# > Partitioning and Transmutation of Nuclear Waste

## Opportunities and Risks in Research and Application

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# SUMMARY


In June 2011, the German Federal Government announced the *Energiewende*, thereby initiating the end to the use of nuclear power for electricity production. No German nuclear power plant is to produce electricity after 2022. However, no conclusive answer has as yet been found to the problem of where and how radioactive waste is to be stored in a repository. In particular, there is at present no repository for heat-generating high-level waste. Although this type of waste constitutes only a small fraction by volume, it produces 99 percent of the radioactivity of all waste from nuclear plants. On July 26, 2013, the Site Selection Act entered into force: A repository site for heat-generating radioactive waste is to be looked for and selected in an unbiased procedure.

Site selection is influenced in particular by the type and volume of waste to be stored in a repository. The technology of Partitioning and Transmutation (P&T), which is to convert part of the longlived high-level radioactive substances contained in the spent fuel rods into shorter-lived fission products, is currently under research and development; it could be one way of reducing the long-term hazard potential of heat-producing waste.

In the process of partitioning, the spent fuels from nuclear power plants are to be separated into uranium not split in the reactor, plutonium, and the minor actinides (neptunium, americium, and curium). This leaves the fission products and activation products for vitrification and disposal in the appropriate repository as heat-generating waste. The partitioning process also gives rise to decontamination water and rinsing water as secondary waste. In countries continuing to use nuclear power, the uranium separated can be fed back into reactors while, in Germany, it must be stored in a repository as waste producing negligible amounts of heat. At the present status of licensing, the secondary waste (decontamination water and rinsing water) requires a repository to be built for waste generating negligible amounts of heat. The transmutation process is only for plutonium and the minor actinides. They are bombarded with fast neutrons in a transmutation plant, which converts at least 90 percent of them into shorter-lived or stable atomic nuclei. Afterwards, the newly produced isotopes must be stored in a repository as heat-generating waste, but containing less long-term radioactivity. A transmutation plant is a nuclear plant (yet to be developed) whose safety requirements must correspond to those applicable to fourth-generation reactors. This makes the plant safer than the reactors currently used for electricity production.

Project work is based on four societal development scenarios, all of which presuppose that Germany opts out of the use of nuclear power. Two scenarios envisage no technical-scale P&T application in Germany: In the "*abstinence*" scenario, P&T is not operated in or out of Germany. In the "*research participation*" *scenario*, Germany conducts research and development within a national, European, and international framework without building any P&T plants. The other two scenarios, on the other hand, provide for technical-scale application of P&T in Europe with German participation ("*European systems participation*") or in Germany proper ("*Application in Germany*"). The consequences of each of these scenarios were worked out on the basis of a broad mix of methods and compared with each other so as to allow the specific opportunities and risks to be estimated.

## CHANCES OF P&T

– Provided it can be successfully applied on an industrial scale, P&T will be able to clearly reduce to one third (from 28,000 to 9,500 cubic metres) the volume of heat-generating waste scheduled for repository storage. This is helped in particular by the dissolution of uranium in the first partitioning step. At the same time, the volume of waste generating negligible amounts of heat would rise by about one third (from approximately 300,000 to approximately 400,000 cubic metres).

- Several centuries after waste emplacement in a repository, the use of P&T reduces the bulk radioactivity in a repository for heat-generating waste, and thus the hazard potential. After 1,000 years, the repository for heat-generating high-level radioactive waste contains roughly the same radioactivity (or, as a weighted quantity, radiotoxicity) (aside from the heat-generating waste already vitrified) as after one million years without the application of P&T. In this way, P&T is able to reduce the hazard potential of the waste emplaced, while the risk of a release from the repository is hardly influenced in the light of the present status of safety analyses.
- The danger of plutonium being stolen from the repository and misused is diminished. The plutonium separated is converted in transmutation plants, which means that only negligibly small amounts of it will be contained in the repository. This is important especially when the self-protection provided by the high local radiation dose has ceased to exist.
- After partitioning, the mobile fission products and activation products separated from the spent fuel and in need of repository storage can be conditioned more effectively (e.g. by incorporation in a matrix to immobilize the residual materials). This reduces the risk of early release from the spent fuel, thus also decreasing the long-term risk of contamination of the biosphere.
- As a consequence of americium separation, P&T reduces heat production in the repository for heat-generating waste after 70 to 100 years. If the waste is emplaced in a repository after that period of time, the minimum spaces between emplacement galleries and the waste containers are reduced which must be observed because of the maximum design temperature. On the other hand, a comparable reduction of heat resulting from natural decay would also occur after a correspondingly long period of interim storage without P&T.

## RISKS OF P&T

- The P&T plants to be built can be a hazard to persons and to the environment. The risk is comparable to that associated with the operation of plants for reprocessing or conditioning spent fuel elements and of fourth-generation nuclear reactors.
- For a period of approximately 150 years of P&T use, there is an increased risk of misuse of radioactive materials by third parties. Depending on the process employed, both plutonium and the minor actinides may be present in a pure or mixed form after partitioning. They might be stolen in transit to the transmutation plants or into an interim store. This hazard exists also because of the need to keep the repository open for a longer period of time.
- As the waste volumes to be partitioned and transmuted in Germany are relatively small, unit costs per ton of waste are high. Building and running P&T plants will not be viable economically, at least in Germany, compared to final storage without P&T.
- Any plant associated with nuclear technology is rejected by the overwhelming part of the German public. Construction and operation of P&T plants most probably would give rise to public opposition.
- As nuclear power regularly used to be in the focus of media interest in the past, media reporting about planning, construction, and operation of P&T plants could mainly be negative.

Some chances of P&T will not work in Germany either at all or only in part, as the opt-out of the use of nuclear power has been decided upon. If pros and cons are to be weighed comprehensively, for instance, the role of the size of a repository on a potential site must be determined. Moreover, P&T in Germany will raise by one third the volume of secondary waste arising in the form of waste producing negligible amounts of heat, for which the appropriate storage space and other repository volumes, respectively, have to be created. On the one hand, it is not advisable, for economic, eco-toxicological and societal reasons, for Germany to build and operate P&T plants on its own. On the other hand, it seems to be premature right now to discontinue research and abandon all P&T options, as those include opportunities as well. Both fundamental research and technical development research ought to be continued within a European integrated research effort. This would leave all options for action open while answering the questions as yet unsolved in connection with this technology. It would also preserve competence and jobs in nuclear research and grant possibilities of co-determination in international bodies.

