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On the lookout for practicable sustainable options for asbestos waste treatment

A technical, sustainability and market assessment

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Colophon

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Date: June 18, 2018

Report on a project commissioned by the Dutch Ministry for Infrastructure and Water Management

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Preface

This report could not have been written without the help, expertise and brainpower of a large group of people. We therefore like to express our thanks to:

- the members of the Advisory Commission, who helped us in our endeavours by asking the right questions; thank you Ronald, Nienke, Peter, Rosalien, Mart, Hein, Marjorie and Evelyn;
- the members of our international Sounding Board, who gave us their fresh opinions and let us pick their brains; thank you Kris, Garry, Sam, Reiner, Hielke, Markus, John, Sven, René, Peter and Matthijs;
- the experts who provided us with their insights from their practical work on the development and introduction of the techniques; thanks to you all;
- all the other people who helped us by critically reflect on our work, amongst whom the project team of the parallel Tauw project (thank you Jeroen and Edwin) and the programme team of ‘Ruimte in regels’.

Notwithstanding all this help and all the efforts we made to be complete and precise in our research and reporting, the responsibility for any possible omissions or errors in this report lies solely with the authors.

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Utrecht / Apeldoorn / Deventer
18 June 2018

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Executive summary

The report *'On the lookout for practicable sustainable options for asbestos waste treatment'* describes the results of an assessment project. This project was commissioned by the Dutch Ministry of Infrastructure and Water Management (I&W) and was carried out in the second half of 2017 and the first half of 2018. This project aimed to establish the state of the development of techniques that make it possible to treat asbestos containing waste and to reuse the remaining product, instead of having to send it to landfill sites. This summary outlines the main outcomes of this study.

Background of the project

The Netherlands will have to be a circular economy by 2050.[1] Raw materials must be used and reused efficiently, without harmful emissions to the environment. This is not a simple task for some raw materials, like, for example, asbestos containing materials. There are so many risks involved in dealing with asbestos, that its fibres have to be fully destroyed in a safe way before it can be reused. If not, all one can do is to safely store and manage it. There are several techniques to strip material from its asbestos content and make it suitable for reuse. So far, there are no such installations available in the Netherlands. In anticipation of initiatives to create such installations, Dutch government has commissioned a systematic review of the development of these techniques and to assess whether they are ready for practicable sustainable application. This was done in the current project.

Parallel to this project, research has been commissioned into what is necessary to ensure that the switch from landfill to processing can actually take place.[2]

Purpose and scope of the project

The project aimed at two things:
1. to develop a method to determine the sustainable practical applicability of asbestos waste treatment techniques (the 'assessment' method); and
2. to determine the current practical applicability of sustainable asbestos destruction techniques (the 'assessment').

For clarity:
– The project identified various techniques, for which all relevant parameters have been determined, not only technical issues. After all: ‘practical applicability' is not just about whether the techniques perform as intended (turn asbestos into a harmless and reusable

[1] Nota ‘Nederland circulair in 2050 –Rijksbreed programma circulaire economie’, 2016.
[2] Tauw: *Onderzoek procesvoorwaarden voor duurzame verwerking asbesthoudend afval*. 2018.

material), but also whether this can be done in a way that is safe for employees, local residents and the environment (and also whether or not there are, for example, high CO_2 emissions) and whether a company can apply these techniques in a profitable way.
- In the Netherlands the process of decontamination, removal and dumping / treatment of asbestos is quite elaborate. This project only looked at the changes that occur when asbestos waste is no longer landfilled, but treated and reused.[3]
- In this project no new, experimental research has been done into the techniques or into the effects of their application. The project team has formed its opinion by making use of all knowledge that is presently available – in literature and by consulting experts.

The approach of the project
A lot of research has already been done on techniques to render asbestos harmless. In Flanders, a report prepared by OVAM on this subject was published in 2016, which was taken as the starting point for this project. [4] The project team has organised a Sounding Board of Dutch and international experts, in which insights have been exchanged on the basis of the OVAM report. Following on this, the project team has drawn up its own assessment method. Next, a search was carried out for newer and additional information, in literature and through experts involved in the development of asbestos waste treatment techniques that are also aimed at the Netherlands. This information was analysed using the assessment method that was developed. Conclusions were drawn about the current state of sustainable practical applicability of asbestos waste treatment techniques (which, subsequently, the same Sounding Board critically reviewed). An Advisory Commission set up by the Ministry of I&W supervised the course of the entire investigation.

About the asbestos waste treatment techniques
There are four basic techniques for destroying asbestos fibres, with several intermediate forms.
1. *Thermal techniques;* these techniques are based on the fact that asbestos decomposes at high temperature (and hence is no longer carcinogenic). For example, there are techniques for destroying asbestos with ovens, plasma torches or microwave radiation. By adding chemicals or clay, the process can be speeded up and operated at a lower temperature.
2. *Chemical techniques;* also with chemicals one can destroy asbestos fibres. There are techniques that work with acids and those that work with bases. Sometimes the process is accelerated by bringing it to higher temperature and/or pressure (there are also chemical processes that generate heat and therefore require cooling). Often an additional purpose is to be able to use organic waste, waste acids from industry or captured CO_2.
3. *Mechanical techniques;* the fibres can be broken down by grinding asbestos very finely. For this purpose, special high-energy mills are used, which not only effect physical, but also chemical and physico-chemical transformations, resulting in very fine, non-toxic powder.
4. *Biological techniques;* finally, fungi and bacteria are also found to be able to break down asbestos. Sometimes this happens – very slowly – in nature. With the creation of the right conditions, this process can be speeded up considerably. For now it has been proved that loose fibres of asbestos of the chrysotile type can be broken down in this way.

[3] Research into the functioning of the system that regulates this process was commissioned by the Dutch Ministry of Social Affairs and Employment. See: Tauw: *Onderzoek functioneren certificatiestelsel asbest,* 2017
[4] OVAM: *State of the art: asbestos – possible treatment methods in Flanders: constraints and opportunities.* Mechelen, 2016.

The assessment method

Now how can one determine to what extent these techniques are practicable and sustainable? The OVAM report mentions various characteristics of these techniques that provide indications for this. In the present report it has been decided to translate these characteristics into four overarching parameters: (1) maturity of the technique, (2) distance to market, (3) sustainability aspects and (4) area of application. These four parameters are about different - and also to be valued differently - matters that cannot be summarized in one score. Together they show where a technology stands in its development and to what extent it can be applied in a practical sustainable way.

In part, the parameters are directly related to physical characteristics of a technique. Other, non-technical issues also play a role, varying from the amount of effort that is made to develop the technique, to circumstances on the market (for example the price of energy or steel), in government policy (which waste is allowed to be landfilled at what cost) or in society (the perceived risks of a specific technique). The image that emerges from these indicators is therefore always of a qualitative nature and subject to change.

What characteristics are expressed in these overarching parameters?

– *Technological maturity*
  As a measure for the technological maturity of an asbestos waste treatment technique, the 'TRL' is used ('Technological Readiness Level'); an indicator developed by NASA and meanwhile internationally recognized, ranging from 1 (the very first invention) to 9 (industrially operated technique). An asbestos waste treatment technique has a higher TRL as it is more of a proven technique on industrial level, as more of the technical parameters are known and as the process is better controlled.

– *Distance to the market*
  This parameter concerns the mostly non-technological aspects that determine whether a technology can reasonably be expected to be licensable, marketable and profitable. The parameter is based on indicators for the extent to which a technique is proven, there is a business case for its operation, the incurred financial risks can be covered and there appear to be administrative and public acceptance.

– *Sustainability aspects*
  The term 'sustainability aspects' is used as shorthand for all risks, circular aspects and other health and environmental aspects associated with a technique. This includes a number of parameters that require further explanation.
  - *Fibre destruction;* this parameter forms the core of an effective technique. Without the (controlled) assurance of complete degradation of asbestos fibres to a non-toxic product, risks remain and there is no reusability.
  - *Reusability;* in most cases, treatment of asbestos-containing waste or asbestos cement, after complete fibre destruction, yields filler with some adhesive properties (not as powerful as new cement, sometimes comparable to clay, for certain applications (certified) usable and therefore of some value). But sometimes the adhesive properties are negligible and the residual product can only be used as an inert filler of limited value.

In certain cases, reuse of asbestos is of secondary importance; another part of the waste stream has the economic value. This is the case, for example, for recycling asbestos-containing metal scrap into clean, reusable metal.
Finally, in soil contaminated with asbestos, the economic value of asbestos waste treatment does not primarily lie in the reusability of the soil itself, but also in the excavation and remediation costs that are avoided.

- *Risk aspects;* the less asbestos-containing waste is transported and pre-treated (dried, shredded or crushed), the less strict measures are necessary for the protection of employees, local residents and the environment, and the smaller the risks that something can go wrong. In addition, certain technologies may require measures to work safely with aggressive substances, increased temperature and/or pressure.
- *Potential CO_2 footprint;* asbestos waste treatment techniques that use relatively more energy have a larger potential carbon footprint (although of course this can be reduced by using energy from renewable sources). For a good comparison, however, this potential footprint must be balanced by what CO_2 emissions the product to be reused would have caused if it had been produced in a regular manner. Steel production from ore or ordinary metal scrap requires similar amounts of energy as recycling asbestos containing metal scrap. The same goes for the regular production of cement. The production of less active fillers requires less energy, but also that needs to be taken into account.

– *Area of application*
The last overarching parameter concerns which types of asbestos-containing waste can be treated most effectively and most cost-effectively using that specific technique.

The assessment
The level and type of development of the various techniques were described and assessed using these parameters. The parameters were first described in detail in the so-called 'analysis sheets'. Next they have been summarized in overview tables. From there, a number of conclusions were drawn about the current sustainable practical applicability of the various techniques. In summary, these conclusions come down to the following.

Thermal techniques
Closest to (the Dutch) market appears to be the technique for *recycling asbestos containing steel scrap in steel melting furnaces*. In essence, this is a regular steel recycling technique with melting furnaces, in which special measures have been taken for dealing with asbestos-containing steel scrap in a safe way. The technology is mature, the business case appears to be sound and there are no indications of lack of administrative and public acceptance at the designated location.

Several other thermal techniques are (a little) more distanced to the (Dutch) market, but could possibly move fast forward (possibly in a few years' time) if the conditions are right. An important example of this is the technique for thermal denaturation, in which asbestos-containing waste is driven (for 75 hours) through a tunnel kiln and is brought to a temperature of 1000 °C, as a result of which the asbestos loses its fibre structure. The distance to market of this technique is mainly a matter of non-technical issues. One of those issues is that in order for this technique to obtain a viable business case, the gate fees must be on a higher level than the present fees for landfill. Furthermore, a steady flow of asbestos cement feedstock is required, which in turn requires buffering capacity and logistic guarantees, as well as acceptance (by authorities and market) of a certified end-product.

Something similar applies to the *thermo-chemical treatment technique*; a combustion technique in which the decomposition of the asbestos (at a temperature around 1200 °C) is speeded up by adding chemicals. However, for this technique also some final technical tests must be passed.

All thermal techniques require larger, static installations and relatively much energy. Consequently they have a relatively large potential CO_2 footprint, although it must be taken into account that the end-products can be substitutes for products whose regular (new) production also entails CO_2 emissions. For that reason, for example, the potential CO_2 footprint of recycling asbestos-containing steel scrap is small.
Due to the size and capacity of the installations, there will be room for one or at the most a few of them in the Netherlands, which implies that the asbestos-containing waste has to be transported to these installations (extra transport when compared to regional landfill). In addition, the processes for recycling asbestos-containing steel scrap and thermo-chemical treatment require pre-treatment of the waste. For all this, measures are necessary to protect employees, residents and the environment against the risks of exposure to asbestos. This is somewhat different for thermal denaturation; no pre-processing is required here, as the asbestos-containing waste, including the packaging in polythene bags, goes straight in the oven.

Mechanical techniques
Something rather similar is the case for the *mechano-chemical treatment technique*. In this technique, dried and shredded asbestos waste is led through a cascade of high-energy mills in which steel balls and sand rotate. In the collisions of rotors, balls, sand and waste, local hot spots occur with very high temperatures (above 1000 °C). Combinations of mechanical, thermal and chemical processes destroy the asbestos fibres and make the waste harmless. The technique is rather mature but some final tests on industrial scale are still taking place. To enter the Dutch market, also a number of practical issues must be addressed, ranging from meeting pre-processing requirements to location and permit arrangements. On the other hand, the mechano-chemical treatment technique is more mobile and flexible and less capital intensive than many of the other techniques, which may allow for a relatively fast entrance on the market.

The mechano-chemical treatment technique uses less energy and has a relatively modest potential CO_2 footprint. The scalable and mobile nature of the installation means that it can be placed close to places where asbestos containing waste originates or at regional landfill sites. This may lead to less transport of asbestos-containing waste. However, pre-processing of this waste is required (drying and size reduction), which will also require the necessary protective measures.

