Note:
This is a translation of the ESK discussion paper entitled “Partitionierung und Transmutation (P&T) als Option für die nukleare Entsorgung Wärme entwickelnder radioaktiver Abfälle in Deutschland”.
In case of discrepancies between the English translation and the German original, the original shall prevail.

E S K

DISCUSSION PAPER of the Nuclear Waste Management Commission (ESK)

Partitioning and transmutation (P&T) as an option of nuclear waste management for heat-generating radioactive waste in Germany

Contents

1 Introduction

The possible conversion of long-lived radionuclides in radioactive waste to short-lived and stable isotopes by irradiation with fast neutrons was first described already in 1964 [1]. This technology referred to as transmutation is aimed at reducing the long-term hazards associated with the radiotoxic inventory of spent fuel from the use of nuclear energy over long periods of time. The focus of current research is on the transmutation of long-term radiotoxic transuranic elements such as neptunium, plutonium, americium and curium, the so-called minor actinides. With a few exceptions, the transmutation of fission products proved to be too expensive. Prerequisite for transmutation is the previous separation of the elements to be transmuted (partitioning) with the help of chemical separation methods. In addition, it is expected from the application of partitioning and transmutation (P&T) that the heat production of the waste will be significantly reduced after a few decades of decay and thus a smaller area is needed for a required repository. The development of P&T concepts is still the subject of international research projects (e.g. EU-funded projects [2], [3]).

According to the Atomic Energy Act (*Atomgesetz* – AtG) in its current version [4] it is stipulated that *"(...) delivery of irradiated nuclear fuel originating from the operation of installations for the fission of nuclear fuel for the commercial generation of electricity to an installation for the reprocessing of irradiated nuclear fuel for the purposes of non-detrimental utilisation shall become unlawful as of 1 July 2005"* and thus also P&T. Nevertheless, P&T concepts are discussed as a possible contribution to nuclear waste management in the context of the ongoing debate on the selection of a repository site for heat-generating (high-level) waste in Germany. Since large-scale P&T facilities are currently not available, concepts such as long-term storage and retrievability options are sometimes justified by arguing that it is intended to wait for technical developments. Within the framework of its statutory mandate, the Commission on the storage of highly radioactive materials *(Kommission Lagerung hoch radioaktiver Abfallstoffe)* also deals with P&T to investigate alternative disposal concepts. As stipulated in the Site Selection Act (*Standortauswahlgesetz* – StandAG) of 23.07.2013 [5], one of its tasks is the
" ... Assessment and decision as to whether, for a proper waste management, other options than the immediate disposal of high-level radioactive waste in deep geological formations should be scientifically investigated and the waste should be stored in above-ground storage facilities until completion of the investigations."

Therefore, the ESK considers it appropriate to collect and compare arguments in favour and against P&T based on issues representing areas of tension. This paper briefly describes different P&T concepts pursued internationally and addresses opportunities, limitations and consequences for the specific situation in Germany. A quite detailed analysis of the opportunities and risks of P&T in Germany can be found in publications of the National Academy of Science and Engineering (acatech) ([6], [7]). This paper does not purport to be exhaustive but is intended to serve as a starting point for further discussion.

2 P&T concepts and technologies

Internationally discussed P&T concepts should always be considered in connection with the respective national situation and boundary conditions. The strategies under consideration pursue different objectives regarding the waste components to be transmuted and require different facilities and systems. All concepts have in common that nuclear facilities are required for the following steps of radioactive waste management:

- handling and opening of transport and storage casks as well as unloading of the spent fuel from the casks after storage,
- disassembly of the fuel assemblies and separation of the fuel from structural components, and
- dissolution of the spent fuel; chemical separation of the main component uranium and of plutonium to optionally produce new nuclear fuel.
- chemical separation of the elements to be transmuted. The so-called minor actinides neptunium, americium and curium are usually considered here, but there are also considerations according to which the fission products are separated group-wise and to either subject them to a transmutation process or to store them until decay or to dispose them of ([8], [9]),
- production of matrices into which the radionuclides to be transmuted are incorporated and which are suitable for irradiation in transmutation facilities. Since complete transmutation cannot be performed in one step, devices must be provided in which these matrices are dissolved after irradiation and the radionuclides not transmuted are again separated from fission products and treated for further irradiation steps,
- irradiation of the respective radionuclides with high energy neutrons in appropriate facilities in order to transmute them,
- conditioning of the radioactive waste generated, which are mainly the fission products that need to be processed such to obtain products suitable for storage or disposal, and
- storage and disposal of the waste generated in order to isolate it from the biosphere in an appropriate manner.

For some of the treatment steps, especially for the first three and storage, large-scale facilities already exist.

The P&T processes in the respective concepts can be designed and structured very differently. Some concepts include very complex separation schemes for the separation and partitioning of transuranic elements and fission products so that for the remaining radioactive waste, only a very small area or space will be needed for a repository in deep geological formations (see e.g. [9]). Here, it is intended to also partition relatively short-lived fission products, such as ^{137}Cs and ^{90}Sr, and to store them above ground for decay of the activity.

The largest part of the work by far focuses on the transuranic elements due to their high radiotoxicity. The discussions in the following chapters will therefore not deal with P&T concepts which involve partitioning and transmutation of fission products. For P&T of transuranic elements, strategies are described in which all transuranic elements are partitioned and recycled together, in groups or individually. Here, americium is of particular importance since, after plutonium, it makes the second largest contribution to the long-term radiotoxicity of the spent fuel. As separation methods, hydrometallurgical (liquid-liquid extraction with immiscible liquids and selective complexing agents) and pyrochemical (electrochemical separation process in molten salts) processes are usually proposed. The suitability of hydrometallurgical partitioning processes has already been demonstrated successfully on a pilot scale. Their realisation on an industrial scale in the form of additional separation stages in modified reprocessing plants appears to be feasible in the near future, while pyrochemical methods have only been tested successfully on a laboratory scale so far and, in fact, still require longer lasting development work.

Intensive research and development work is under way on the method of further processing of the elements to be transmuted. Matrices in which the radionuclides are to be incorporated for irradiation have to meet high requirements. They must be made of materials that, on the one hand, can withstand the high loads (intense neutron irradiation, thermal gradients, gas formation, etc.) in a transmutation reactor but, on the other hand, must also be relatively easy to dissolve in order to enable recycling. Various metallic, ceramic (oxides, nitrides, carbides) or also composite materials are currently under development. The subject of research activities is also the development of long-term stable conditioning matrices suitable for disposal for waste components which cannot be transmuted or only with considerable effort.

So-called reactors of the fourth generation are discussed, among others, as irradiation or transmutation facilities. These could be, for example, liquid metal cooled fast reactors already far advanced in their technological development, or molten salt reactors which, however, are still at an early stage of development. In these cases, it concerns power reactors which are primarily intended to generate electricity. In Germany, the discussion focuses, in particular, on reactors solely for the purpose of transmutation. These are the so-called accelerator-driven systems (ADS) where high-energy protons are produced in a particle accelerator and shot at a heavy metal target (consisting of lead or lead-bismuth), thus generating high-energy neutrons in a nuclear reaction, which can be used for the transmutation of radionuclides. The latter facilities can be operated in subcritical mode, i.e. in contrast to the Generation-IV facilities, no self-sustaining chain reaction is produced. In principle, the energy released by the transmutation reaction could also be used here to generate electricity. However, given the political decision to phase out the use of nuclear energy in Germany, ADS facilities are regarded as pure transmutation machines. While sodium cooled fast reactors are already in operation or under construction worldwide, ADS are regarded to be technically feasible, but their realisation on an industrial scale is expected to be possible only in a few decades.