### acatech RECOMMENDATIONS IN A NUTSHELL:

- P&T research should be conducted within a European context.
- Future participation of Germany in P&T in Europe should be examined.
- Participation in research should not mean dependence on a specific path in the direction of P&T application.
- An interdisciplinary comprehensive study should be conducted which could be used as a basis on which to decide whether Germany is to participate in P&T in Europe. This decision will have to be taken probably ten or fifteen years from now. The processes defining when and how stakeholders and the public should be involved should be planned in time.
- Germany should follow a European perspective and keep in mind national research approaches by including the legally defined objectives of opting out of the use of nuclear power.
- German industry should see the potential implementation of P&T in Europe as an opportunity to be used where possible.
- Research should focus on these key areas:
  - efficient partitioning
  - efficient transmutation of the transuranium elements partitioned
  - assessing technical safety of plants
  - evaluating societal implications in all options for action.
- Research must adopt an interdisciplinary position if it is to evaluate and communicate scientific-technical findings.
- A research alliance should be established.

# PROJECT

This POSITION PAPER was elaborated on the basis of the acatech STUDY, *Partitionierung und Transmutation: Forschung – Entwicklung – Gesellschaftliche Implikationen* (Renn 2014).

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An analysis of the scientific-technical aspects (module A) served as a basis for evaluating societal implications and recommending communication and action with respect to the future position to be taken in the field of P&T (module B).

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# 1 INTRODUCTION

When the German Federal Government in June 2011 announced the Energiewende, it simultaneously proclaimed the end of the use of nuclear power for electricity production. No German nuclear power plant is to produce electricity after 2022.[1] However, the problem of the final storage of radioactive waste has not yet been solved conclusively. In Germany, there is at present no repository for heat-generating radioactive waste and spent fuel. On July 26, 2013, the Site Selection Act entered into force. From now on, a science-based, transparent procedure is to be conducted in the search for a repository site for heat-generating radioactive waste without any bias with respect to the outcome.[2] The repository problem is an urgent one also on a European and an international level, all the more so since many countries, such as France, Spain, the Czech Republic, USA or China, continue to rely on nuclear power for electricity production and, as a consequence, are going to produce radioactive waste also in the future. Sweden, Finland, and France are in the middle of, or shortly before, a licensing procedure for the construction of repositories for spent fuel; the first repositories are to be commissioned in approximately ten years' time.

Factors important in the selection of such a repository site in particular are the types of waste (producing heat or producing only negligible amounts of heat) and the waste volume (see box on p. 13). Several repositories for waste generating negligible amounts of heat are already available in Europe.[3] There is one such repository site also in Germany, namely the Morsleben repository (which is currently undergoing the plans approval procedure for decommissioning); the Konrad repository (Salzgitter) will be another such repository available in a few years' time.[4] However, nowhere in the world is there a repository for heat-generating waste in operation right now. On the other hand, a solution to this problem is particularly important as heat-generating waste, while constituting only a small volume fraction, makes up 99 percent of the whole radioactivity of all waste arising in the operation of nuclear facilities.[5] To this day, finding and selecting a repository site for heat-generating waste has tended to fail less for the scientific and technical aspects of final storage but rather as a result of societal opposition.[6]

The long-term safety of a repository is determined not only by the type and amount of waste, but also by the length of time for which the waste must be stored safely. One way of reducing the long-term hazard potential of heat-generating waste could be Partitioning and Transmutation (P&T), a technology currently under research and development.

P&T serves to separate (partition) the actinides (uranium and transuranium elements) from radioactive waste and convert (transmute) the transuranium elements with long halflives into nuclides with shorter halflives, see Fig. 2 (page 14). As a consequence, total radioactivity and radiotoxicity[7] decrease more quickly.[8] In the partitioning process, uranium, plutonium, and the minor actinides (neptunium, americium, and curium) are separated very much as in reprocessing. What remains are the fission products and the activated structural materials which must be emplaced in the repository for heat-generating waste. Some longlived fission products and activation products, which must be stored safely for long periods of time, could require new waste matrices to be developed (such as ceramics) to slow down mobilization of these radionuclides in the repository in case immobilization in glass (vitrification) is not sufficient.

1 see BMU 2011.
2 see BMU 2013.
3 Such as the Loviisa and Olkiluoto repositories in Finland or SFR Forsmark in Sweden.
4 see BfS 2012.
5 see BfS 2012.
6 see Hocke/Grunwald 2006.
7 Radiotoxicity is determined by the type of radiation, the radiation intensity, and the uptake and residence time of the respective elements in the human organism.
8 see Knebel et al. 2013, Lübbert/Ahlswede 2008.

In energy generation from nuclear power, uranium and plutonium undergo fission. The spent fuel from nuclear power plants is highly radioactive and must be disposed of in a safe, non-polluting way. Besides uranium not split in the reactor and its fission products, it contains transuranium elements (plutonium and the minor actinides, neptunium, americium, and curium) produced in operation as well as activation products resulting from the structural materials used for the fuel. After several hundred years, it is the transuranium elements which represent the main hazard potential. It takes several hundred thousands of years for their radioactivity to decline to the level of uranium of a natural composition. Although these radionuclides constitute just slightly more than 1 percent of the mass of the heat-generating radioactive waste (Fig. 1), they are longlived and highly radioactive (and thus generate heat). Consequently, they need to be stored safely. Either the spent fuel elements are kept in repositories as radioactive waste or they are reprocessed. In reprocessing plants, the residual uranium and the newly produced plutonium from the fuel rods are separated and recycled in nuclear reactors. Up until 2005, also Germany transported its spent fuel for reprocessing to La Hague in France and Sellafield in the UK. Now this shipping of spent fuel is legally prohibited. On the other hand, there is still waste held in plants abroad which must be returned to Germany in the form of so-called vitrified waste.