Biological techniques
Biological techniques – which aim at accelerating the natural degradation of asbestos fibres by bacteria or fungi – are currently still technologically immature. However, soon as this

technique is somewhat more under control, an immediate positive business case can be expected for in situ treatment of asbestos contaminated soil, and the barriers to entry to the market appear to be very low. Energy consumption and potential CO_2 footprint of biological techniques are minimal. However, the safety of working with fungi, bacteria and any additives must be guaranteed.

Chemical techniques
The historical record of chemical asbestos waste treatment techniques is rather poor. It has been known for quite some time that asbestos fibres can be destroyed by attacking them with strong acids or bases. Attempts to apply this principle on larger scale have so far mostly failed because of problems with controlling the risks of the chemical process and the need to neutralize the end-product before it can be reused. Still, a new development drive has come into Dutch trials, also from an interest of making use of industrial acid waste streams. For the time being, however, there still is a considerable amount of technical and non-technical issues that needs to be addressed, including some relating to sustainability aspects. The distance to market, therefore, still appears to be big.

Other assessed techniques for asbestos waste treatment are either still in an embryonic stage, are in a standstill after less successful pilot studies, or are in the slow process of being scaled up.

Areas of application
A further look into the areas of application of the different techniques indicates that several of them may have their own markets or niches of asbestos waste that they can treat most effectively and profitably:

- *recycling asbestos containing steel scrap in steel melting furnaces:* asbestos containing steel scrap;
- *thermal denaturation:* a constant and homogeneous stream of asbestos cement roofings or pipes;
- *thermo-chemical treatment:* a mix of asbestos containing waste and high-energy waste (‘sorter residues’ to be used as alternative process fuel);
- *mechano-chemical treatment:* (differing amounts, due to the scalable technique, and more local) homogeneous stream of asbestos cement;
- *biological treatment of asbestos in soil:* soil contaminated with asbestos fibres (chrysotile), possibly in situ.

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18 June 2018

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Samenvatting

Het rapport *'On the lookout for practicable sustainable options for asbestos waste treatment'* beschrijft een 'assessment'-project van asbestafvalverwerkingstechnieken. Dit project is uitgevoerd in de tweede helft van 2017 en de eerste helft van 2018, in opdracht van het Ministerie van Infrastructuur en Waterstaat (IenW). Het project was erop gericht om vast te stellen wat de stand van zaken is van de ontwikkeling van technieken om asbesthoudend afval te kunnen verwerken en het verwerkingsproduct nuttig te kunnen hergebruiken, in plaats van het te storten. Deze samenvatting geeft de uitkomsten van dit project op hoofdlijnen weer.

Achtergrond van het project

Nederland moet in 2050 een circulaire economie zijn.[5] Grondstoffen moeten efficiënt worden ingezet en hergebruikt, zonder schadelijke emissies naar het milieu. Voor sommige grondstoffen is dat geen eenvoudige opgave. Dat geldt bijvoorbeeld voor asbesthoudende materialen. Aan de omgang met asbest kleven zoveel risico's, dat je het óf op een veilige manier helemaal onschadelijk moet kunnen maken voor je het kunt hergebruiken, óf je het zó moet opslaan dat het nooit meer vrijkomt. Er zijn technieken om asbesthoudend materiaal onschadelijk en voor hergebruik geschikt te maken. Maar kant en klare oplossingen (installaties) zijn er in Nederland nog niet. Daarom heeft de Nederlandse Rijksoverheid opdracht gegeven om de ontwikkeling van deze technieken systematisch tegen het licht te houden en te beoordelen of ze klaar zijn om in de praktijk toe te passen. En dat is wat er in dit project is gebeurd.

Parallel aan dit project heeft onderzoek plaatsgevonden naar wat nodig is om de overschakeling van storten naar verwerking daadwerkelijk te laten plaatsvinden.[6]

Doel en reikwijdte van het project

Het ging bij het project om twee dingen:
1. het ontwikkelen van een methode om de duurzame praktische toepasbaarheid van asbestverwerkingstechnieken te kunnen vaststellen (de 'assessment' methode); en
2. het vaststellen van de huidige stand van praktische toepasbaarheid van duurzame oplossingen (het 'assessment').

[5] Nota 'Nederland circulair in 2050 –Rijksbreed programma circulaire economie', 2016.
[6] Tauw: *Onderzoek procesvoorwaarden voor duurzame verwerking asbesthoudend afval.* 2018.

Voor de duidelijkheid:

– Het project richt zich op diverse technieken, en kijkt naar méér dan alleen technische zaken. Immers: bij 'praktische toepasbaarheid' gaat het er niet alleen om of de technieken doen waarvoor ze bedoeld zijn (asbest onschadelijk en het restproduct herbruikbaar maken), maar ook of het voor werknemers, omwonenden en het milieu veilig kan gebeuren (en ook bijvoorbeeld of er niet een hoge CO_2-uitstoot plaatsvindt) en of er op een rendabele manier een bedrijf mee opgericht en draaiend gehouden kan worden.
– Er komt in Nederland veel kijken bij het saneren, afvoeren en storten/verwerken van asbest. In dit project is alleen gekeken naar wat er verandert als asbesthoudend afval niet meer gestort, maar verwerkt en hergebruikt wordt. Aangezien de huidige manier van asbest saneren daar niet door verandert, is daar verder dus ook niet naar gekeken.[7]
– Er is in dit project geen *nieuw, eigen* experimenteel onderzoek gedaan naar technieken of naar de effecten van hun toepassing. Het projectteam heeft zich daarover een oordeel gevormd door gebruik te maken van alle kennis die daarover tot op heden – in de literatuur en bij experts – beschikbaar is.

De aanpak van het project

Er is al veel onderzoek gedaan naar technieken om asbest onschadelijk te maken. In Vlaanderen verscheen in 2016 een door OVAM opgesteld rapport over dit onderwerp, dat voor dit project als vertrekpunt is genomen.[8] Het projectteam heeft een klankbordgroep van Nederlandse en internationale experts samengesteld, waarin op basis van het OVAM-rapport inzichten zijn uitgewisseld. Mede op grond daarvan heeft het projectteam een eigen assessment methode opgesteld. Vervolgens is gericht gezocht naar nieuwere en aanvullende informatie, zowel in de literatuur als door experts te interviewen die betrokken zijn bij de diverse asbestverwerkingstechnieken waarvoor initiatieven zijn om ze in Nederland te gaan toepassen. Deze informatie is met behulp van de ontwikkelde assessment methode geanalyseerd. Op grond daarvan zijn conclusies getrokken over de huidige stand van praktische toepasbaarheid van duurzame asbestverwerkingstechnieken (waar dezelfde klankbordgroep vervolgens haar kritische licht over heeft laten schijnen). Op het verloop van het gehele onderzoek heeft een door het Ministerie van IenW samengestelde begeleidings-commissie toegezien.

Over de asbestverwerkingstechnieken

Er zijn vier basistechnieken om asbestvezels te vernietigen, met een aantal tussenvormen.

1. *Thermische technieken;* deze berusten op het gegeven dat asbest bij hoge temperatuur zijn vezelstructuur (en daarmee zijn carcinogene eigenschappen) verliest. Er zijn bijvoorbeeld technieken om asbest met ovens, plasmatoortsen of magnetronstraling te vernietigen. Door chemicaliën of klei toe te voegen kan men het proces versnellen en op lagere temperatuur laten werken.
2. *Chemische technieken;* ook met chemicaliën kunnen asbestvezels worden vernietigd. Er zijn technieken die met zuren of met basen werken. Soms versnelt men het proces door het op hogere temperatuur en/of druk te brengen. (Er zijn ook processen die van zichzelf warm

[7] Het ministerie van Sociale Zaken en Werkgelegenheid heeft recentelijk onderzoek laten doen naar het functioneren van het stelsel dat dit proces reguleert. Zie: Tauw: *Onderzoek functioneren certificatiestelsel asbest,* 2017
[8] OVAM: *State of the art: asbestos – possible treatment methods in Flanders: constraints and opportunities.* Mechelen, 2016.

worden en waarbij juist koeling moet plaatsvinden). Vaak is een bijbedoeling om hiermee ook organisch afval, afvalzuren uit de industrie of afgevangen CO_2 nuttig te kunnen gebruiken.

3. *Mechanische technieken;* door asbest heel fijn te malen kunnen de vezels worden afgebroken. Hiervoor worden speciale hoge-energie molens gebruikt, die niet alleen fysische, maar ook chemische en fysisch-chemische transformaties bewerkstelligen, waardoor heel fijn, niet-toxisch poeder overblijft.
4. *Biologische technieken;* tot slot blijken ook schimmels en bacteriën asbest te kunnen afbreken. Soms gebeurt dat ook al – heel langzaam – in de natuur. Met het creëren van de juiste omstandigheden kan men dit proces aanzienlijk versnellen. Vooralsnog is voor losse vezels van het asbesttype chrysotiel aangetoond dat ze op deze manier kunnen worden afgebroken.

De assessment methode

Hoe kan nu bepaald worden in hoeverre deze technieken duurzaam praktisch toepasbaar zijn? Het OVAM-rapport noemt diverse kenmerken van de technieken die daarvoor indicaties geven. In het onderhavige rapport is ervoor gekozen deze kenmerken te vertalen in vier overkoepelende parameters: (1) rijpheid van de techniek, (2) afstand tot de markt, (3) duurzaamheidsaspecten en (4) toepassingsgebied. Deze vier parameters gaan over verschillende – en ook verschillend te waarderen – zaken die niet in één score zijn samen te vatten. Bij elkaar geven ze weer waar een techniek in zijn ontwikkeling momenteel staat en hoe duurzaam toepasbaar deze is.

Voor een deel hangen de parameters rechtstreeks samen met fysische kenmerken van een techniek. Daarnaast spelen ook andere, niet-technische zaken een rol, variërend van de inspanning die wordt gedaan om een techniek te ontwikkelen, tot omstandigheden op de markt (bijvoorbeeld de prijs voor energie of staal), in het beleid (welk afval mag hoe worden gestort) of in de samenleving (de risicopercepties bij een specifieke techniek). Het beeld dat uit de vier indicatoren naar voren komt, is dan ook altijd kwalitatief en aan verandering onderhevig.

Wat voor zaken komen in deze overkoepelende parameters tot uiting?

– *Technologische rijpheid*
  Als maat voor de technologische rijpheid van een asbestverwerkingstechniek wordt de ‘TRL’ gebruikt (‘Technological Readiness Level’); een door de NASA ontwikkelde en inmiddels internationaal erkende graadmeter die loopt van 1 (de allereerste uitvinding) tot 9 (op industriële schaal toegepaste techniek). Een asbestverwerkingstechniek krijgt een hogere TRL naarmate het meer een bewezen techniek is, meer van de technische parameters bekend zijn en het proces beter beheerst wordt.

– *Afstand tot de markt*
  Deze parameter betreft de diverse, goeddeels niet-technische, parameters die maken dat wel of niet te verwachten is dat een toepassing van een techniek vergund en geaccepteerd, vermarkt en kostendekkend kan worden. Hieronder liggen parameters die aangeven in hoeverre sprake lijkt te zijn van een bewezen techniek, een renderend verdienmodel, afdekbare financiële risico’s en bestuurlijke en publieke acceptatie.