In combination with the recycling of uranium and plutonium (reprocessing), P&T allows using natural uranium as nuclear fuel much more efficiently and minimising the formation of transuranic elements in the waste generated. Such a concept could e.g. be realised by means of a fast sodium-cooled power reactor (fast breeder reactor) in which, however, at the same time, fissile plutonium is to be generated by neutron capture reactions and, in addition, new minor actinides are formed. Fast reactors can also be operated as burners. In this case, fuels are used that contain minor actinides so that less minor actinides are generated by neutron capture than transmuted. Transmutation of radiotoxic transuranic elements in a double-strata strategy is also being discussed. Here, ADS reactors are used, in addition to power reactors, whose main task is to burn unwanted minor actinides or fission products. Their amount can be minimised in this way.

States (A) that continue using nuclear energy, and those (B) phasing out nuclear energy could jointly use P&T as part of so-called regional strategies within the framework of systems participation models. Minor actinides in spent nuclear fuel of country (B) could then be transmuted, while uranium and plutonium of country (A) can still be used to generate electricity. Such strategies are expected to allow for the synergistic use of facilities, thus optimising the required resources (European Systems Participation). Against the background of the current political and social situation and conditions, regional P&T concepts are particularly discussed in Germany ([6], [7]).

3 Impact of P&T on the radioactive waste management situation in Germany

3.1 Amounts of waste, repository footprint[1]

By the end of the use of nuclear energy in Germany, the following heat-generating radioactive waste will have been generated:

Approximately 10,500 tons of heavy metal (tHM) in fuel assemblies are to be disposed of directly. In addition, there will be approximately 8,000 canisters filled with vitrified waste from the reprocessing of 6,700 tHM in Germany and abroad, and fuel assemblies and fuel rods from experimental and prototype nuclear power plants and research reactors [10].

When using POLLUX casks, the waste volumes will amount to 21,000 m^3 of fuel assemblies to be disposed of directly, 1,400 m^3 of vitrified or compacted products from reprocessing, and 5,700 m^3 of fuel from experimental and prototype nuclear power plants as well as from research reactors and the pilot reprocessing plant Karlsruhe (WAK) [11]. In addition, there will also be about 300,000 m^3 of radioactive waste with negligible heat generation. These figures were postulated in Table 1 for the scenario “Abstinence”" (no application of P&T). The waste in the Asse II mine and the uranium tails from enrichment are not included here. According to the current figures published in the Programme for the responsible and safe management of spent fuel and radioactive waste (National Programme) [10], this could amount to another 300,000 m^3. These figures have been adopted in Table 1 for the scenario “Abstinence” (no application of P&T). In case of application of P&T, the volume of heat-generating radioactive waste decreases, while the amount of radioactive waste with negligible heat generation increases. The amounts of the respective waste produced depend on the type of separation (hydrometallurgical or pyrometallurgical separation) and the number of recycles. For the scenario “European Systems Participation”, the acatech study [6] estimates that the amount of heat-generating radioactive waste will be reduced to between 9,500 and 12,900 m^3, while waste with negligible heat

[1] The term footprint is used in connection with disposal synonymously to the area needed for the disposal facility. The size of the area needed depends on the emplacement concept, the thermal output of the waste and the host rock of the disposal facility.

generation

will increase by 60,000 m^3. This additional amount of waste with negligible heat generation results from the reprocessing of LWR fuels, the fabrication and reprocessing of transmutation fuels, and the operation of transmutation facilities. For the scenario "Application in Germany", the dismantling of P&T facilities and facilities for fuel fabrication would result in additional 36,000 to 49,000 m^3 (acatech study [6]). The comparison of roughly estimated waste amounts for the different scenarios is given in Table 1

Table 1: Amounts of waste in m^3 [6]

Table 1: Amounts of waste in m^3 [6] **Scenario**	**Abstinence (no application of P&T)**	**European Systems Participation**	**Application in Germany**
Heat-generating waste	≈ 28,000	9,500-12,900	9,500-12,900
Waste with negligible heat generation	≈300,000	≈360,000	≈400,000