Figure 1: Percentages by mass of spent fuel from nuclear reactors

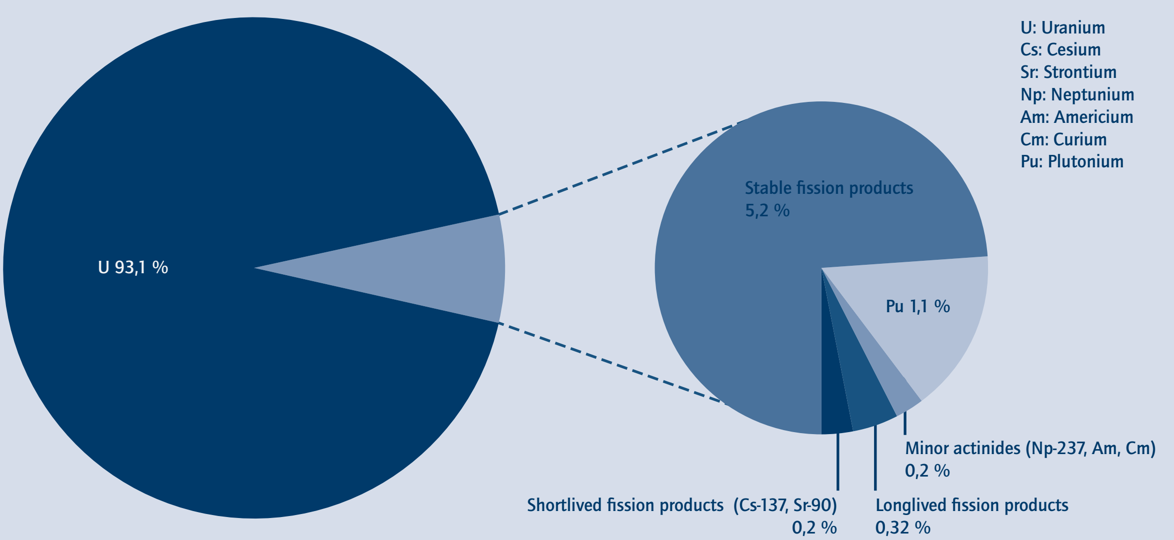
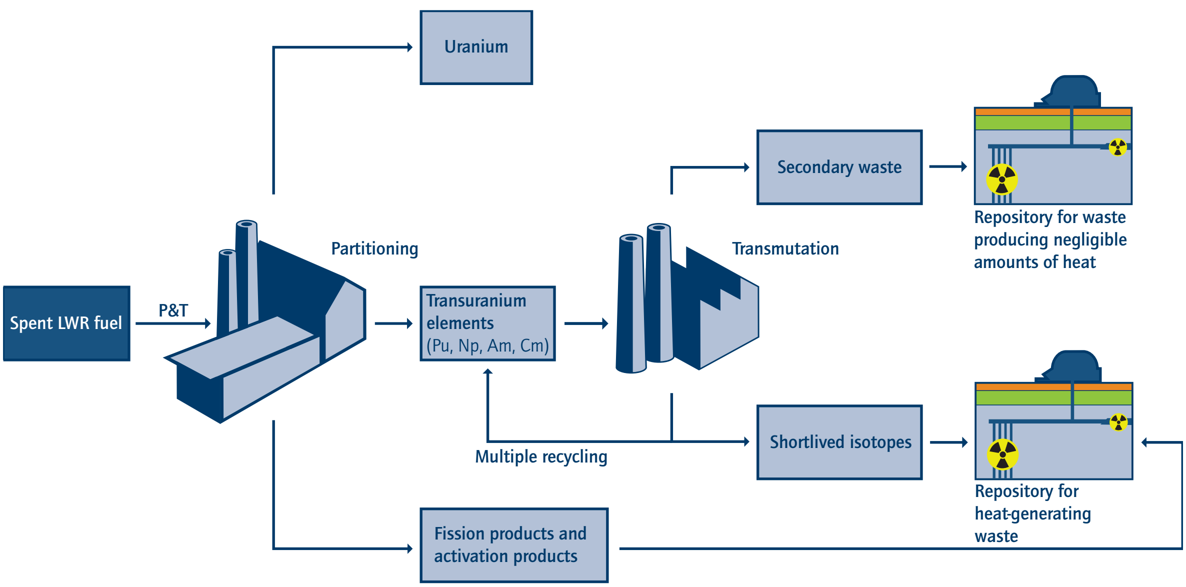


Figure 2: Flowchart of Partitioning and Transmutation




In the absence of partitioning, some of these radionuclides would occur in the spent fuel in a slightly more mobile form. The uranium separated can be recycled in reactors to produce nuclear power or must be kept in a repository as waste producing negligible amounts of heat. The secondary waste, which continues to arise also in P&T (such as water from decontamination and rinsing), requires additional repositories to be built for waste producing negligible amounts of heat. The transmutation process is only for plutonium and the minor actinides. These are bombarded with fast neutrons in a transmutation plant and, in this way, are converted into shortlived or stable atomic nuclei at a rate of at least 90 percent. A transmutation plant is a nuclear facility (yet to be developed) whose safety requirements are determined by those applying to fourth-generation reactors, which makes them safer than the nuclear reactors currently operated for electricity production. After the P&T stages, the newly produced isotopes (fission products) must be emplaced in repositories as heat-generating waste. After one thousand years, leaving out the waste already vitrified, roughly the same radioactivity (or radiotoxicity as a weighted quantity) exists in the repository for high-level heat-generating radioactive waste as would exist after one million years without the application of P&T.

P&T processes have been investigated in Europe and in countries outside of Europe since the 1970s.[9] These research activities so far have been primarily scientific and technical studies seeking to examine and demonstrate the feasibility and suitability of the P&T technology. One problem under investigation was whether and to what extent P&T on a technical scale would be able to reduce the hazard potential of radioactive waste.[10]

9 see RED-IMPACT 2008; OECD 2011; Feder 2009; Knebel/Salvatores 2011.
10 see Kettler/Heuters et al. 2011.

This position paper is based on the fact of Germany giving up the use of nuclear power. Worldwide, however, the use of nuclear power is likely to increase, as is the volume of radioactive waste. A global assessment of P&T therefore would have to take into account both the rising demand for repositories and recycling in the interest of sustainable energy production.