– *Duurzaamheidsaspecten*
  De term 'duurzaamheidsaspecten' wordt gebruikt als een soort verzamelterm voor alle risico's, circulaire aspecten en andere gezondheids- en milieuaspecten die met een techniek samenhangen. Daaronder gaat een aantal parameters schuil die nadere toelichting behoeven.
  - *Vezelvernietiging;* deze parameter vormt de kern van een effectieve techniek. Zonder de (gecontroleerde) zekerheid van volledige afbraak van asbestvezels tot een niet-toxisch restproduct blijft er sprake van risico's en is er geen herbruikbaarheid.
  - *Herbruikbaarheid;* in de meeste gevallen levert verwerking van asbesthoudend afval of asbestcement, na volledige vezelvernietiging, een vulmiddel op met nog enige hechtwerking. Veelal is dit niet meer zo krachtig als nieuw cement, maar is het voor bepaalde toepassingen (gecertificeerd) bruikbaar (bijvoorbeeld als kleivervanger) en is het dus van enige waarde. Maar soms is de hechtende werking verwaarloosbaar en is het restproduct alleen nog bruikbaar als inert vulmiddel van beperkte waarde.
    In bepaalde gevallen is hergebruik van de reststof van het asbest van secundair belang en heeft vooral een ander onderdeel van de afvalstroom economische waarde; dit is bijvoorbeeld het geval bij recycling van asbesthoudend staalschroot tot schoon, herbruikbaar staal.
    Bij met asbest vervuilde grond is de economische waarde van asbestverwerking niet in de eerste plaats gelegen in de herbruikbaarheid van de grond zelf, alswel in de uitgespaarde afgraving- en saneringskosten.
  - *Risicoaspecten;* hoe minder asbesthoudend afval getransporteerd en voorbehandeld (ofwel gedroogd, geshredderd of vermalen) moet worden, hoe minder maatregelen noodzakelijk zijn om werknemers, omwonenden en het milieu te beschermen, en hoe kleiner de risico's dat er een keer iets misgaat. Daarnaast kunnen bij bepaalde technieken maatregelen noodzakelijk zijn om veilig te kunnen werken met agressieve chemische stoffen, verhoogde temperatuur en/of druk.
  - *Potentiële CO_2-voetafdruk;* verwerkingstechnieken die relatief meer energie gebruiken, hebben een grotere potentiële CO_2-voetafdruk (al kan die natuurlijk verkleind worden door meer energie van hernieuwbare bronnen te betrekken). Voor een goede vergelijking moet op deze potentiële voetafdruk echter in mindering worden gebracht wat het te hergebruiken product aan CO_2-uitstoot teweeg zou hebben gebracht als het op reguliere wijze was vervaardigd. Staalproductie uit erts of gewoon staalschroot, vraagt net zo goed veel energie als de recycling van asbesthoudend schroot. Datzelfde geldt voor de reguliere productie van cement. De productie van minder actieve vulmiddelen vraagt minder energie, maar ook dat moet worden meegewogen.

– *Toepassingsgebied*
  De laatste overkoepelende parameter betreft welke typen asbesthoudend afval met een bepaalde techniek het meest effectief en rendabel te verwerken zijn.

De beoordeling

Met behulp van deze parameters zijn de ontwikkelingsstadia van de verschillende technieken beschreven en beoordeeld. Eerst zijn de parameters uitgebreid beschreven in zogenaamde 'analysis sheets'. Vervolgens zijn deze samengevat in overzichtstabellen. Van daaruit is een aantal conclusies getrokken over de huidige duurzame praktische toepasbaarheid van de diverse technieken. Samengevat komen deze op het volgende neer.

Thermisch
Het dichtst bij de (Nederlandse) markt bevindt zich de techniek voor de recycling van asbesthoudende staalschroot in smeltovens. In wezen gaat het hier om een reguliere metaalrecyclingtechniek met smeltovens, waarbij speciale maatregelen zijn getroffen om veilig met asbesthoudend schroot te kunnen omgaan. Deze techniek is rijp, er lijkt sprake van een solide verdienmodel en er is momenteel niets dat wijst op gebrek aan bestuurlijke of publieke acceptatie op de beoogde locatie.

Diverse andere thermische technieken staan iets verder af van de Nederlandse markt, maar zouden zich niettemin snel kunnen aandienen als de omstandigheden in gunstige richting ontwikkelen. Een belangrijk voorbeeld daarvan is de techniek voor thermische denaturatie, waarbij asbesthoudend afval (75 uur) door een tunneloven wordt gereden en op een temperatuur van 1000 °C wordt gebracht, waardoor het asbest zijn vezelstructuur verliest. Voor deze techniek is de afstand tot de Nederlandse markt vooral een kwestie van niet-technische factoren. Zo kan alleen sprake zijn van een sluitend verdienmodel als een hoger tarief per ton te verwerken asbest kan worden gerekend dan het huidige storttarief. Bovendien dient men verzekerd te zijn van een gestage aanvoer van te verwerken asbesthoudend afval, wat op zijn beurt enige buffercapaciteit en logistieke waarborgen vergt, alsook van acceptatie (door overheid en markt) van een gecertificeerd eindproduct.

Iets dergelijks geldt voor de techniek van thermochemische behandeling; een verbrandingstechniek (bij een temperatuur rond 1200 °C) waarbij de asbest door toevoeging van chemicaliën sneller tot ontbinding wordt gebracht. Wel zal bij deze techniek eerst nog een aantal technische tests succesvol doorlopen moeten worden.

Voor alle thermische technieken geldt dat ze grotere, statische installaties vereisen en relatief veel energie vragen. Daarmee hebben ze ook een relatief grote potentiële CO_2-voetafdruk, al moet hier wel in meegewogen worden dat de eindproducten vervangers kunnen zijn voor producten waarvan de reguliere (nieuw-) productie ook CO_2-uitstoot met zich meebrengt. Daardoor is bijvoorbeeld de potentiële CO_2-voetafdruk van het recyclen van asbesthoudend staalschroot klein.
Vanwege omvang en capaciteit van de installaties zal hooguit sprake kunnen zijn van één of enkele vestiging(en) in Nederland waarheen het asbesthoudend afval getransporteerd moet worden (extra transport ten opzichte van regionaal storten). Daarnaast vergen de processen voor recycling van asbesthoudend staalschroot en thermo-chemische behandeling enige voorbewerking van het afval. Bij dit alles zijn maatregelen noodzakelijk om werknemers, omwonenden en het milieu te beschermen tegen risico's van eventueel vrijkomend asbest. Bij thermische denaturatie ligt dit deels anders. Hierbij is geen voorbewerking nodig, het asbesthoudende afval gaat, inclusief de verpakking in polytheen zakken, linea recta in de oven.

Mechanisch
Ook de mechano-chemische techniek is redelijk rijp. Bij deze techniek wordt kleingemaakt asbestafval door hoge-energiemolens geleid waarin stalen kogels en zand meedraaien. In de botsingen van rotors, kogels, zand en afval ontstaan lokaal 'hot spots' met zeer hoge temperaturen (boven 1000 °C) en treden combinaties op van mechanische, thermische en chemische processen die de asbestvezels vernietigen en daarmee onschadelijk maken. De

laatste tests van deze techniek op industriële schaal moeten nog plaatsvinden. Tevens speelt hier nog een aantal praktische zaken alvorens de Nederlandse markt betreden kan worden. Aan de andere kant geldt dat de techniek meer mobiel en flexibel inzetbaar en minder kapitaalintensief is dan sommige andere technieken. Hierdoor zou van een relatief snelle toetreding tot de markt sprake kunnen zijn.

De mechano-chemische verwerkingstechniek gebruikt minder energie en heeft een relatief bescheiden potentiële CO2-voetafdruk. Het schaalbare en mobiele karakter van de installatie kan maken dat ze dicht bij plaatsen waar het asbesthoudend afval ontstaat of bijvoorbeeld op regionale stortplaatsen geplaatst kan worden. Dat leidt mogelijk tot minder transport van asbesthoudend afval. Wel is voorbewerking van dat afval nodig (drogen en verkleinen) en ontstaat een heel fijn stof als eindproduct, wat de nodige beschermingsmaatregelen zal vergen.

Biologisch
Biologische technieken – die erop gericht zijn om de natuurlijke afbraak van asbestvezels door bacteriën of schimmels te versnellen – zijn op dit moment nog onvoldoende uitontwikkeld. Zodra deze technieken ook maar enigszins beheerst kunnen worden, is echter per direct een positief verdienmodel te verwachten voor de in situ behandeling van met asbest verontreinigde grond, met minimale marktdrempels. Energieverbruik en potentiële CO_2-voetafdruk van biologische technieken zijn minimaal. Wel zal de veiligheid van het werken met schimmels, bacteriën en eventuele additieven geborgd moeten zijn.

Chemisch
Historisch gezien heeft de chemische asbestverwerking een matige staat van dienst. Al langer is bekend dat asbestvezels met sterke zuren of basen vernietigd kunnen worden. Pogingen om dit principe grootschalig toe te passen liepen tot op heden meestal dood op problemen met het in de hand houden van de risico's van het chemische proces en de noodzaak om het eindproduct te neutraliseren alvorens het te kunnen hergebruiken. Niettemin zijn ook op dit gebied nieuwe initiatieven waarneembaar, mede ingegeven door een belang om industrieel afvalzuur nuttig te gebruiken. Vooralsnog is er echter een aanzienlijke hoeveelheid technische en niet-technische kwesties die het hoofd geboden moeten worden, inclusief een aantal die verband houden met duurzaamheidsaspecten.

Andere beoordeelde technieken verkeren nog in een embryonaal stadium, staan na minder succesvolle pilot studies stil in hun ontwikkeling, of verkeren in een vroeg stadium van opschaling.

Toepassingsgebieden
Nadere beschouwing van toepassingsgebieden laat zien dat een aantal van de technieken hun eigen deelmarkten of niches hebben waarin ze asbesthoudend afval het meest effectief en rendabel kunnen verwerken:
– *recyclen van asbesthoudend metaalschroot in smeltovens:* asbesthoudend ijzer- en staalschroot;
– *thermische denaturatie:* een constante en homogene stroom asbestcement golfplaten, gevelplaten en buizen;

- *thermo-chemische behandeling:* asbesthoudend afval of een mengsel van asbesthoudend en hoogenergetisch afval (sorteer residuen, te gebruiken als alternatieve brandstoffen voor het verwerkingsproces);
- *mechano-chemische behandeling:* (gezien de meer schaalbare en flexibel inzetbare techniek) meer lokale homogene stromen asbestcement in wisselende hoeveelheden;
- *biologische behandeling van asbestvervuilde grond:* met asbestvezels (chrysotiel) vervuilde grond, in situ.

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18 juni 2018

1. Introduction

1.1 Background and goal of this assessment

It is the Dutch government's ambition to make the Netherlands a circular economy by 2050. As part of this ambition, the government has announced that it will investigate in which way, by means of existing or promising new treatment techniques, asbestos fibres can be rendered harmless, thus making it possible to reuse the cleaned-up (construction) material.[9] Up till now, controlled landfill of asbestos (containing) waste is standard practice. This practice is deemed unsustainable, even more so in the light of the upcoming ban on asbestos cement roofings,[10] which will lead to a new massive stream of asbestos waste. The announced investigation project should enable the authorities to direct innovations in asbestos waste treatment towards the most sustainable options at hand, and to do so in a well-considered way that can be accounted for in the public arena.[11]

It is clear that decisions to change the current way of dealing with asbestos cannot be taken light-heartedly. It is a well-recognized fact that asbestos is a highly carcinogenic fibre. Exposure to asbestos must be avoided. The best way to pre-empt the possibility of exposure, better than isolation, is to completely destroy the asbestos' fibrous structure. Without doing that, the risks of being exposed to asbestos will continue to be passed on to future generations.

However, the extra handling of the asbestos that comes with the destruction process itself or with the altered logistics of getting it to the destruction site, may create new exposure risks. Before the cleaned material can be reused in any way, it must be established beyond doubt that destruction techniques are consistently effective and resistant to human error and ill-will. Other aspects must be taken into account too, like additional chemical or biological risks that come with these destruction processes, or the possible impact of their energy-intensity on global warming. The introduction of new ways of dealing with asbestos waste disturbs present institutional arrangements and their checks and balances, which only makes sense if a stable and more desirable situation can be established – which also requires a solid business case and a societal licence to operate.

All in all, there are many aspects to be considered to establish what are the most suitable options at hand.

[9] *Nederland circulair in 2050 – Rijksbreed programma circulaire economie*. Beleidsnota van het ministerie van Infrastructuur en Milieu en het ministerie van Economische Zaken, mede namens het ministerie van Buitenlandse Zaken en het ministerie van Binnenlandse Zaken en Koninkrijksrelaties. Den Haag, 2016.

[10] See *'Ontwerpbesluit houdende wijziging van het Asbestverwijderingsbesluit 2005 in verband met het invoeren van een verbod op het voorhanden hebben van asbesthoudend materiaal toegepast als dakbedekking';* to be introduced July 2017.

[11] The European Parliament has adopted a resolution to the same effect, in which it "points out that, as regards the management of asbestos waste, measures must also be taken - with the consensus of the populations concerned - to promote and support research into, and technologies using, eco-compatible alternatives, and to secure procedures, such as the inertisation of waste-containing asbestos, to deactivate active asbestos fibres and convert them into materials that do not pose public health risks" (Resolution EU-P7_TA, 2013).

Following the announcement of this investigation, the Dutch ministry of Infrastructure and Water Management (ministry of IandW) commissioned an assessment of asbestos waste treatment techniques.[12] This assessment was carried out in the last two quarters of 2017 and the first two quarters of 2018. The outcomes of this assessment are presented in this report.

The aim of the assessment project is twofold:

- ✓ To develop and present an assessment method for asbestos waste treatment techniques that enables the ministry of IandW to carry out (or have carried out) assessments that
  - ➢ are integral (i.e. include all relevant aspects to judge the effectiveness and viability of these techniques),
  - ➢ are of high quality (lead to well-balanced and scientifically-based (or expert-) judgements) and that
  - ➢ can form the basis of an as transparent as possible assessment process.
- ✓ And to assess – on the basis on the method described above – all presently known asbestos waste treatment techniques, and in so doing, identify
- ✓ which techniques currently (if any) have the highest potential for sustainable practical application

To highlight the exact meaning of this formulation, the words used in this goal statement are clarified in the text block below.