Would disposal be preceded by a P&T method, the volume of heat-generating radioactive waste to be disposed of could be reduced to one third. This is mainly due to the separation of uranium, as it would be also performed for reprocessing without P&T. The procedure for dealing with the separated uranium is ultimately a political decision. It could be used as a resource in reactors for energy production or, as waste with negligible heat generation, directly be emplaced in a repository. In any case, a repository is needed for heat-generating radioactive waste also in case of application of P&T for the already existing vitrified waste, the spent fuel from experimental and prototype nuclear power plants and research reactors which cannot be treated by P&T, and the heat-generating radioactive waste remaining after P&T (vitrified fission and activation products as well as heat-generating secondary waste). The determining factor for its size is the generation of heat, which partly decreases significantly faster for waste from the P&T cycles than for spent nuclear that would have to be disposed of directly. However, it should be noted that the fraction of the footprint required for the infrastructure areas of a repository, and the fraction for the emplacement of the already existing reprocessing waste would remain constant. According to [12], in case of application of P&T, the area needed for this repository would therefore decrease by a maximum of 50%. It should be noted that a major reduction of the decay heat (by several orders of magnitude) may take several 100 years, depending on the P&T cycle. In order to take credit from the reduced heat generation in the design of a repository, an appropriate time of storage would therefore be required.

Furthermore, a solution must be found for the management of additional waste produced with negligible heat generation: emplacement in the repository for heat-generating radioactive waste, change in the plan approved for the Konrad mine, or construction of an additional repository for waste with negligible heat generation.

3.2 Safety aspects

Safety aspects are to be considered in connection with the operation of P&T facilities, the necessary transport of radioactive material, the operation of waste management facilities (including buffer and storage facilities, conditioning facilities, disposal facilities) and, finally, the long-term behaviour of the sealed repository.

Most publications on P&T discuss only the impacts on the long-term safety of disposal. Given the fact that the construction of several P&T facilities would be required, which would have to be operated for decades, it should be noted that their operation would also require the performance of comprehensive safety assessments. An exact quantitative assessment of the radiological hazard potential of P&T facilities for man and the environment cannot be made at this stage. A declared objective in the development of Generation IV reactors is, among other things, to increase safety standards compared to those of currently available facilities. For all examined types, including subcritical ADS reactors, safe removal of the decay heat is to be ensured, thereby significantly reducing the probability of occurrence of severe accidents compared to current reactors. Safety reviews for the planned reactor types of Generation IV are available ([13], [14]) but must be considered as provisional at this stage. Potential radiological consequences due to further facilities needed for P&T should be comparable to existing facilities for reprocessing or conditioning of spent fuel. In addition to the risks associated with the facilities themselves, potential environmental impacts resulting from P&T secondary waste with negligible heat generation are also to be mentioned in this context. Moreover, there could be an increase in the required transports of radioactive material between the facilities (nuclear power plants, storage facilities, P&T facilities), with the number of transports largely depending on the scenario considered ("European Systems Participation" and "Application in Germany").

Some impacts of the application of P&T on disposal have already been mentioned above. After a period of decay, the application of P&T leads to a reduced heat output and total activity as well as to a reduced fraction of radiotoxic transuranic elements in the repository for heat-generating radioactive waste. This means that after about a thousand years, the activity (or, as a weighted quantity, the radiotoxicity) would be comparable to that after one million years without the application of P&T (not having taken the vitrified waste into account here). In a number of safety reports, the evolution of the radiotoxicity is used as an indicator to illustrate the reduction of the potential hazards emanating from the repository and to justify the choice of assessment periods for the safety of a repository after closure through comparisons with naturally occurring radiotoxicity concentrations [15]. The assessment of the safety of a repository after closure takes place based on systematically derived scenarios that are relevant for the containment behaviour of the repository system and that can lead to adverse effects for man and the environment from radiotoxic and chemically toxic substances in case of incomplete containment. Here, release rates, mobility/transport behaviour and bioavailability of radionuclides and chemotoxic substances are to be considered for the different waste components. The respective significance of the different radionuclides contained in the waste is determined by their release behaviour from the waste package, their mobility, half-life and radiological effectiveness.