In view of the opportunities and risks of P&T, the German Federal Government is confronted with the decision whether and to what extent, respectively, such processes could become building blocks of the national nuclear waste management strategy. This means weighing technical and safety-oriented, ecological, economic, and social opportunities and risks. Potential opportunities, for instance, could be seen in the fact that the entire radioactivity would decrease faster, and the repository volume for heat-generating radioactive waste would be smaller. Also the preservation of competence in the nuclear field could be a positive effect.[11] Potential risks include the newly added ecotoxicity potential arising from P&T plants to people and the environment, and the time and cost involved in building, operating, and demolishing these plants.[12] Another fact to be considered is the limited impact of P&T on repository size. There is also the question of the attitude towards the construction of P&T plants of the public in the vicinity of the site.

For this reason, the German Federal Ministry for Economics and Technology (BMWi) and the German Federal Ministry for Education and Research (BMBF) commissioned an interdisciplinary research project designed to study the technical and societal opportunities and risks of P&T in the light of various scenarios. The supreme objective was to work out a factual, balanced basis on which to decide Germany's future position in matters of P&T research.

The findings were summarized in the acatech STUDY, "Partitionierung und Transmutation: Forschung – Entwicklung – Gesellschaftliche Implikationen."[13] On the basis of the results of that acatech STUDY, this acatech POSITION PAPER contains recommendations about the future management of P&T addressed to players in politics, industry, and science.

11 acatech 2011.
12 see Lübbert/Ahlswede 2008.
13 Renn 2013.

# 2 OPPORTUNITIES AND RISKS OF P&T

Operating P&T implies both opportunities and risks. Identifying and characterizing the opportunities requires some assumptions to be made. The authors consider P&T being applied to all spent light water reactor (LWR) fuel which, otherwise, would have to be treated by direct disposal; especially the vitrified waste from reprocessing cannot be influenced by P&T. Another assumption is that the heat-generating waste only arising from the application of P&T, i.e. the new isotopes generated by transmutation, will be stored in a repository to be built for that purpose, while the recyclable fuel, i.e. the uranium separated, can continue to be used in reactors, for instance in countries still using nuclear power for electricity production:

- If final storage were preceded by a P&T process, the volume of heat-generating waste to be stored in a repository could be reduced remarkably to one third. This is due especially to the separation of uranium in the first partitioning step. What to do with this uranium would be a political decision. It could be used as an energy resource in reactors for further energy production or directly emplaced in a repository. The storage volume this would require in the repository for heat-generating waste would be smaller, as would be the repository area needed.
- In any case, Germany needs a repository for heat-generating waste, namely for
  1. the heat-generating waste already vitrified,
  2. the spent fuel from prototype and experimental nuclear power plants as well as research reactors, none of which can be treated by P&T,
  3. the heat-generating waste remaining after P&T (vitrified fission products and activation products as well as heat-generating secondary waste).
- In addition, at the present state of licensing procedures, another repository will be needed for the secondary waste, producing negligible amounts of heat, arising from P&T (water from decontamination and rinsing) and for the uranium separated unless re-used abroad.
- P&T will reduce the total activity in the repository for heat-generating waste, and thus the hazard potential, several centuries after emplacement. Disregarding the heat-generating waste already vitrified, approximately the same radioactivity (or, as a weighted quantity, radiotoxicity) will be contained in the repository for high-level radioactive heat-generating waste after one thousand years as would be after one million years without P&T. In this way, P&T is able to reduce the hazard potential of the waste emplaced, while the risk of a release from the repository is hardly influenced in the light of the present status of safety analyses.
- The use of P&T reduces the hazard of plutonium being stolen from the repository and misused. This is important particularly after the end of the period of self-protection, as the fission products surrounding the plutonium will have a high level of radioactivity for some 300 years until a major part will have decayed into stable isotopes. Provided that the plutonium separated is converted in transmutation plants or recycled as mixed oxide fuel for energy production, the repository will contain only negligibly small amounts of plutonium.
- After partitioning, the mobile fission and activation products separated from the spent fuel and to be kept in a repository can be conditioned more easily, i.e. immobilized in a stable matrix. This reduces their early release from the spent fuel and also diminishes the long-term risk of contamination of the biosphere. However, this requires the heat-generating waste to be immobilized in a waste matrix different from that used for spent fuel. What waste matrices are suitable for this purpose also needs to be investigated and developed further. At present, for instance, ceramic materials are being studied as a potential matrix.
- P&T reduces heat generation in the repository for heat-generating waste from an interim storage period of 70 to 100 years. If final storage follows after that period of time, the minimum spacing of the emplacement galleries and waste containers to be observed in the light

of a maximum design basis temperature in all probability can be reduced, provided design requirements under aspects of rock mechanics are taken into account. Comparable heat reduction by natural disintegration would result also after an appropriately long period of interim storage without P&T.

Some of these opportunities will not work at all or only in part in Germany, as the country will stop using nuclear power. Undoubtedly, repository space could be smaller as the separation of uranium and the transuranium elements in the repository for heat-generating waste would release less heat and, in addition, the waste volume would be smaller. However, the entire process of weighing needs to clarify the fundamental importance of the repository size for the potential sites. This is where the volume of spent fuel to be stored in repositories plays a role; it is limited because of Germany phasing out the use of nuclear power. Moreover, it must be taken into account that P&T will cause arisings of radioactive waste for which the appropriate storage capacity or further repository volumes must be created for waste generating negligible amounts of heat.

In addition to the technical advantages outlined above, there are potential opportunities

- strengthening Germany's internationally acknowledged role in driving innovative and future technologies,
- in the active collaboration of Germany in important international agencies, for instance, in helping define safety standards,
- in the capacity for independent safety assessment also of foreign plants, and
- in maintaining the acknowledged high German competence in the nuclear field.