'Assessment' of techniques	An assessment of techniques is a process of identifying, quantifying and prioritizing (or ranking) relevant characteristics of techniques. The goal of this project is to carry out an assessment, not to do research. What's meant by this, is that no new data on asbestos waste treatment are produced, only already existing data are gathered and (re-) interpreted.
'Well-balanced assessment'	This term refers to an assessment in which all relevant aspects are considered and are weighed against each other. However, in the basis this 'weighing' is mainly a political process. Therefore, it is to be carried out by policy makers, not only by researchers. Consequently, this assessment project first and foremost provides the elements that are to be weighed; if and where elements are weighed in the context of this project, this is done in an open and transparent way.
'Treatment' of asbestos waste	This is the process by which asbestos waste is changed in such a way that it no longer poses a threat to human health and the environment (and after which possibly reuseable material remains).

[12] Next to this investigation of techniques (the 'what'), the ministry also commissioned a project to investigate which parties have to cooperate in what way to make collection and reuse of treated asbestos possible (the 'how'). The results of this project have been reported separately, see: Tauw, 2018.

'Asbestos waste material' *(Also: ACM (asbestos containing material) or ACW (asbestos containing waste)*	This is waste material consisting of, or containing one or more of the six (widely used) types of asbestos.[13] Asbestos waste material can range from pure asbestos to waste that is slightly polluted with asbestos. For the purpose of this study the prime focus lies on the higher volumes of asbestos containing waste material (and higher levels of asbestos pollution), most of all asbestos cement, asbestos containing metal scrap (mainly steel) and asbestos contaminated soil.
'Techniques'	The word 'techniques' refers to material methods (in a more or less developed stage) for effecting a process or result. Techniques can be either young and untested (in statu nascendi), tested in a pilot project or mature and tested in full operation on industrial scale.
'If any'	This study acknowledges the possibility that none of the assessed techniques harbours a potential or a promise to a level that justifies practical application or calls for further development (as compared to the reference scenario: controlled landfill).

1.2 Methodology of the study

This assessment project has chosen as its basis the OVAM[14] study '*State of the art: asbestos – possible treatment methods in Flanders: constraints and opportunities'*[15] (OVAM (a), 2016)[16]. This was done because the study provided an authoritative and state-of-the-art overview and assessment of available techniques for asbestos waste treatment for application in Flanders at the time the present study was commissioned. The study was carried out from the same overall perspective as that of the present assessment project: 'sustainable land use, recycling and closing material cycles' (OVAM (a), 2016,).

Building on this basis, a three step approach was adopted.

1. First, an international expert Sounding Board meeting was held. The aim of this Sounding Board meeting was to bring about a critical discussion of the OVAM report and to identify possible needs for updates and completion of the report's findings, as well as possible additional assessment parameters. The general conclusion of the discussions was that the OVAM report does indeed offer a solid starting point for an assessment of asbestos waste treatment techniques, but that several critical adjustments and supplements need to be made:
   - landfill as a reference scenario needs full elaboration;
   - a number of upcoming techniques must be included;
   - a more critical approach to the quality of information and sources is required;
   - the factor time for technology development and application (short, medium and long term) must be included;
   - some assessment parameters used in the OVAM report need more elaboration, some need a clear definition and some new parameters must be added.

[13] The term 'asbestos' is used for six minerals — chrysotile, amosite, crocidolite, anthophyllite asbestos, tremolite asbestos and actinolite asbestos — belonging to the serpentine (chrysotile) and amphibole families (the others).
[14] OVAM is the Flemish Public Waste Company ('Openbare Vlaamse Afvalstoffenmaatschappij').
[15] The OVAM report can be found at:
http://www.ovam.be/sites/default/files/atoms/files/State%20of%20the%20art%20asbestos%20waste%20treatement.pdf
[16] The study was commissioned by OVAM and was carried out in cooperation with Ecorem nv and ABO Group nv.

The full report of the Sounding Board meeting is included as part 1 in the Appendix report. Annex 2 to this report provides the list of participants to the Sounding Board's meeting.

2. Following up on the conclusions of the meeting of the Sounding Board, the project team developed its own proposal for assessment parameters and carried out additional data collection. The assessment parameters were further refined in confrontation with the reinterpreted existing data and the newly acquired and interpreted data.

   The actual data gathering and (re)interpretation activities that were carried out in this phase, were threefold:
   - Firstly, the data included in the OVAM report, as well as the sources from which they were derived, were reinterpreted with the help of the newly developed or refined assessment parameters.
   - Secondly, a literature search was carried out in order to include additional and more recent data. This search provided important additional insights into publicly available scientific data. The search also made clear, however, that part of the expertise in this field is not publicly available for reasons of protecting intellectual property rights and market competition considerations. Also, an important part of relevant expertise is of a different, often more practical nature than the type of expertise that finds its way into scientific publications. Therefore, a third course of action was adopted as well.
   - This third course of action consisted of interviews with experts involved in the – often commercial – development of techniques. For practical and workload reasons, the interviews were restricted to initiatives with a Dutch connection. In these interviews the experts were invited to disclose any information they were willing to share. As it turned out, excellent cooperation was obtained from relevant experts from all initiatives known to the project team.
     Annex 2 to this report provides the list of experts that were interviewed. The full (approved) reports of the interviews are included in part 2 of the Appendix report.

3. Finally, the first step of the assessment process was carried out, by pooling all available information on the different techniques and by carrying out an analysis of this information based on different established assessment parameters. These analyses were documented in so-called 'Analysis sheets'. For optimal transparency, these analysis sheets are included in Annex 1 to this report.

   In order to be as clear as possible about the quality of the sources, in the descriptions a distinction is made between factual and 'claimed' properties and aspects of a technique. 'Claims' may well be accurate, but are by nature less - independently – underpinned and therefore run the risk of being biased by interests. The more a statement is scientifically underpinned, made public in peer-reviewed journals and confirmed in different publications, the more it is considered to be factual. Subsequently, the more the statements about properties and aspects of a technique are 'factual', the more they are considered to be conclusive data, that prove for example the readiness of a technique and that can indicate that operations and risks are under control.

The first results of this analysis were presented (in writing) to the members of the Sounding Board for a critical appraisal. A summary of the comments received during this round are included as part 3 of the Appendix report, as well as responses of the project team about the way these comments have subsequently been handled.

In between the different stages and at the end of this project, an Advisory Commission has overseen and critically reflected on the adopted approach and the resulting analyses. The members of this Advisory Commission are listed in Annex 2 to this report.

1.3 About this report

In order to provide readers an easy access to the findings, the following chapters of this report contain a concise description of the assessment project results. Jargon is avoided as much as possible. In case the use of technical terms is necessary, they are explained. Further details and underpinning can be found in the annexes and the Appendix report. For those readers who look for specific elements of the assessment project report, now follows a description of its structure.

The report starts in the next chapter (***chapter 2***) with a general description and classification of the different asbestos waste treatment techniques. Techniques are described, ordered by the typically different mechanisms on which their operation is based. Also new developments within the different types of technologies are indicated. The classification of techniques will form the basis of detailed analytical descriptions by means of the assessment parameters in later chapters – but may also serve as an introduction into the world of techniques for rendering asbestos harmless.

The assessment parameters are presented in ***chapter 3***. The basic principles underlying the choice of parameters are briefly discussed. The different types of basic parameters are named, described and part of them also operationalised. An explanation is given how, based on these parameters, four overarching assessment parameters are established (i.e. technology readiness level, distance to market, sustainability aspects, area of application). With all of this, the first element of the goal of the study is delivered: the assessment method.

Chapters 4 to 8 contain the actual assessment of the different techniques. Based on the classification of different technical approaches as described in chapter 2, and employing the assessment parameters that were described in chapter 3, an assessment of all techniques is presented (as far as data are available), resulting in conclusions on where and how the developments of the different techniques stand.

In ***chapter 9*** the results of the assessment of the different techniques are presented next to one another. Specific technological characteristics are highlighted. Differences between techniques as to their stage of development, their relative strengths and their weaknesses are pointed out. With all of this, the second element of the goal of the study is delivered: the assessment itself and its conclusions.

Chapter 10 summarises the conclusions that follow from the assessment exercise. Conclusions concern both the assessment method that was developed and the outcome of the assessment.

Annex 1 to this report contains the analysis sheets of assessed types of techniques. **Annex 2** provides an overview of all persons consulted or interviewed. **Annex 3** contains the list of references.

The Appendix report contains:
- The report of the meeting of the Sounding Board, November 2017
- The reports of the interviews held with experts
- The report of the review of the final assessment report by members of the Sounding Board

2. Asbestos waste treatment techniques: basic mechanisms

2.1 Introduction

This chapter gives an overview of the basic types of techniques for the treatment of asbestos waste, i.e. ways in which asbestos containing material (ACM) can be changed in such a way that it no longer poses a threat to human health and the environment and that the remaining product can be reused in one way or another.

There are different techniques that aim to reach such an effect. These techniques can be classified to their underlying mechanisms. They are:
- Thermal treatment
- Chemical treatment
- Mechanical treatment
- Biological treatment

Overviews of these techniques can be found in several publications. The OVAM report (OVAM (a), 2016) is an important example of such a publication, that is also used as the basis for the overview presented in this chapter. Other recent overview publications have provided additional information (LLW Repository Ltd, 2016; Spasiano and Pirozzi, 2017). These publications use similar types of classification of techniques as the one presented here, though sometimes with different terminology. In addition to this, insights are added from recent publications that describe new findings or tests and from interviews that were held that point at further developments.

It should be noted that to some extent the classification that is used here, is arbitrary. There are several actual techniques in which the underlying mechanisms blend in together, like when chemicals are added in order to speed up a thermal process or when micro-organisms are used to produce acids that break down the asbestos. In many cases the final destruction of the asbestos fibres is the combined result of thermal, chemical and mechanical forces. Nevertheless, in this report the techniques are classified according to their dominant mechanism and without using a – just as arbitrary – separate category of 'combined or mixed techniques'.

The following paragraphs describe the separate types of techniques, the underlying treatment mechanisms and the different variants in which they are developed and employed. For 'benchmark' purposes, these descriptions are preceded by a description of the reference scenario: landfill.

2.2 Landfill (and stabilisation)

Landfill and stabilisation are not actual treatments of asbestos as such, since they do not alter its fibre structure and do not render it *intrinsically* safe for man and environment.

The landfill technique is merely presented here for reference purposes and because it has generally been considered as a safe and appropriate waste management strategy.[17]

The basic landfill 'technique' consists of accepting properly bagged ACW (in accordance with applicable certification schemes), having it 'laid down' in landfill sites and covering it with a layer of soil or comparable material. After the landfill site had been filled completely, the resulting – if so desired, hilly – landscape can be used for a number of specified purposes.[18] When left untouched, the dumped asbestos does not present any risk. The waste is stable and does not leach nor produces gases. The landfill site will require everlasting management and protection from risks deriving from deterioration or interference (for which funds are built up).

Before landfill, additional stabilisation measures can be taken to reduce risks of release of fibres. An example can be found in Flanders, where friable asbestos must be encapsulated in concrete blocks before landfill (OVAM (b), 2016).

2.3 Thermal treatment

A well-known and often used technique for the destruction of asbestos fibres basically consists of heating ACM to high temperatures for sufficiently long time. At certain (higher) temperatures asbestos fibres are unstable and naturally decompose (see textbox). Several underlying mechanisms of thermal decomposition are at play here. With increasing temperatures overall evaporation of adsorbed water, dehydratation and crystallization take place (Spasiano and Pirozzi, 2017). This conversion process goes through different phases, in which different intermediate mineralogical stages are passed (Kusiorowski et al., 2012). At extreme temperatures (up to 1600 °C or even 2000 °C) all (mineral) waste – including asbestos – is converted into a stable and homogeneous (silicate) glass. This latter process is called 'vitrification'.

Other components of the ACW, like the bags in which it is packed or the cement matrix of the asbestos cement composite, also decompose at these temperatures (the cement is mainly decomposed into SiO_2 and CaO, which are deemed harmless substances).

Decomposition temperatures of asbestos types
(source: Gomez et al., 2009)

– $T_{decomposition}$ (chrysotile) = 450-700°C
– $T_{decomposition}$ (crocidolite) = 400-600°C
– $T_{decomposition}$ (tremolite) = 600 - 850°C
– $T_{decomposition}$ (amosite) = 600-800°C
– $T_{decomposition}$ (anthophylite) = 620 - 960°C
– $T_{decomposition}$ (actinolite) = 950 - 1040°C

A number of thermal treatment techniques –most of which are already known for some time – can be distinguished:

– *Vitrification:* the before-mentioned technique that transforms substances into glass (by plasma gun (Heberlein and Murphy, 2008), conventional ovens or electric furnace (Geomelt vitrification process (Finucane et al., 2008)).

