactive waste through continuing nuclear energy production? Additionally, it has been inquired that if contemporary analyses of the safety of geological disposal are correct, then the risks and burdens of geological disposal facilities would be low in the future. Is it then justifiable to place safety, security and economic burdens on present generations to minimize a future risk that is already considered small (Taebi and Kadak, 2010)? Conversely, it needs to be asked whether transferring any risks to the distant future is acceptable and what role could P&C/T play here.

Intra-generational considerations. There is also a range of intra-generational issues that need to be contemplated, as the needs and interests of not only future, but also present generations need to be taken into consideration in P&C/T decision-making. In terms of technical factors, compared to direct SNF disposal, P&C/T requires increased treatment and transportation of radioactive materials, which adds a new layer of risks and increases the number of workers and communities affected by the management of the back-end of the nuclear fuel cycle. While it has been argued that closed fuel cycles, including P&C/T, can provide significant benefits for future generations, they also increase risks in the shorter term (Taebi and Kloosterman, 2008; Posiva, 2012). One central aspect in weighing the ethical acceptability of P&C/T is decision-making – and in particular questions about who should be involved in decision-making processes and to what extent?; what (technical) questions should be open for deliberation and debate?; how is the siting process organized?; should there be a form of compensation for potential host communities? Mounting experience from geological disposal evinces that these questions form the nuts and bolts of the implementation process, thus highlighting the co-productionist understanding of the relationship between science, technology and society. They have also proven out to be difficult questions to solve and answer. Therefore, if the P&C/T is going to be pursued, incorporating ethical discussions and reflections in the process already in the R&D stage is vital.

6. CONCLUSION

This report presented six country cases and their relations to P&C/T. Adopting a co-productionist analytical framework motivated by Responsible Research and Innovation (Section 3), the report identified a range of interconnected dimensions that demonstrate the interplay between and co-production of science, technology and society (Section 5). More specifically, policy contexts, economic markets, ethics, infrastructures and divisions of labour are considered as laying out a set of socio-technical boundary conditions for P&C/T development. In so doing, the discussion above illustrates that while P&C/T has been presented as a solution to the wicked problem of geological disposal, the development and implementation of P&C/T, too, is entwined with multiple factors, and actors, and can itself be considered as a wicked problem with all the accompanying uncertainties, ambiguities and complexities.

Through the co-productionist framework, P&C/T is not conceptualized as a linear innovation or scientific progress, but as dependent on the interplay between different dimensions, which can allow P&C/T to evolve in different ways towards different possible, rather than predetermined, futures. As such, these futures cannot be decoupled from decisions, actions, artefacts and experiences of the past. Policies favouring an open or a closed fuel cycle, their underlying rationales, related ethical concerns, historic experiences, responsibilities and infrastructures, failures or incidents contribute to different future potentials of and for P&C/T. In doing so, they set 'boundary conditions' for P&C/T and require reflection and consideration in an effort towards responsible research on and development of P&C/T.

Similarly, anticipated or imagined nuclear futures impact on current practices, infrastructures and decisions. An imagined future which, for example, emphasises how P&C/T (partially) 'solves' the issue of HLW and SNF management can be very different from an imagined future which envisions P&C/T as a next step in 'closing' the nuclear fuel cycle in order to assure continued nuclear energy production. While not necessarily mutually exclusive, these different imagined futures invoke different kinds of nuclear infrastructures and activities, and are significant in terms of the investments societies might be willing to make towards translating these imaginations into realities.

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