In many release scenarios which have been analysed in the past for different host rocks, the significance of the transuranic elements remains limited due to their low mobility. Accordingly, the influence of P&T cycles on the long-term safety is limited when considering resulting waste inventories ([16], [17]). Against this background, justification of assessment periods based on radiotoxicity considerations (see above) does not seem to be consistent. However, scientific studies show that transuranic elements are not always immobile and small amounts can be transported over distances of several kilometres under certain conditions [18]. In a systematic development of scenarios it is to be examined whether and under what circumstances, e.g., colloid-borne transport of transuranic elements can occur. Uncertainties in this respect could be circumvented with a transmutation of transuranic elements.

For some radionuclides (e.g. ^{14}C, ^{129}I), there are no reliable statements on the mobility behaviour and retention in a repository, which is why high mobility is postulated in the release calculations for long-term safety assessments. These radionuclides cannot or only hardly be transmuted. With the development of P&T strategies, new conditioning techniques (e.g. ceramics) could also be developed, which may lead to a significant reduction in the release of fission and activation products (see also [8]). In scenarios that postulate water ingress to the material emplaced in the repository, this would result in a reduction of uncertainties regarding the release and migration behaviour of these nuclides.

The scenarios referred to postulate release and fluid-borne transport of radionuclides into the biosphere. If, however, future human intrusion into a repository is postulated without being aware of the existing hazard potential, the hazard for the intruder primarily emanates from the radiotoxicity of the material emplaced since it becomes immediately bioavailable. Related calculations show a significant reduction in the exposure level for an intruder from waste inventories arising from the application of P&T ([13], [14]). After some hundred years, the radiotoxicity of the waste from P&T is smaller than the radiotoxicity of natural uranium used for fuel. The BMU Safety Requirements [19] require optimisation of the repository with regard to such scenarios. It is classified as a “secondary priority” and shall be carried out with regard to the probability of occurrence and the consequences for the general public (i.e. not for the intruder). A reduction in this probability results from the reduction of the footprint described above.

Long-term safety considerations are naturally subject to uncertainties.

The uncertainties of (model) predictions increase with increasing periods of time, especially if the forecast is to cover a period of one million years. Minimisation of the emplaced radiotoxic material also means a reduction of the associated uncertainties. The reduced footprint of a repository could contribute to a reduction of uncertainties and possibly increase the number of suitable sites.

In summary, the following can be stated: With P&T, there would be no fundamental changes with regard to the long-term safety of a repository for heat-generating radioactive waste in Germany, but it could contribute to the limitation or reduction of uncertainties. Moreover, there is a potential to reduce the area needed for emplacement, which could facilitate site selection. On the other hand, it has to be considered that nuclear P&T facilities have to be operated for several decades and additional quantities of radioactive waste with negligible heat generation would have to be stored or disposed of, possibly with additional uncertainties and with additional space needed in a suitable repository.

3.3 Criticality risks

The term criticality refers to a nuclear chain reaction where fissile nuclides and neutrons cause a nuclear fission reaction which results in the production of further neutrons which, in turn, cause fission reactions. The BMU Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste [19] stipulate that the exclusion of critical arrangements for both probable and less probable developments of the repository system must be proven. The occurrence of uncontrollable critical arrangements of fissile material in a repository for heat-generating radioactive waste in the post-closure phase is considered to be extremely unlikely for some scenarios, but cannot be entirely ruled out [20]. The latter applies, in particular, to the disposal of fuel with lower burn-up or mixed oxide fuel (MOX: uranium-plutonium mixed oxide). Critical arrangements can only occur if the containers corrode, water contacts the waste form and hypothetical, very selective geochemical reactions occur. When treating spent fuel by means of P&T, criticality events in a repository are also to be excluded for unlikely repository evolutions, since the waste from P&T facilities does not contain fissile material in significant concentrations.