[17] In the Netherlands the necessary legal provisions are in place that make it possible to quickly implement a landfill ban on asbestos cement. This decision will however only come into effect when proper asbestos waste treatment techniques are available and meet with certain capacity requirements (see footnote 28).
[18] Examples are known where these landscapes are used for sports and leisure activities and for the placement of specific types of buildings.

- *Ceramitization:* a technique in which ACM is mixed with clay and brought at high temperature, at which the material is converted into ceramic products.
- *Thermo-chemical treatment*: a chemically catalysed thermal degradation process; accelerated remineralisation process at lower decomposition temperatures by using a fluxing agent (Downey and Timmons, 2005).
- *Thermal denaturation:* ACM is heated in tunnel kilns or furnaces for a longer time until all asbestos has decomposed; afterward the end-product is grinded into powder.
- *Microwave heating:* thermal denaturation by means of microwave heating.
- *Treatment of asbestos containing steel scrap in steel melting furnaces:* a technique that reclaims steel from asbestos containing steel scrap in steel melting furnaces. As an intended side effect asbestos is decomposed; its remains are part of the slags.

Also, scientific publications hint at some thermal techniques in early stages of development. These include:
- SHS (self-propagating high temperature synthesis); a thermal method exploiting the highly exothermic and fast self-propagating high-temperature reaction between Fe_2O_3 and magnesium powder. Experiments with mixtures of different ACW and different amounts of reagents (25 to 50 weight % for friable asbestos and 40 to 50 weight % for asbestos cement) were reported (Gaggero et al., 2016).
- Laser induced rapid melting: the use of pulse CO_2 laser irradiation for melting and decomposing of asbestos containing slate (Fujishige et al., 2014)

2.4 Chemical treatment

Asbestos fibres can be decomposed by exposing the fibres to chemicals that destroy the crystalline fibre structure. Most of these reactions are based on dehydration. Chemical decomposition mechanisms can be divided into different categories (Spasiano and Pirozzi, 2017):
- *Acid decomposition:* Chrysotile will decompose in a strong acidic environment (such as HCl, H_2SO_4 , H_3PO_4 and HNO_3).
- *Asbestos decomposition using weak acids and/or combined with capturing CO_2:* Some processes describe the use of weak acids such as oxalic acid (Turci et al., 2010) or waste acids from agro industries (such as whey from a cheese factory (Alimenta, 2017)). All serpentine (chrysotile) and related minerals, such as olivine (alkaline solid wastes), are able to capture CO_2 by forming carbonates (carbonation), which is at natural conditions a slow process (Pan et al., 2012).
- *Alkaline destruction:* Alkaline destruction of asbestos (Cioska et al., 2006) is possible at high temperature (200-500 ^oC) and elevated pressure.
- *Specific decomposition of amphibole asbestos using iron capturing chelates:* For destruction of the amphibole fibres chelating additives as citric acid, oxalic acid or EDTA are needed. Besides driving the acid reactions, oxalic acid and citric acid are also chelate forming agents, which is a necessary ingredient to leach out iron from the amphibole structure. Iron is a major element in the amphibole asbestos types crocidolite and amosite.

2.5 Mechanical treatment

Asbestos fibres can also be broken down by mechanical treatment. The mechanical treatment techniques that are effective, use advanced types of milling (high energy milling (Baláz et al., 2006; Baláz, 2008)). In this process no heat or chemicals are added. All inserted energy is of a kinetic nature, therefore it is categorised as 'mechanical treatment'.

The mechanism by which the fibres are broken down, however, consist of the chemical and physic-chemical transformations of substances in all the aggregation states produced by the effect of mechanical energy (Colangelo et al., 2011; Spasiano and Pirozzi, 2017). Therefore, this type of treatment is often referred to as 'mechano-chemical'. Plescia (Plescia et al., 2003) describe the phenomenon that mechano-chemical treatment of crystalline substances can lead (on micro scale) to an extremely high degree of amorphisation and phase change, generally seen in thermal reactions exceeding 1.000 °C (whereas mechano-chemical processes generally (on macro scale) do not exceed 160–180 °C).

Effective mechano-chemical treatment of ACW results in ultra-fine non-carcinogenic amorphous powders.

2.6 Biological treatment

Asbestos fibres exposed to fungi (and/or lichens and bacteria) and/or other natural occurring environments such as peat soil (low pH) will be chemically affected. This phenomenon was described first in 2003 by Torino University in Italy, followed by later publications (Daghino et al., 2009). Certain types of natural occurring fungi were isolated, which were found on serpentine rock formations. These types of fungi grow best on the 'diet' as provided by these minerals combined with the local environment (temperature, humidity et cetera).

The underlying mechanism of the treatment is that these types of fungi produce organic acids and/or chelates which can leach out magnesium (from chrysotile) whereas other fungi are able to leach out iron from crocidolite and amosite. If this reaction is completed, the typical chemical and crystalline structure of asbestos should be decomposed in such a way that the typical carcinogenic properties of the asbestos fibres have disappeared (the effectiveness of this decomposition process is still being researched). In nature such a process will take decades, but if optimum conditions are created (concentration of fungi, nutrient medium, temperature, humidity, available fibre surface et cetera) this process can be speeded up considerably. The reaction kinetics in this process are of significant importance: if the available fibre surface decreases, or the fibre is embedded in a cement matrix, the reaction will slow down exponentially. Therefore the completeness of the asbestos decomposition must be controlled carefully, using state of the art analytical techniques such as micro Raman spectroscopy (Turci et al., 2010).

Bacterial weathering of asbestos in natural occurring sources (India, Rajasthan mines) is described by Bhattacharya (Bhattacharya et al., 2015).

A combined process for the biochemical denaturation of asbestos containing materials, using fungi as well as bacteria, is described by Roveri in a U.S. Patent document (Roveri et al., 2017).

3. The assessment parameters

3.1 Introduction

3.1.1 The development of the assessment parameters

The assessment parameters have been developed from two directions. The one direction built upon the methodology of the OVAM study (OVAM (a), 2016). In this OVAM study a set of parameters was developed to describe and analyse the different treatment techniques. Next, the researchers used quantified representations of these parameters in multi-criteria analyses in order to identify the techniques with the best potential on different aspects.

Whereas the parameters distinguished and developed by OVAM proved to be quite helpful, the multi-criteria analyses approach of OVAM was hard to combine with the principles of the present study as described on page 22 of this report, and particularly the principle that the final weighing of parameters is mainly a political process, to be carried out by policy makers.

Consequently, the second direction worked the other way around and started with elements that (Dutch) public policy makers require for carrying out the final weighing. Four elements have been postulated that provide meaningful weighing aspects, largely of a qualitative nature:

– *'Technology readiness level':* the level of technological maturity (as defined by NASA and the EU), expressed on a scale from 1 to 9.
– *'Distance to market':* a term referring to the mostly non-technological aspects that determine whether a technology can reasonably be expected to be licensable, marketable and profitable.
– *'Sustainability aspects':* a parameter that refers – as a kind of collective term – to the different characteristics of a technique with an impact on risks, aspects of a circular economy and other health and environment issues.
– *'Area of application'*: i.e. the types of ACW for which a particular technique is most applicable or profitable.

The resulting assessment method is a combination of the work from both directions. The four elements mentioned above (named 'overarching parameters') have been logically connected to the 'improved' OVAM criteria. In that way, a description of all aspects of a technique (using all parameters that are considered relevant) forms the basis for clear and well-documented statements on four well-understandable and highly relevant aspects that are to be weighed (by policy makers).

3.1.2 Working from the OVAM parameters

The OVAM parameters are intended to help obtain a full description and appraisal of the techniques. For an impression of the OVAM parameters, see the textbox on page 34. Further discussion and elaboration of these parameters (see also the report of the Sounding Board meeting in part 1 of the Appendix report) has led to a number of remarks on the OVAM parameters, and requirements for the parameters to be developed in this study.

These include:
– Some parameters must be clarified (e.g. ‘end-product’), some must be added (e.g. public acceptance, the factor process time and scale/mobility of the installation), some require elaboration (e.g. safety, end-product, control and costs).
– The weight and impact of some parameters are heavily dependent on the regulation and standard setting that is actually in place.
– The final weighing process at the same time includes numerical assessments, expert judgements and political considerations. The parameters must feed these judgements in a transparent way.

Textbox: OVAM’s assessment matrix

The assessment matrix of the OVAM study analyses techniques on the basis of the following parameters, both in a qualitative and a quantitative way (see p. 122 and further):

- Acceptance criteria
- End-product
  - *End-product*
  - *Applicability*
  - *Standardized*
- Process
  - *Supply product*
  - *Batch/continuous*
  - *Buffer*
  - *Separation*
  - *Size-reduction/Crushing*
  - *Laborious/automated*
  - *Control*
  - *Installation*
- Energetic
  - *Primary energy*
  - *Additives*
  - *Water consumption*
  - *Others*
- Emissions
  - *Water*
  - *Air*
  - *Solid*
  - *Others*
- Safety aspects
- Financial
  - *Cost process*
  - *Cost business model*
- State of the art
  - *Proven/failed*
  - *Patented*
  - *Optimization*
  - *Alternative*

3.1.3 Aiming at the elements to be weighed

As mentioned before, four overarching parameters are distinguished. The ‘content’ of these parameters is derived from underlying (basic) parameters and comes as close as possible to serving – in an objective way – the purpose of the assessment, that is, to identify which techniques have the highest potential for sustainable practical application.

These four overall parameters are not fully determined by only the strictly technical aspects of a given technique. In the descriptions on the previous page, it was already indicated that ‘distance to market’ is mostly determined by non-technological aspects. These aspects – like costs, prices, market acceptance, public acceptance – determine whether a technology can reasonably be expected to be licensable, marketable and profitable. Thus, non-technical aspects must be included in the assessment, albeit in a different, more qualitative fashion than the technical aspects, that can often be quantified.

Therefore a distinction is made between three types of basic parameters:
1. *technical parameters*, referring to characteristics of a largely natural scientific and quantifiable nature. These parameters are more or less by definition objective;
2. *non-technical parameters of a reasonably objectifiable nature*, as they are largely determined by technical characteristics of the techniques; and
3. *non-technical parameters of a hardly objectifiable nature*, which are mainly determined by non-technical (regulatory, economical, societal or other) factors.

Together, the three sets of basic parameters and the four overall assessment parameters constitute the assessment method that is proposed here. In the following paragraphs they are first described as separate building blocks and later presented as a coherent structure. However, the explanation – or even justification – of the inclusion of parameters in the total structure works the other way around, and is in fact teleological (starting from the end and reasoning back): all basic parameters are, either directly or indirectly, functional for the establishment of the overall parameters.

In the next paragraphs the three types of parameters and the four overall parameters are described and operationalised.

3.2 Technical parameters

The first set of parameters is of a largely natural scientific and quantifiable nature. Table 1 names the parameters, describes them and indicates the way they are operationalised, either in exact terms, on a scale or in terms of different options.

Table 1. Technical parameters

Parameter	Description / clarification	Way of quantification (or qualitative description)
Process time	Duration of the process to effect 'full destruction of asbestos fibres'[19] (excl. pre-processing time)[20]	*Scale:* mins / hrs / days / months / years / centuries
Process temperature	Temperature at which the destruction process takes place	ºC
Energy requirements	Amount of energy required per ton of treated ACM *(Note: the asbestos weight percentage can vary widely between different waste streams. So does their composition. The energy requirements of different techniques (applied at different types of waste streams) can therefore not easily be compared on the basis of one digital parameter. This will be explained / discussed with the different techniques.)*	kWh/ton
Input requirements / acceptance criteria	Types of ACM that can (only) be treated with the technique	*Options:* chrysotile / 'pure, friable' asbestos / asbestos cement/ asbestos containing scrap metal / asbestos containing soil / all ACM / other (to be explained)

[19] Unless stated otherwise, 'full destruction of asbestos fibres' is meant to refer to asbestos levels below detection level with all available detection techniques.
[20] Not in all techniques pre-processing and process time can be distinguished. Where this is the case, this will be mentioned.