Aside from these opportunities, especially the empirical findings derived from expert inquiries within the framework of this study have shown the risks outlined below:

- Hazard potential to persons and the environment: While the radiological and the non-radiological ecotoxicity potentials of P&T plants cannot be estimated in exact quantitative terms, they are comparable to the risk arising from the operation of plants for reprocessing or conditioning spent fuel, and of fourth-generation nuclear reactors, which makes it lower than that of present power reactors. Besides the risks posed by the plants proper, it is also the increased quantities of waste generating negligible amounts of heat produced by P&T, and the additional transports, which would not be necessary in a repository concept without P&T.
- The risk of misuse of radioactive materials: In the approximately 150 years of P&T use, there is an increased risk of misuse by third parties. Depending on the process employed, both plutonium and the minor actinides could be present in a pure form after partitioning. On the one hand, the radioactive material must be transported from plant to plant (interim store, plants for partitioning and transmutation) and, on the other hand, the plants proper must be protected sufficiently from access by third parties. Moreover, the repository must be kept open longer if P&T is used than would be necessary after an opt-out of the use of nuclear power. This also entails a higher risk of misuse of radioactive substances.
- The costs of plant construction, operation, and demolition: Where waste volumes are relatively small (as in Germany), unit costs per ton of waste are high. For this reason, construction and operation of P&T facilities will not be viable economically, at least in Germany, compared to direct disposal without P&T. However, not only economic reasons should count when the interests of future generations are at stake.
- Public acceptance: All facilities associated with nuclear technology are rejected by the majority of the German public. The construction and operation of P&T facilities also would be seen in a negative light and probably spark off opposition.

- Negative coverage by the media: The topic of P&T could become attractive for the media because it would be associated with risks to the environment and to health, and potentially high costs as well as the potentially critical attitude to P&T of the public and the host municipalities, respectively, would have to be considered. This is true in particular because nuclear power in the past regularly attracted media interest. In this situation, planning, construction, and operation of the facilities could receive predominantly negative coverage in the classical and modern mass media (print, TV, radio, internet).

# 3 P&T IN THE CONTEXT OF FINAL STORAGE OF RADIOACTIVE WASTE IN GERMANY

In 2022, when all German nuclear power plants will have ceased to produce electricity, the total volume of spent fuel classified as nuclear waste in Germany will amount to approximately 10,500 tons of heavy metal (tHM). By 2005, approximately 6,700 tHM of spent nuclear fuel were treated in the reprocessing plants of La Hague (France), and Sellafield (UK), and the resultant heat-generating waste was vitrified on the spot.

The possibility of partitioning and transmutation has been considered in this study only for the spent fuel remaining in Germany. Theoretically, also the vitrified waste from reprocessing could be treated in P&T facilities, although this makes little sense for economic and ecological reasons, in particular as uranium and plutonium have already been separated from that waste. At any rate, Germany will need a repository for heat-generating waste for

**(1)** the heat-generating waste already vitrified,
**(2)** the spent fuel from prototype and experimental nuclear power plants as well as research reactors, which cannot be treated by P&T,
**(3)** the heat-generating waste remaining after P&T (vitrified fission products and activation products as well as heat-generating secondary waste), and
**(4)** in the light of the present licensing situation, the secondary waste arising from P&T producing negligible amounts of heat.

Technically feasible separation factors taken into account, roughly the same total radioactivity would be present in the repository for high-level heat-generating radioactive waste after 1,000 years as would be reached after 1 million years in the absence of P&T. When all existing waste (vitrified waste from reprocessing in France and the UK and the spent fuel from prototype and experimental nuclear power plants as well as research reactors) is taken into account as well, this reduced time span is approximately 10,000 years.

If final storage of the heat-generating waste were preceded by a P&T process (including separation of uranium in partitioning), the emplacement volume, depending on the repository concept, could be reduced to a maximum of one third (namely from 28,000 to 9,500 cubic metres), while the volume of waste generating negligible amounts of heat would rise by up to 100,000 cubic metres (corresponding to an increase by roughly one third). One third of the emplacement fields to be provided for heat-generating waste is earmarked for existing waste from reprocessing and remains unaffected by P&T. On the whole, the space requirement of a repository for heat-generating waste (secondary waste excluded) and without new heat-generating waste from P&T therefore decreases by a maximum of 50 per cent. In this way, the cavity volume and the emplacement space of the repository for heat-generating waste will be reduced, while the waste from P&T producing negligible amounts of heat will have to be emplaced in a new repository as required by present licensing conditions. The volume of heat-generating longlived secondary waste from reprocessing will rise by approximately a factor of two or three compared to working without P&T. That waste is present already as a result of previous reprocessing and comprises approximately 10 per cent of the volume of all waste reprocessed and returned abroad. It comprises mainly medium-active water from decontamination and rinsing.

For transmutation, a variety of reactor configurations can be imagined in principle, the pros and cons depending very much on the specific targets.

In Germany, those configurations are particularly interesting which do not give rise to more fissionable material as they are compatible with the objectives of giving up the use of nuclear power. This would be possible in a transmutation facility of the ADS (Accelerator Driven System) type or in critical reactors using liquid fuel. Despite extensive research and development (R&D) on ADS in the past, experimental studies are necessary to examine the usability of P&T in greater detail. This includes both in-pile experiments and post-irradiation examination as well as experiments from which transients and accidents can be assessed. In the case of a molten salt reactor, extensive experiments would have to be carried out on thermodynamics and the stability of the fuel and carrier salt. An important step for both systems would be further development and testing on a larger scale, and the experience accumulated in the operation of a real prototype plant.

# 4 THE FOUR BASIC SCENARIOS

Project work was based on a total of four societal development scenarios (so-called basic scenarios). A scenario is a potential picture of the future showing what society as a whole or a specific part of it can look like.[14] The scenarios are focused on key features, such as economic development, population growth, or level of education. In this case, the key features were opportunities and risks which can be linked to P&T. The scenarios will be described in summary in the next section. They model the period between 2012 (starting year) and 2150 (target year), presupposing that Germany will opt out of the use of nuclear power.

Two scenarios do not provide for a technical-scale application of P&T in Germany. In *basic scenario 1 ("Abstinence")*, P&T will not be operated in, and out of, Germany. This model of the future serves as a reference point (reference scenario) for comparison with the other scenarios. In *basic scenario 2 ("Research Participation")*, Germany conducts national research within the framework of European research initiatives, participating in European and international research programs. However, no P&T plants will be built in the country.

The other two scenarios, however, foresee technical-scale use of P&T in Europe and Germany, respectively. In *basic scenario 3 ("European Systems Participation")*, Germany runs a national research program and participates actively in international research programs and in European initiatives about the construction of P&T facilities. However, no P&T plants will be built in the country, as in the "research participation" scenario. In *basic scenario 4 ("Application in Germany")*, P&T in Germany will be operated actively as part of the final storage strategy.