Nevertheless, potential criticality risks in P&T facilities are to be considered in which fissile material is separated and partitioned, and enriched in different steps [6]. By appropriate measures, processes can be designed so that critical arrangements in separation plants are excluded. However, for some P&T process concepts, such as the electrochemical separation of actinides, the concentration to critical amounts of transuranic elements is conceivable and must be prevented by technical measures. Risks due to supercritical behaviour in transmutation reactors are not expected, which applies, in particular, to the ADS reactors operated in subcritical mode.

Although criticality risks associated with direct disposal and in P&T facilities are low, the consequences of occurrence for man and the environment are to be assessed significantly differently. The occurrence of a nuclear chain reaction in a repository in deep geological formations is only conceivable as a result of slow geochemical reactions, but, in theory, can continue over long periods of time. Explosive excursions are to be excluded [20]. The consequences will remain limited to the close vicinity of the emplacement area. By contrast, criticality events in nuclear facilities may have direct radiological impacts on operating staff (see e.g. [21]). In addition, unlike repositories in deep geological formation, nuclear facilities are within the biosphere with correspondingly direct impacts on man, nature and the environment.

3.4 Proliferation risks

The term proliferation risk is referred to as the potential misuse of fissile material for military or terrorist purposes. In principle, scenarios are conceivable in which, e.g., weapons-grade material is diverted for unauthorised use. Plutonium in spent nuclear fuel from power reactors with high burn-up is less suitable for the production of nuclear weapons due to its isotopic composition (content of ^{240}Pu). However, military or terrorist use cannot be ruled out [22]. The use of radiotoxic waste components for the production of “dirty bombs” is also conceivable.

Access to irradiated nuclear fuel assemblies that are located in a sealed repository at a depth of several hundred meters is only possible with difficulties and by mining engineering measures, requiring considerable expenditure of time. Moreover, spent nuclear fuel “protects” itself for about a few hundred years, since handling of the spent nuclear fuel can only take place in special plants with efficient shielding and by remote control due to the intense gamma radiation emission of fission products. However, after decay of relatively short-lived fission products – in particular of ^{137}Cs and ^{90}Sr (half-lives of about 30 years) – after about 300 years, less handling efforts will be required. While in the case of direct disposal of spent fuel also nuclear fuel, e.g. plutonium, will be emplaced in the repository, this is practically to be excluded when applying P&T concepts.

Access to plutonium seems to be easier to achieve after partitioning of the highly radioactive fission products. Although civilian reprocessing plants and thus also future partitioning facilities are subject to strict international controls, proliferation-resistant methods are considered in the development of separation processes for P&T. Through the joint partitioning of uranium, plutonium and, where appropriate, minor actinides, it is intended to prevent the occurrence of pure plutonium material flows. In this case, complex nuclear facilities would be required to first partition plutonium and, moreover, produce nuclear weapons-grade material.

3.5 Time scales

According to the Site Selection Act (*Standortauswahlgesetz* – StandAG) [5] and the National Programme (*Nationales Entsorgungsprogramm* – NaPro) [10], the legislator provides the following schedule for the disposal of heat-generating radioactive waste:

- Decision on the site of the disposal facility for heat-generating radioactive waste by the year 2031, and
- commissioning of the disposal facility around the year 2050.

The operating time until sealing will be several decades, depending on the disposal concept.