Parameter	Description / clarification	Way of quantification (or qualitative description)
Pre-processing (energy) requirements	Necessary preparation in order to make the ACM suitable for treatment, and the amount of energy this requires (as compared to the pre-processing that is required in the landfill reference scenario (i.e. double bagging)).	*Options:* pre-separated / reduced in size / grinded / milled / dried / none / other; plus kWh/ton
Additives (chemicals or other)	Other material ingredients added to the asbestos treatment process	*Options: r*eactive chemicals / inert substances / other
Fibre destruction	Type/mechanism and level of fibre destruction effected by the technique *(Clarification: some reactions have a clear turning point (e.g. when reaching the decomposition temperature). Others slow down when asbestos or reagent concentrations decrease (some chemical and biological processes), hence the asymptotical decay of the reaction rate.)*	*Options:* full destruction / asymptotical decay of reaction rate / none / other
Mass / volume reduction	Extent to which the technique reduces (or increases) mass or volume of waste streams *(Clarification: mass / volume reduction can be of importance for the amount of space required for landfill, energy required for transport, et cetera).*[21]	%
Reusability of end-product	Way in which the end-product can be reused	*Options:* None[22] / inert filler / building material (civil engineering) / active substance (cement, clay) / clean soil / other
Installation type / size	Typical characteristics of the treatment installation following from its technical properties	*Options:* On site / mobile / temporary / fixed medium scale / fixed large scale / other
Installation capacity	Amount of ACM the installation can typically treat on yearly basis (= 300 business days)	*Scale:* <1.000 / 1.000 – 10.000 / 10.000 – 100.000 / > 100.000 tons/year
Proven technique	The extent to which the technique is developed and has been proven in practice	*Options:* lab scale / pilot trials / upscaled / fully operational

Of course, several of these parameters are interdependent (though *not fully* determined by one another).

– Process time and temperature are important factors in process energy requirements.

[21] Note: this parameter has been taken over from the OVAM parameters. However, in the Netherlands it proves to be hardly relevant whether treated waste requires less space for landfill. Most developers of asbestos waste treatment techniques build their business cases on higher gate fees than the present gate fee for landfill. However, according to LAP3 a landfill ban for asbestos can only come into place if there is a market for end-products of the asbestos treatment (and thus the end-product cannot be dumped).

[22] Strictly speaking this option disqualifies a technique, given the requirements of LAP 3 (see footnote 21).

– The nature of the process, but also the type, size and capacity of the installation largely determine the types, forms and quantities of asbestos waste that can be recycled, and therewith the acceptance criteria and input requirements.
– These input requirements in turn determine the required pre-processing.
– The level of fibre destruction also determines the reusability of the end-product.
– The more data are available about the different technical parameters, the more probable it is that a technique can be considered as ‘proven’.

The double-sided arrow in figure 1 indicates these interdependencies.

Figure 1. Technical parameters

Technical Parameters
Process time
Process temperature
Energy requirements
Input requirements / acceptance criteria
Pre-processing (energy) requirements
Additives (chemicals or other)
Fibre destruction
Mass / volume reduction
Reusability of end-product
Installation type / size
Installation capacity
Proven technique

3.3 Non-technical parameters (reasonably objectifiable)

The second set of parameters is non-technical by nature. The parameters can however be described in more or less objective terms, given their strong relation to the technical aspects of the treatment technique (see table 2). Thus, again there are strong interdependencies with the technical parameters that were described in the previous paragraph. However, given the fundamental non-technical nature of this second set of parameters, several of these parameters cannot be uniformly quantified and must be described in a qualitative way.

Table 2. Non-technical parameters, reasonably objectifiable

Parameter	Description / clarification	Way of quantification (or qualitative description)
Logistical aspects	Logistical consequences of applying the technique, e.g. in terms of ACM transportation to installation, buffering and storage requirements, plant logistics including effects of packaging and pre-processing (as compared to the logistical consequences of the reference scenario: landfill (i.e. double bagging and transport)).	*Qualitative*

Parameter	**Description / clarification**	**Way of quantification (or qualitative description)**
Quality Assurance (QA) aspects	Required amount of fine-tuning and process control; number of process parameters which had to be controlled ('less is better'); robustness; sensitivity to process disturbances; intrinsic safety of process; influence of human factor; employees working under 'asbestos conditions'	*Qualitative*
Risk aspects (in relation to trans-port, occupational H&S, for residents and environment, of end-product)	Risks characteristics, (possible) exposure and emission levels in relation to: – transport (see also logistical parameter), – occupational health and safety (see also QA aspects), – risks for residents (local surroundings) and environment (idem), – risks of end-product (see also technical end-product parameter). – risks of (other) process waste	*Qualitative*
Energy balance with replacement product	Comparison / offset of energy use of on the one hand the asbestos treatment process to produce reusable end-product, and on the other hand the regular production process to obtain the product that is to be replaced.	*Qualitative*
Costs in relation to energy use	Costs of energy use per ton of treated ACM (see also technical energy requirements parameter).	*Costs (in actual market prices) in* €/ton *and/or (scale):* < € 10/ton; € 10 – 100/ton; € 100 – 200/ton; € 200 – 500/ton; > € 500/ton
Installation investments	(Claimed) Investment costs of installation (see also (technical) installation type / size parameter (table 1))	*(Claimed) investments in* € *and/or scale*: < 1 million € 1 million – 20 million; > € 20 million
(Market) value of end-product	(Claimed) Price or capitalized value of the end-product of the treatment of ACM, or avoided costs of dealing with asbestos contamination in another way (e.g. avoided landfill costs; avoided costs of soil excavation)	*(Claimed) value in* €/ton *and/or (options):* avoided soil decontamination costs / < € 10/ton / > € 10/ton
Other costs	Any other costs that are relevant and associated to the technique in question (e.g. labour costs, added material costs, maintenance costs, site protection costs)	*Qualitative*

The large extent to which these non-technical parameters are determined by the previously described technical parameters, is illustrated by the big arrow in figure 2. Examples of such interdependencies are:

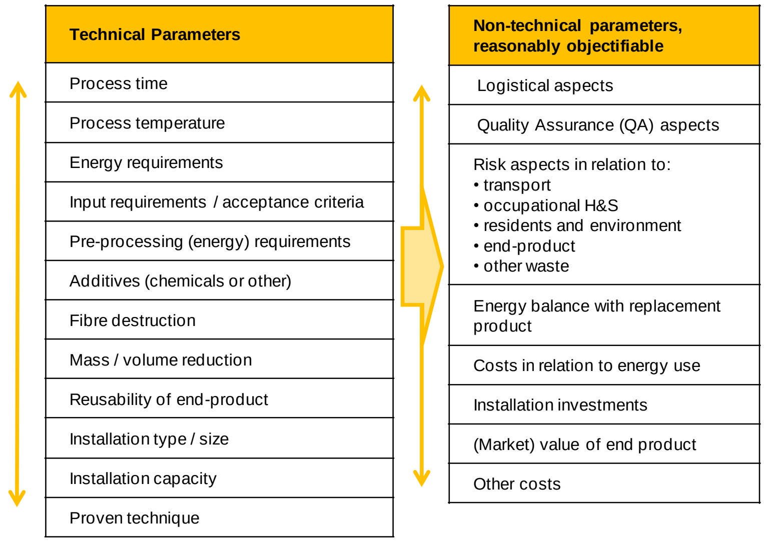
– the impact of the energy requirements of the treatment itself and of the pre-processing on the energy costs of the process;
– the impact of pre-processing requirements on the logistical aspects of the process;

- the impact of the type and reusability of the end-product on its (market) value;
- the impact of size and type of installation on the installation's investment costs;
- the impact of the level of fibre destruction on the risks from the end-product;
- the impact of the logistical and the quality assurance aspects on the level of risks in relation to transport, occupational health and safety, risks for residents and the environment, and risks from other waste (also depending on the type of installation).

Again, the level of interdependency between these parameters is not such that they fully determine one another. For example: the energy costs of a process are not a direct consequence of its energy use, but also of the choice for the type of energy that is used (fossil fuels, solar or wind power) and of the market price of this type of energy.

Figure 2 represents these parameters and their interdependencies.

Figure 2. Technical and non-technical, reasonably objectifiable parameters



3.4 Non-technical parameters (hardly objectifiable)

The third set of parameters is non-technical and can hardly or not be described in objective terms (see table 3). They are to a large extent determined by non-technical (regulatory, economical, societal) factors. Hence the heavy reliance on qualitative description. Nevertheless, also these parameters are to a certain extent influenced by technical and other non-technical parameters.

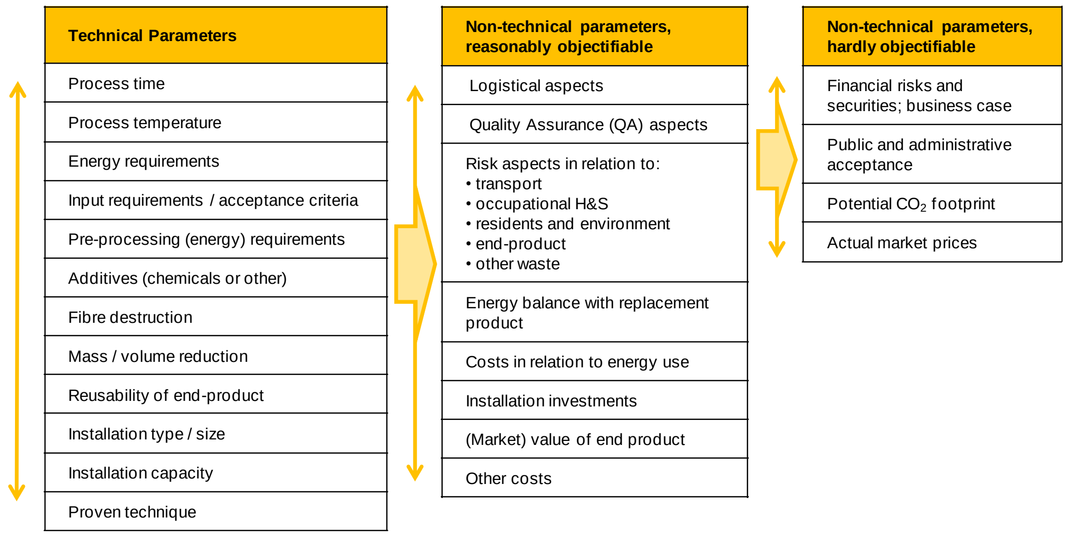
Table 3. Non-technical parameters, hardly objectifiable

Parameter	**Description / clarification**	**Way of quantification (or qualitative description)**
Financial risks and securities; business case	The way in which the overall risks and opportunities, costs and benefits of the asbestos waste treatment constitute an earnings model and bolster investor confidence	*Qualitative*
Public and administrative acceptance	The societal 'licence to operate'; the extent to which an asbestos waste treatment installation is passively or actively accepted by its societal and administrative environment	*Qualitative*
Potential CO_2 footprint	An indication of the potential (equivalent) amount of CO_2/ton emitted as a possible consequence of (the energy use of) this particular technique of asbestos treatment, including the energy balance with the replacement end-product. *(Whether the potential footprint is actually realised, depends for instance on the chosen energy source (e.g. grey or green)).*	*Options: Small / medium /large / very large (For the purpose of this study it would take too far to actually calculate the potential CO_2 footprint; therefore a rough scale is used, built on more concrete and precise basic parameters)*
Actual market prices	Actual price for which the asbestos waste treatment is on offer at the market place	*Actual price in €/ton*

Again, the technical and other non-technical parameters can have their effects on these non-technical, hardly objectifiable parameters. Examples of these interdependencies are:
- the impact of the different costs of the process on the actual market prices for the treatment;
- the impact of the (perception of) QA aspects and of the different risks on public and administrative acceptance;
- the impact of all of these parameters on the financial risks and securities and on the overall business case;
- the impact of the energy use of the process and of the energy balance with replacement products on the potential CO_2 footprint.

Figure 3 provides the overview of the complete set of basic parameters and their interdependencies.

Figure 3. Technical and non-technical parameters



3.5 Overall assessment parameters

3.5.1 The overall assessment parameters

As described in paragraph 3.1, four overarching parameters are adopted that provide meaningful weighing aspects. These parameters summarize the aspects of the techniques that have previously been described and allow for a transparent appraisal of these techniques.

3.5.2 Technology readiness level

The first of these four parameters is the Technology Readiness Level (TRL). This concept was first introduced by NASA to describe technological maturity and has meanwhile gained widespread use in different fields of innovation (Mihaly, 2017). The TRL is a one-dimensional ranking method that places a technology's readiness on a scale from 1 to 9. The nine levels of technology readiness are shown in the figure 4.

The TRL of a specific asbestos waste treatment technique is determined qualitatively on the basis of three parameter elements:

1. First of all, the value of the parameter 'proven technique'; the higher the scale on which the technique has been proven, the higher the TRL.
2. Secondly, the extent to which conclusive data are available on all technical parameters. This is in fact a meta-criterion. The more conclusive data are available, the stronger the underpinning of the 'proven' character of the technique, substantiating a higher TRL.
3. Thirdly, the extent to which quality assurance aspects are clear and have been brought under control. This is an indicator for the extent to which the system can function in operational use, and therefore for its TRL.