[14] Gausemeier et al. 1996.

# 5 COMPARISON OF THE CONSEQUENCES OF THE FOUR SCENARIOS

The technical basic scenarios outlined below were enriched by societal development paths on the basis of a broad mix of methods. Literature searches, expert workshops, telephone interviews with environmental protection groups and public action committees as well as group Delphi processes[15] were combined and supplemented by specific ecological, economic, and legal opinions. However, this applies with the proviso that, despite this systematic multi-method process, the long time horizon and the manifold possible developments harbor great uncertainties about assessing societal options.

All four scenarios assume that the decision by the German Federal Government about phasing out nuclear power by 2022 and about final storage of heat-generating high-level radioactive waste on a site on the territory of the Federal Republic of Germany will continue to be valid. This means that the scenarios do not foresee the use of uranium for energy production in Germany. However, it is assumed that other European countries will continue to employ nuclear power as a power source. Under these assumptions, the four scenarios can be sketched as follows.

## ABSTINENCE

In the "Abstinence" scenario, the P&T process is not applied to the spent fuels arising up to the opt-out time. For this scenario, the quantities of heat-generating radioactive waste to be disposed of in a repository in Germany even now can be estimated in a very good approximation. This model of the future serves as a reference point for comparison with other scenarios (reference scenario).

As no P&T is carried out in the reference scenario, it has no impact on societally relevant aspects, such as the ecotoxicity potential, acceptance of P&T facilities, and legal aspects. However, economic factors play a particularly important role in this scenario. If Germany does not participate in research and development of P&T, the research funds earmarked for P&T saved in this way could be invested into other energy policy projects within the framework of the *Energiewende*, such as renewables or the expansion of the power grid (opportunity costs[16]). On the other hand, it will no longer be possible then to acquire third-party funds for P&T, especially through the funding instruments of EURATOM. Moreover, it must be assumed that the loss of jobs and of competence in the nuclear field, especially in matters of reactor safety, will give rise to an indirect economic disadvantage. It is very likely that internationally recognized experts and scientists will go abroad. This reduces nuclear competence at home and, consequently, could imply a potential loss of possibilities to influence policy in international agencies, such as the International Atomic Energy Agency (IAEA) or the Nuclear Energy Agency (NEA). In addition, the abstinence strategy could make any future participation in a European solution of P&T facilities impossible.

## RESEARCH PARTICIPATION

In the "Research Participation" scenario, Germany will invest into research and development both nationally and within the European framework as long as no final decision has been taken about implementation or non-implementation of the P&T process. These activities are to help better understand the challenges to be faced and assess the benefits and risks of a potential further pursuit of P&T.

[15] The group Delphi process is a process of technology assessment. It involves an iterative process in which opinions of experts in various disciplines are invited. The sequence of Delphi steps is as follows: First of all, experts express opinions in a written interview campaign, e.g., about future societal developments. These opinions are then presented at a joint workshop before the questionnaire is discussed again and filled out in small groups. In a plenary session, any dissenting opinions must then be explained, which again is followed by discussion in small groups. Questions about which no differences of opinion exist are sorted out. The objective of group Delphi is to either arrive at a consensus opinion or find reasons for differences in opinion (consensus about dissenting opinions) (Webler et al. 1991; Schulz/Renn 2009).

[16] Opportunity costs are profits not realized which arise from the failure to make use of a possibility (opportunity).

Initially, this scenario has no impact on the waste volumes to be managed in Germany.

Societally, it probably offers most opportunities while, at the same time, minimizing the risks. Research and development basically are accepted in a positive way by the German public; hence, only opposition at specific points must be expected. In this respect, P&T would be assessed more positively by the media as Germany, in this scenario, would retain its competence in assessing individually the safety of P&T plants abroad and cooperate in international agencies, such as IAEA or OECD/NEA. The ecological and economic impacts on Germany could be neglected by and large. However, there are indirect positive economic effects: Competences and jobs are preserved, and Germany will remain capable of taking action also in the future.

### EUROPEAN SYSTEMS PARTICIPATION

In the "European Systems Participation" scenario, Germany takes part not only in European research projects but also in technical-scale P&T facilities on a European level. This approach requires close cooperation with other European countries within a clearly defined regulatory framework and allows joint development, construction and R&D use and operation of European facilities. Technical analyses show that the reduction in arisings of heat-generating waste, in thermal power, and in total radioactivity on a European scale as a result of P&T can be significant at later points in time. The reduction in thermal power and in total radioactivity later is at least around one or two orders of magnitude, while the reduction in radiotoxicity is even more significant. However, because of the vitrified waste from reprocessing, which is not to be treated any further, the effect on a repository in Germany is limited.

Such a scenario, in which Europe makes joint use of the facilities and also shares their costs, shows some opportunities. Possible benefits to Germany, for example, exist in the lower investments, merely pro-rata costs of decommissioning as well as research and development, and in not needing to build new facilities in the country. A problem could arise from the impression of Germany in this way indirectly participating in the nuclear objectives of the other European countries, such as the further expansion of nuclear power in Europe or using the nuclear fuels obtained in partitioning for new reactors. These objectives are incompatible with those of the German nuclear opt-out. However, further detailed studies are required for a more precise description of expected pros and cons.

If one or more European facilities were built in which also German waste would be treated, transports of that waste to those facilities must be ensured. Transports always imply additional risks of accidents and emissions and, above all, public opposition. However, if those transports were to take a major burden off radioactive waste management in Germany, they could be explained to the public.

Unlike P&T application in Germany, the European scenario includes chances for public acceptance of the implementation of P&T. Depending on plant location(s) beyond German national borders, moderate acceptance in Germany may be assumed. The German media most probably, if at all, will report negatively about planning, construction, and operation. On the other hand, an important factor with respect to the frequency and tendency of media coverage is the location of the plant(s) near or far from the German borders. Splitting the costs among various countries would mean that financial burdens could be shared and would thus be more tolerable. On the other hand, increased requirements of harmonization and coordination in awarding contracts could mean considerable extra costs of construction and commissioning of the P&T plant(s). The ecotoxicity potential affecting the German public will be lower for P&T plant(s) not built close to the national borders. Participation in European research activities allows competence in reactor physics and plant safety and also in technologies for high-temperature applications to be preserved in Germany, thus securing for the country the competence for independent safety assessment of foreign P&T plants also in the future.