Until application of P&T on an industrial scale, it is still required – regardless of the technology chosen – to carry out extensive research and development work. According to [8], P&T could be realised within the framework of a European Systems Participation on an industrial at the earliest from 2040. This would require the conclusion of appropriate international agreements and the creation of the legal basis as well the creation of the prerequisites for reaching political and social consensus within a relatively short period of time. Furthermore, it has to be considered that there will also be uncertainties in the related planning activities due to the dependence of the respective P&T development progress in the partner country. In case of a purely national development, a significantly longer period would have to be expected.

Against this background, the time scales for the construction of a disposal facility (according to the StandAG) and the development of a P&T concept seem to be compatible – at least in the case of a European Systems Participation – since both the realisation of a disposal facility as well as construction and commissioning of a P&T facility is expected to take several decades.

For the development and comparison of disposal concepts and repository sites, waste types and quantities should be known as early as possible. Therefore, an early decision in favour of or against the application of P&T for the treatment of spent nuclear fuel is to be regarded as expedient for the site selection procedure that has now been launched in Germany. However, it can be assumed that the waste produced by P&T at least will not lead to stricter requirements for a repository site for heat-generating radioactive waste.

Thus, the planning of a repository in deep geological formations does not rule out parallel pursuance of P&T. From this, it has to be concluded that, given the compatible periods of time, there is no reason to delay a procedure for the selection and construction of a repository for heat-generating radioactive waste in order to wait e.g. for the technical maturity of P&T. On the other hand, in case of additional delays in the process of waste management planning, those uncertainties become greater that are related e.g. to the storage of spent nuclear fuel for very long periods (e.g. > 100 years) (see [23]).

It is considered certain that there will be extended storage periods, and also the closure of the repository will be delayed by decades due to the operating periods of P&T facilities expected according to [6]. In addition, it is to be ensured that there will be a repository available that is ready for acceptance of the radioactive waste with negligible heat generation that will arise in larger quantities from the application of P&T.

3.6 Social and economic aspects

3.6.1 Public acceptance

Due to the considerable public controversy over the disposal of radioactive waste, the question arises as to whether a waste management concept would find greater public acceptance when including P&T.

So far, representative surveys on society's attitude towards the P&T concept are neither available at the national nor at the European level. Recent Eurobarometer surveys of the European Commission from

2008 [24] and 2010 [25] on the use of nuclear energy do not take into account any questions on the attitude of European society towards the P&T concept.

In the national context, the acatech study [6] currently includes the most detailed examination of the societal implications of P&T. The representatives of environmental organisations interviewed in the study held the view, inter alia, that P&T is currently virtually unknown to the public. Whether a better knowledge of the P&T concept will ultimately lead to either greater acceptance or rejection in society could not be clarified within the framework of the acatech study.

According to the results of the acatech study [6], a positive attitude among the German public towards the construction of P&T facilities in Germany is very unlikely. The results from [25] on the use of nuclear energy are not directly transferable to P&T facilities, but confirm the fundamentally sceptical attitude towards nuclear facilities: 52% of the Germans surveyed were in favour of reducing the number of nuclear power plants, and only 7% were in favour of an increase. It is not to be expected that these figures have changed significantly in the last five years.

This means that at most participation in and/or use of P&T facilities in other EU countries could be considered. In this case, according to [6], aspects of acceptance among the German public would most likely play a role for sites near the border.

Regardless of the distance to the border, the participation in European P&T facilities would be connected with the transport of spent fuel from German nuclear power plants abroad. In addition to the risks of transport, which could be explained to the public according to [6] *(“However, if those transports were to take a major burden off radioactive waste management in Germany, they could be explained to the public.")*, such a transport might also raise the question in the public and political discussion as regards the ethical acceptability of exports of fissile material. Moreover, the question of whether supporting the use of nuclear energy in other countries through the export of fissile material is compatible with the German policy of phasing out nuclear energy would be controversial.

If assuming such a European option, the question arises whether the disposal of radioactive waste after application of a P&T concept will find greater acceptance than disposal at the earliest possible stage without treatment of the fuel by P&T.