Figure 4. Technology readiness levels

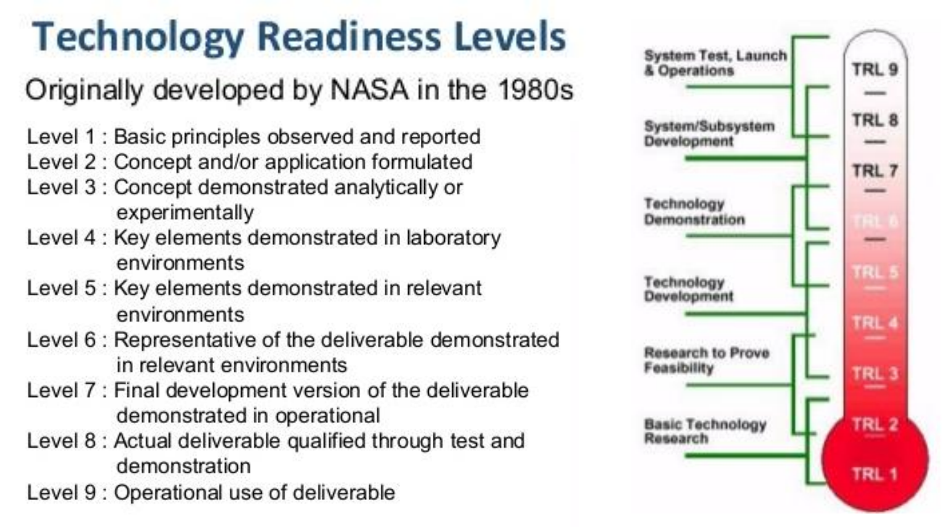
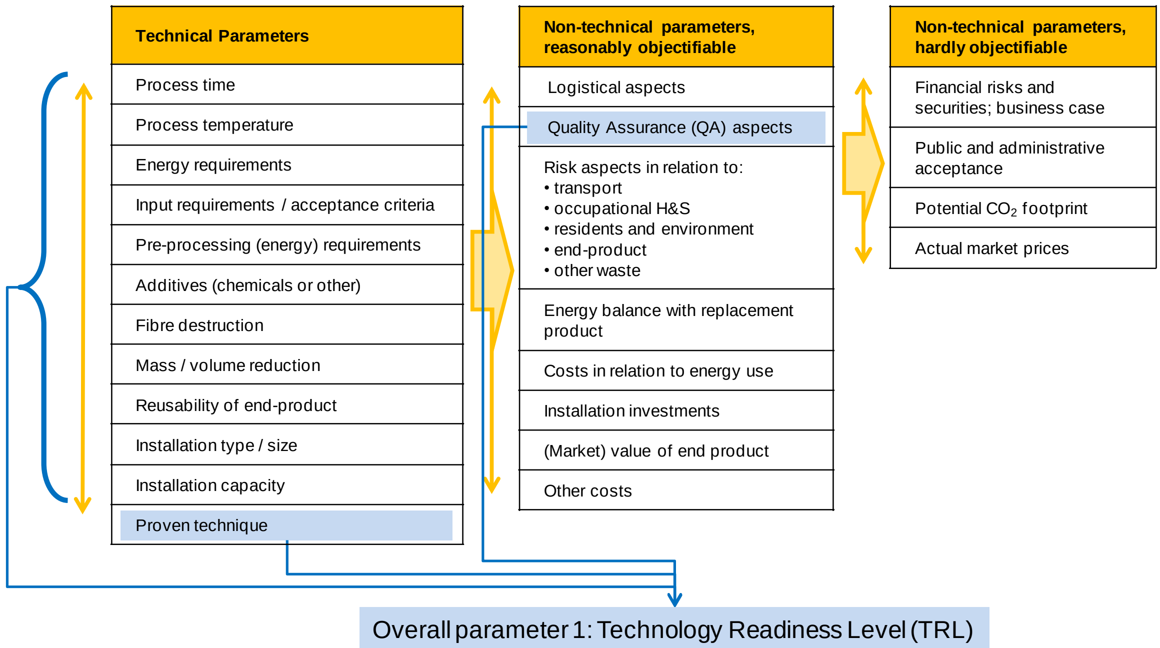


Figure 5 shows how the overall parameter TRL is based on a selection of the basic parameters.

Figure 5: Establishment of overall parameter 1: Technology Readiness Level (TRL)



3.5.3 Distance to market

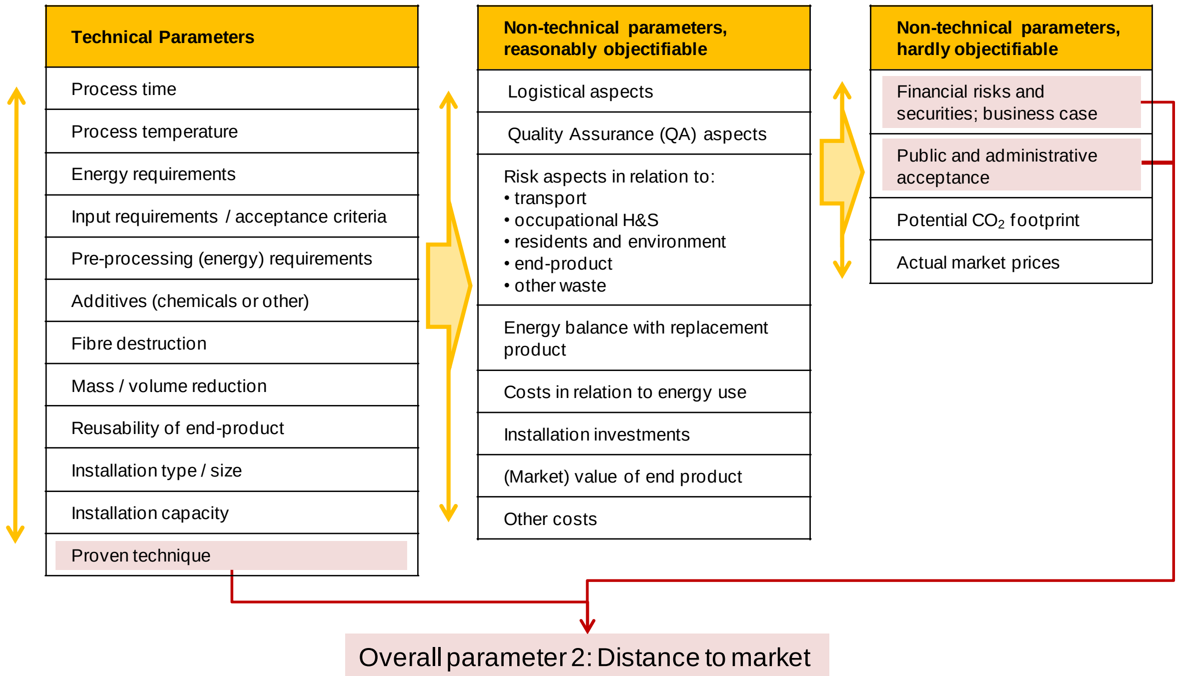
The second overall parameter is coined ‘the distance to market’. This concept refers to the mostly non-technological aspects that determine whether a technology can reasonably be expected to be licensable, marketable and profitable.

The 'distance to market' of a specific asbestos waste treatment technique is determined qualitatively on the basis of several parameters:

1. The parameter 'proven technique'; in the end only proven techniques are marketable.
2. The parameter 'financial risks and securities / business case'; an operational earning model and investor confidence is crucial.
3. The parameter 'public acceptance', which signals the cooperation that is to be expected from local and other authorities ('legal license') as well as the 'social licence to operate' granted by the wider audience.

Figure 6 shows how the overall parameter 'Distance to market' is based on a selection of the basic parameters.

Figure 6: Establishment of overall parameter 2: Distance to market



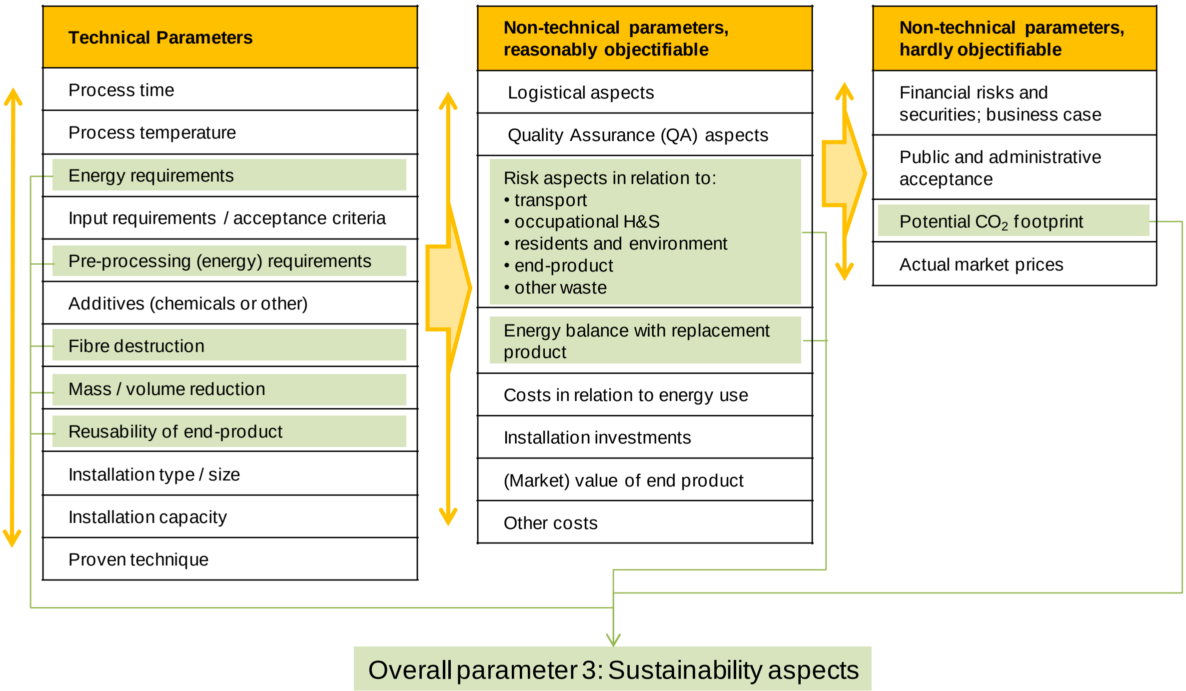
3.5.4 Sustainability aspects

The third overall parameter concerns the sustainability aspects (which is intended to refer to all different characteristics of a technique with an impact on risks, aspects of a circular economy and other health and environment issues).

Several parameters are relevant for these 'sustainability aspects'. They are: fibre destruction, reusability of end-product, energy requirements and balance, mass/volume reduction, potential CO_2 footprint, and a number of different risk aspects (in relation to transport, occupational H&S, residents and environment, end-product and other waste).

Figure 7 shows how the overall parameter 'Sustainability aspects' is based on these basic parameters.

Figure 7: Establishment of overall parameter 3: Sustainability aspects



3.5.5 *Area of application*

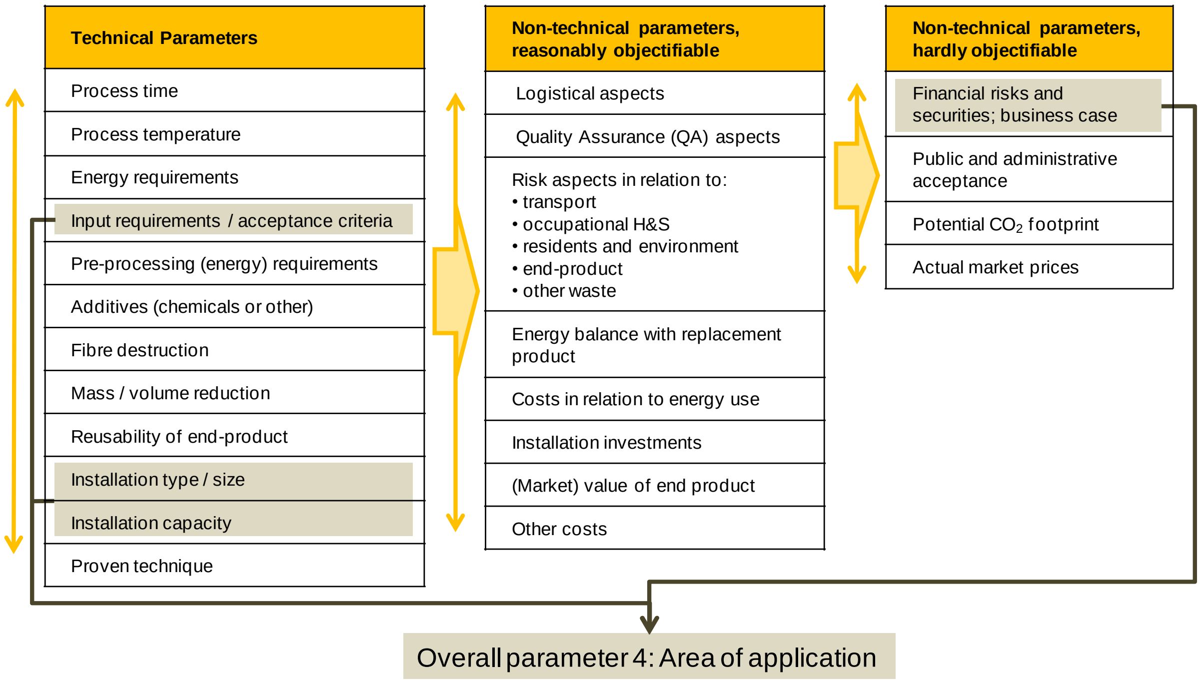
The fourth and last overarching parameter concerns the area of application. This parameter indicates for what types of ACW a particular technique is most applicable or profitable.