## P&T APPLICATION IN GERMANY

The "P&T Application in Germany" scenario provides for at least one P&T facility built and operated in Germany.[17] This scenario implies that all necessary facilities (partitioning of spent fuel, fabrication and transmutation plants and so on) will be developed and built. There are various technical options to this end. As in the "European Systems Participation" scenario, the arisings of heat-generating waste, thermal power, and total radioactivity at later points in time can be reduced significantly as a result of P&T. However, the waste already vitrified, which is not to be treated any further again, limits this effect.

On the societal level, there is little to advocate P&T use in Germany only. Acceptance of new P&T plant construction by potential site municipalities and by the German public is low. Skeptical media coverage could enhance this negative opinion. People and the environment face additional risks from the radiological and non-radiological ecotoxicity potential of P&T facilities. As a consequence of the relatively small arisings of waste, construction and operation of one or more P&T plants in Germany probably will not make sense economically. One positive connotation is that operation of a P&T plant in Germany would help preserve national competence in reactor physics and plant safety as a result of the development of specific P&T concepts compatible with the decision to opt out of the use of nuclear power. In principle, also various combinations of the "European Systems Participation" and "P&T Application in Germany" scenarios can be imagined in which parts of the processes are combined in Europe while some plants are operated nationally. This type of approach has been used before. Reprocessing is an international project while reactor operation comes under national regulations.

[17] A precise indication of the exact number of P&T plants is not possible at the present time because of remaining uncertainties. The number will depend, among other things, on the state of the art at the time of planning.

# 6 RECOMMENDATIONS

On the basis of the key statements outlined above, acatech makes these recommendations:

## POLITICS:

- ***An option in which P&T research is conducted within a European context and future German participation in P&T in Europe is examined seems to be more advantageous, in the light of evaluations of the different scenarios, than the two options, "Germany going it alone" or "Complete opt-out."*** On the one hand, it is not particularly attractive, for economic, ecotoxicological, licensing and societal reasons, that Germany build and operate P&T facilities on its own. On the other hand, discontinuing research work and giving up all P&T options seems to be premature at least, from the present vantage point, and also makes no sense, given the opportunities offered by these options. acatech recommends that research work be continued, both in fundamental research and in technical development research (laboratory-scale and pilot plants) within the framework of a joint European research effort. The existing German research program should always be pursued further, with the added objective of integrating German research into a European research program and examining whether participation in technical-scale implementation on a European level would be meaningful. In this way, highly developed expertise in Germany can be incorporated in the European P&T development process, and all options possible on economic and technical grounds will be preserved. Moreover, any open questions in connection with the use of this technology could be answered in this way. This option would mean that the funds invested annually for continued P&T research would be earmarked also for the future on roughly the same scale and, where necessary, increased if European demonstration projects require German co-financing.
- ***Participation in research should not imply dependence on any path regarding P&T application.*** The decision whether the German heat-generating spent fuel from power reactors (and the non-vitrified waste) should be reduced in a transmutation facility should be kept open for a medium term, i.e. ten or fifteen years in the light of the present timetable of deciding on a repository site and its exploration. However, a near-term decision is needed about German research institutions, acting on behalf of the German Federal Government, participating in international P&T projects, such as MYRRHA in Belgium. acatech would welcome this in principle. However, it would have to be clarified first whether the funds would be used efficiently and for a specific objective and whether German participation in these projects would be in accord with the decision to opt out of the use of nuclear power. At a later point in time, after more extensive research and development, there would be a better chance to assess more precisely the prospects of P&T from a German point of view. Moreover, the picture then will show more clearly whether, at the state of the art at that time, the risk of German as well as European nuclear waste can be reduced considerably. It must be ensured that participation in research is not linked to any potential dependence on a specific path towards technical-scale application.
- ***An interdisciplinary comprehensive study as a basis for deciding whether Germany should participate in P&T, which would emphasize in particular the potential and the challenges of a European scenario, should be performed early enough before the decision, to be taken probably in ten to fifteen years' time, about a potential deeper commitment to this approach. Planning the time and the way associations and the public are to be involved should begin in time.*** Besides the potential advantages of P&T, a rational and prospective policy should also consider the negative consequences which could result from P&T. Before a decision is taken about Germany joining potential European P&T

plants, acatech recommends a comprehensive study to be made of the opportunities and the risks of such plants which would be based on existing preparatory work, discuss potential waste management strategies (including transport, interim storage, and conditioning), and further differentiate hazard potentials to persons and to the environment in accordance with the state of the art of P&T. That analysis should follow a holistic approach and include not only the technical and safety features of P&T but also the social, political, economic, legal/licensing and communication aspects on a European level. The current research findings then available and the experience accumulated in other countries should be incorporated. It is also advisable to involve associations and the public in these debates. Given the probably very complex national and international decisionmaking and participation processes about P&T a few years from now, these concepts should be considered and planned in time.

– ***Germany is to adopt a European approach without giving up national lines of research.*** The decision to opt out of the use of nuclear power is the basis of future work on P&T. Technical possibilities of handling nuclear waste continue to be important to future generations. Here are the main areas of future activity:
  - **Strive for European cooperation** in fundamental research and technological research and future cooperation in the potential implementation of P&T on a European level.
  - **Develop research policies specific to Germany:** The purpose of P&T under the conditions of nuclear opt-out is to burn all transuranium elements (plutonium, minor actinides) as far as possible instead of keeping the plutonium in the nuclear fuel cycle. For this reason, all transmutation options must be examined in the light of the opt-out decision. Transmutation can become very important not only in a sustainable execution of the opt-out policy but also to avoid accumulation of transuranium elements when running a park of light water reactors. In this case, Germany could play an important role in sustainable burning of transuranium elements. Once a decision has been taken about the transmutation system to investigate, fundamental problems and tentative solutions allow a large part of the knowledge base to be developed together with other EU partners.