The optimisations resulting for a repository for highly radioactive waste due to actinide partitioning (and use in Generation IV reactors or transmutation in ADS reactors in other European countries), described in Chapter 3.1, could speak in favour of a greater acceptance. In addition, it would have to be expected that the extended period of time until sealing of the repository when applying P&T is perceived as positive by the actors that plead for a postponement of the decision on disposal with the argument that development of newer better technologies should be waited for (see discussion in Chapter 3.5).

On the other hand, the volume of radioactive waste with negligible heat generation increases. If such waste could not be emplaced in one of the repositories planned in Germany, it is not to be expected from today's perspective that any necessary additional repository site for the technological and operational waste from P&T will in the future meet significantly less rejection than currently a repository for heat-generating radioactive waste. Furthermore, the current discussions on a site for a repository for heat-generating radioactive waste do not suggest that public acceptance for a site would be easier to achieve with the optimisations achievable by application of P&T since details of the size and inventories to be emplaced are rather marginal aspects of the discussion so far. Further postponement and the considerable costs of P&T, which cannot be covered by the existing provisions, could also lead to a lower acceptance of the P&T concept should it become apparent that a considerable amount of costs has to be borne by the public sector.

3.6.2 Economic aspects

A cost estimate for the implementation of P&T is difficult to be made because such facilities are, for the most part, still under development and, in addition, the required investments depend on the P&T concept. Reliable figures for costs incurring are therefore neither available nor to be expected in the near future. A comparative economic study for different P&T concepts is described in [26]. Cost increases for the price of electricity were estimated relatively to the reference concept “direct disposal of spent fuel”. However, all P&T concepts considered in this comparative study include the same assumption that electricity will continue to be generated with partitioned uranium and plutonium. The only model that might be “matching” for Germany is European systems participation. For such an approach, an electricity price increase compared to direct disposal of about 10 to 20% was estimated. Scenarios that are based on such estimates provide that some of the facilities, e.g. seven ADS facilities, would have to be operated in Germany for about 30 to 40 years [6]. Another European study estimates an electricity price increase of about 50% for various P&T scenarios, relative to the price of electricity from nuclear energy with direct disposal of spent nuclear fuel [8]. An exclusively national P&T solution without intention to generate electricity with P&T facilities and the fissile actinides uranium and plutonium would certainly involve such high costs that it is uninteresting from an economic point of view [6].

4 Summary

- P&T cannot replace a repository for heat-generating radioactive waste, but reduce the repository footprint. This reduction is limited by the already existing vitrified waste containing transuranic elements that cannot be treated by P&T. Moreover, additional waste with negligible heat generation will be produced.

- The impacts of P&T on results of long-term safety analyses for repositories are low. Transuranic elements that are convertible through P&T are regarded as largely immobile under repository conditions.

- The significant reduction in the long-term radiotoxicity of the waste from P&T compared to the direct disposal of spent fuel can help to reduce uncertainties in long-term safety assessments for a repository. This applies, in particular, to human intrusion scenarios.

- The reduction of uncertainties in long-term safety assessments has to be weighed against conceivable risks arising from the operation of nuclear P&T facilities over several decades and the production of further radioactive waste with negligible heat generation.

- Under the special conditions in Germany (decision to phase out the use of nuclear energy, low acceptance of nuclear technology by the public) and for economic reasons, the development of a separate national P&T concept for Germany appears to be rather unreasonable. The cooperation with countries that continue to rely on nuclear energy and P&T in terms of systems participation represents a more favourable P&T strategy.

- The time scales for the development of P&T technologies and site selection for a repository seem to be compatible. Therefore, a parallel development of both processes would also be possible. Accordingly, delays in repository projects by waiting for P&T are therefore not necessary.

- Greater public acceptance for P&T compared to direct disposal is currently not recognisable.

- At present, an economic cost/benefit analysis for P&T cannot be made. However, significantly higher costs have to be expected compared to direct disposal.

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