### INDUSTRY:

– ***German industry should see the potential implementation of P&T in Europe as an opportunity to be used:*** Industry in Germany, especially manufacturers of technical facilities, specialized companies and suppliers, has a background of many years in manufacturing and delivering high-technology components and systems solutions of decisive importance in transmutation facilities. These include complete solutions for proton accelerator components, electrical engineering instrumentation and control as well as safety technologies, measurement, power plant components such as pumps, heat exchangers, transformers and special materials, often developed in close interaction with German research institutions. Implementing P&T in a European context will establish new markets for German industry to sell its products and services, thus enabling it to increase its revenue and protect competence and jobs. acatech recommends that German industries participate in tendering for European P&T facilities in accordance with the principle of European systems participation.

### SCIENCE:

– ***Research should concentrate on these key areas:*** P&T incorporates a variety of scientific challenges not only in natural science and engineering, but also involving sociology, ecology, and economics. Safety research assumes an outstanding importance in P&T transcending all areas. The key requirements to be fulfilled by research can be outlined as follows; acatech recommends to focus research on these areas:

- ***Efficient separation (partitioning)*** of the longlived, high-level, heat-generating transuranium elements from spent fuel (as well as the burnt transmutation fuel): The challenges arise from the need to minimize process losses and secondary waste arisings, develop safe partitioning processes polluting the environment as little as possible, and condition the waste streams.
- ***Efficient transmutation of the transuranium elements partitioned*** in transmutation plants specially developed for this purpose. Requirements include the safety of these plants, a high transmutation rate, minimization of the number of recycling cycles and potential associated environmental pollution, and reduction of nuclear transports. In addition, economic viability studies (and the corresponding optimizations) must be conducted in connection with the different concepts of transmutation facilities.
- ***Advanced development of methods for assessing the technical safety of P&T facilities:*** If partitioning and transmutation facilities are to be assessed in terms of technical safety, appropriate assessment methods must be developed and made available (safety approach). In addition, computer models and the necessary software tools are required.
- ***Assessment and evaluation of the societal implications of all options for action.*** The technical options must be embedded in an economic, political, and social environment. This is not only a matter of acceptance but also, and mainly, of coherent integration into democratically legitimized energy policy and increasingly more participative planning culture.

– ***Research is to take an interdisciplinary stance:*** These key areas (see box on page 28) can be covered by a combination of scientific disciplines and areas. For the scientific and technical aspects, these are radiochemistry (partitioning, conversion, conditioning), reactor physics and safety, development of transmutation fuel, thermal hydraulics, materials research and technology development, basic research for component development (such as accelerators and neutron spallation targets). Moreover, the law, humanities, economics, and social sciences should be involved in establishing institutionalized regulations, making cost-benefit comparisons, determining social acceptance and legal compatibility, all with a view to the overall waste management system (including transport, interim storage, conditioning).

From a technical point of view, the research problems outlined below must be taken up in future P&T research and development:

- **Partitioning:**
  The research issues to be addressed range between fundamental research in radiochemistry (development of highly efficient extraction processes) on a laboratory scale and scaling studies for industrial-size plants designed to separate plutonium and minor actinides from spent LWR fuel and produce transmutation fuels specific to certain plants. Optimizing and conditioning the waste streams arising from partitioning is another part of this activity.
- **Plant-specific research:**
  On the basis of an assessment of the strengths and weaknesses of various transmutation facilities (critical reactors or subcritical facilities, solid fuel or liquid fuel), and in the light of the objectives of the opt-out of the use of nuclear power, the partitioning and transmutation strategy/strategies desired by German politics must be defined and the resultant plant-specific research must be advanced, such as:
  - **ADS: Production of fast neutrons (proton accelerator and spallation neutron source)**
    Today's superconducting linear accelerators need to be advanced in the interest of very high reliability in continuous beam production and, at the same time, optimized prices. Moreover, further development of "classic" external spallation targets should be endeavored; this is to create a neutron source of high power in the reactor core (design and coupling to the accelerator, safety, materials development, thermal hydraulics, neutronics, and nuclear data). Moreover, the development of fuels free from blanket materials, i.e. not giving rise to new transuranium elements, should be advanced for efficient transmutation.
  - **Reactors with liquid fuel:**
    **Safety approach and fuel conditioning**
    A strategy must be developed to assess plant safety in reactor systems with liquid fuel and integrated fuel purification. Continuous removal of fission products must be advanced and optimized.
- **Nuclear data and reactor physics:**
  Appropriate experiments and improved models must reduce uncertainties in the nuclear databases both fundamentally and, in particular, with regard to the minor actinides. Especially for ADS, simulation and experimental validation (in so-called zero-power reactor experiments) must allow the safety parameters of fast subcritical systems to be studied. Specifically for reactors using liquid fuel, simulation tools for modeling fuel flow and continuous fuel feed and fuel purification would have to be expanded.
- **Transmutation:**
  Research problems under this heading in particular include safety-related aspects (validation of safety parameters specific to certain types of facilities for various operating conditions) and the "transmutation potential" of facilities. Thermal hydraulics, fuel behavior, materials research, and technology development (models, laboratory experiments, and also full-scale component tests) are required for safe operation of the coolant in the transmutation reactor, and need to be studied. At the same time, in-pile experiments are necessary for transmutation fuel and structural materials.

– ***A research alliance is to be established:*** Reliable scientific evaluations of the P&T option can be achieved by concentrating German research activities in the key areas. This concentration can be brought about by establishing a research alliance or a competence center with these objectives: (a) Development of a research strategy with a plan of activities agreed upon among the players, also with respect to the tools available within the Horizon 2020 framework research program of the European Commission, (b) Priorization and execution of research work of a fundamental nature, and (c) identification and execution of projects spanning several domains or specific to certain topics. As a research program of that type will build on current research activities and on the advanced development of existing technologies (such as reprocessing, fuel development, fast reactors), the level of research funds required roughly corresponds to the amounts so far raised for that research area. However, there may be additional funding requirements for specific European initiatives or studies compatible with the German opt-out of the use of nuclear power. In principle, German research and development should be incorporated in the European or international context but also reflect the objectives established by the decision to opt out of the use of nuclear power. After all, P&T in Germany, with the country's decision to give up using nuclear power, would serve a different purpose: While the European partners regard plutonium and uranium as valuable materials, these elements are considered waste in this country. The research activities performed by German institutions in a European and international context even now have such a broad base that they include, or could include, options compatible with the *Energiewende* and allowing all transuranium elements to be burnt as efficiently and as completely as possible.

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