For this, the following parameters and questions are relevant:

- Input requirements / acceptance criteria (what types of ACW can be treated by the technique?)
- Installation type and size (where – central or local? – and how can the ACW be treated?); and
- Financial risks and securities / business case (what aspects of ACW treatment constitute a viable earning model?).

Figure 8 shows how the overall parameter ‘Area of application’ is based on these basic parameters.

Figure 8: Establishment of overall parameter 4: Area of application



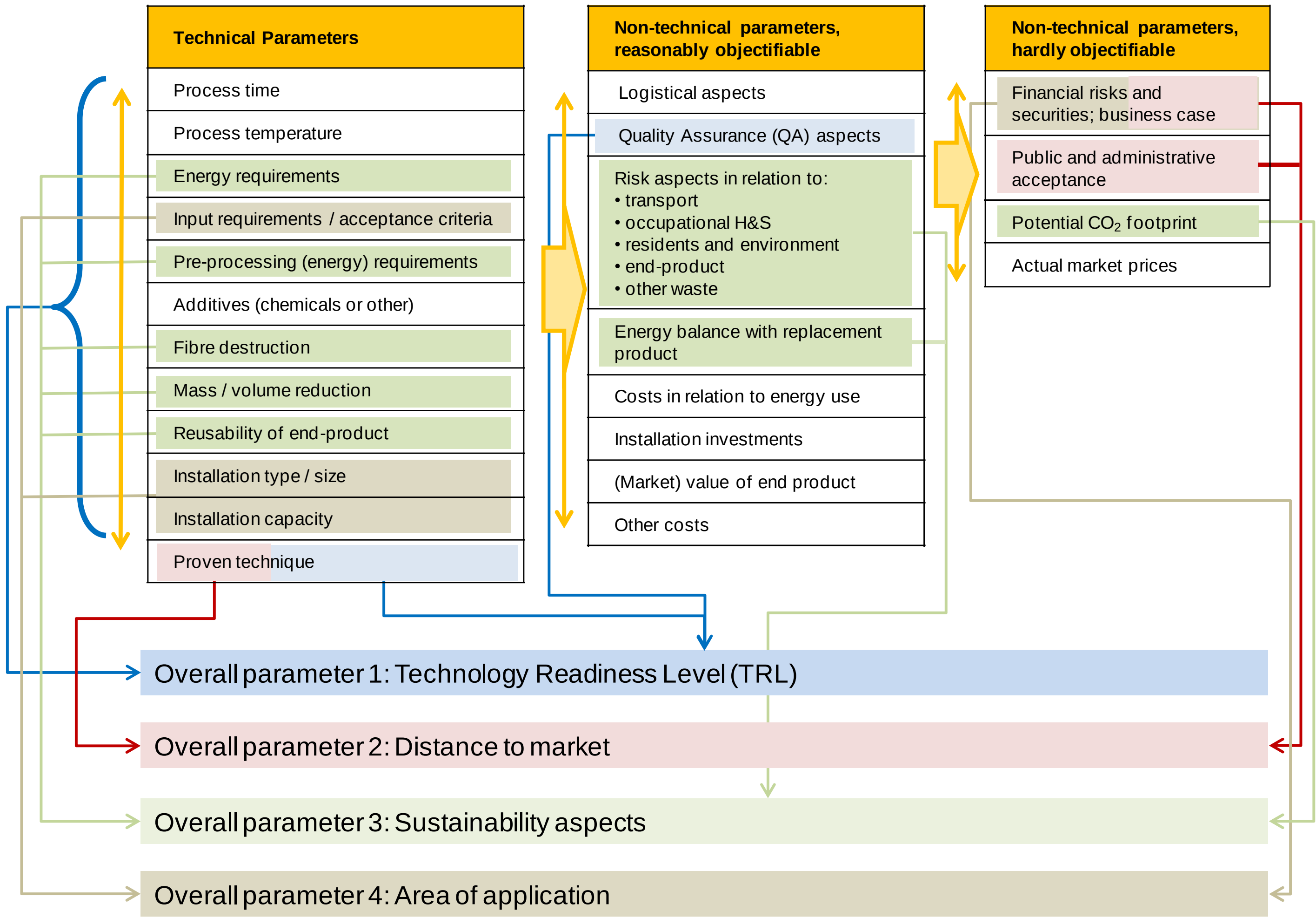
3.6 The assessment model

With these sets of basic parameters and overarching parameters the assessment model is presented. Figure 9 presents the overall model.

Figure 9 shows that most basic parameters directly feed the four overarching parameters. Notwithstanding their evident relevance, some basic parameters only feed indirectly into the overarching parameters. This is because their relevance is in fact expressed via/through other basic parameters. As can be seen in figure 9, this is the case for:

– Process time and process temperature: their relevance is expressed in the process's energy requirement.
– Additives (chemical or other): their relevance is expressed in QA and risks aspects.
– The logistical aspects of the process: their relevance is expressed in the QA and risk aspects.
– The different costs of the process and the market value of the product; their relevance is expressed in the financial risks and securities and in the business case, as well as in the actual market prices.

Figure 9: Overall assessment model



Based on these basic and overall parameters, in the next chapters the actual assessment of the different techniques will be performed and described.

4. Assessment of asbestos waste treatment techniques – reference

4.1 Introduction

For the actual assessment of the different techniques all data from literature and interviews were gathered and ordered to the basic parameters that were presented in the previous chapter. The resulting descriptions (in tables that were coined 'analysis sheets') are included in Annex 1 of this report.

These analysis sheets in turn formed the basis for an assessment of the techniques where use was made of the four overarching parameters. In this and the following chapters the outcomes of these assessments are presented. Every chapter addresses a specific class of techniques (as they were distinguished in chapter 2 of this report), starting – in the present chapter – with landfill as the reference.

In case within the different classes there are more than one specific technology, they are discussed separately within the chapters and paragraphs themselves.

4.2 Assessment of the reference scenario: ACW landfill

As was already mentioned in paragraph 2.2, ACW landfill is only included for reference and benchmark purposes. The root cause of this study – the drives to make the Netherlands a circular economy by 2050 and to prevent risks from being passed on to future generations – render ACW landfill an unwanted option.

4.3 Technology readiness level ACW landfill

ACW landfill clearly is a fully proven 'technique'. It has been practiced for several decades in the Netherlands. The quality assurance aspects are under control, although there may be some doubts about quality assurance aspects in the very long run (decades and centuries from now). On the technology readiness scale ACW landfill scores at the highest level: 9.

In conclusion:
TRL ACW landfill = 9

4.4 Distance to market ACW landfill

Given the fact that ACW landfill is on the market for several decades now, its distance to market is zero. In the Netherlands the actual gate fees (ranging from 55 to 130 €/ton depending on regional authorities (average 90 €/ton) (plus € 13/ton taxes)) and the present legal conditions, allow for a steady business case to operate and maintain ACW landfill practices and to build up funds for everlasting control and protection activities.[23] There are, with a few exceptions, hardly any signals indicating lack of public acceptance.

[23] See: *Nazorgregeling Wet Milieubeheer* and the RINAS calculation model (http://www.nazorgstortplaatsen.nl/Default.aspx).

In conclusion:
The distance to market of ACW landfill is zero.

4.5 Sustainability aspects ACW landfill

From a sustainability point of view ACW landfill has stronger and weaker points. Its strong points are: the marginal amount of energy that is required for the landfill activity as such and consequentially the small (potential) CO_2 footprint; the easy logistics and well-tried and tested control of risks for man and environment; the opportunity to earmark 'full' landfill sites as 'safe' landscapes (in which the ACW is a kind of 'filler'), to be used for specific purposes.[24]
Negative points are: the remaining intrinsic risks of the landfilled asbestos that are passed on to future generations; no mass/volume reduction, hence no reduction of space for landfill; the need for continuous control and protection of the site.

In conclusion:
The sustainability aspects of ACW landfill:
- (+): marginal energy use and small CO_2 footprint; control of logistics and risks; use of ACW as a filler for 'safe' landscapes
- (-): unreduced use of space, remaining intrinsic risks of asbestos as well as need for ongoing control and protection of site passed on to future generations

4.6 Area of application ACW landfill

Dutch landfill sites (with the appropriate licences) accept all types of ACW, indiscriminate of the actual asbestos mass percentage in the waste stream and the other waste items that have come along in the removal process. The already permitted capacity for landfill sites exceeds the required space for the full amount of asbestos cement roofings and pipes waste that may have to be dumped in the years to come.[25]

In conclusion:
The area of application of ACW landfill is: all ACW.

[24] Examples are known where these landscapes are used for sports and leisure activities and for the placement of specific types of buildings.
[25] According to the report *Afvalverwerking in Nederland, gegevens 2016* ('Waste treatment in the Netherlands, data 2016') the total remaining landfill capacity per 31-12-2016 was 34,3 million m^3, next to 8,3 million m^3 planned/permitted capacity that is yet to be realised.

5. Assessment of thermal asbestos waste treatment techniques

5.1 Technology readiness level thermal ACW treatment techniques

Thermal asbestos waste treatment techniques have been applied on industrial scale in several countries.

Well-known is the plasma-torch ***vitrification*** installation of Inertam of the Europlasma group at Morcenx, France, that has been functioning since 1999.[26] Vitrification by means of Joule-heating (which is a thermal process involving the use of high power currents made to flow through the material to be melted (Dellisanti et al., 2009)) has been done on large scale in Japan (Spasiano et al., 2017). Vitrification with an electrical furnace has been called 'best demonstrated available technology' by the US EPA (OVAM (a), 2016).

There have been ***thermal denaturation*** installations in Germany (e.g. in Hockenheim (Boeren et al., 2004), in the United Kingdom (LLW Respository Ltd, 2016) and elsewhere (OVAM (a), 2016)). The LLW study considers 'asbestos incineration' (2 hours at 1100 – 1250 °C) as a mature technique with TRL 9.
In the Netherlands, a series of initiatives to build an asbestos thermal denaturation installation has been undertaken, in which several studies have underpinned the effectiveness and the required process parameters of the thermal denaturation technique (Infestos / Twee "R" interview; see Appendix report).

An initiative in the Netherlands for ***recycling asbestos containing steel scrap in steel melting furnaces*** has been supported by several studies that demonstrate the technology's effectiveness in destroying asbestos fibres (Purified Metal Company interview (see Appendix report) and references). This in turn has led to concrete investment plans for an installation (expected to be operational in 2020).[27]

Thermo-chemical treatment has been developed into a patented process (TCCT: thermo-chemical conversion technology). Test runs of several days took place in the USA, most recent in 2002 and 2007 (ARI Technologies Inc., 2007), followed by some business activities of candidate licensees in Ireland, Japan, Australia and the Netherlands.
In the Netherlands a new initiative is developed, based on a combination of TCCT and DTO (Dynamic Thermal Oxidation – of energy rich waste streams) and/or P2F (plastic to fuel – pyrolysis of non-recyclable plastics); the latter two techniques are expected to provide a substantial part of the energy consumption of TCCT (AM&P-Groep interview; see Appendix report).

There are ***other thermal techniques*** that have proved effective on lab scale, but that don't seem to be upscaled. This seems for instance to be the case for the technique of ceramitization (the CORDIAM process; Abruzzese et al., 1998).

[26] See: http://www.inertam.com
[27] See http://www.purifiedmetal.com

For thermal denaturation by microwave the impression is somewhat confusing; several references point at effective asbestos debris destruction by mobile microwave installations in Japan after the Tohoku earthquake in 2011 (e.g. Kashimura et al., 2015). However, no instances of replication are known and new studies (on MTT: Microwave Thermal Treatment) still appear to be on pilot scale (Parosa, 2017).
Other new thermal treatment concepts, like Laser induced rapid melting (Fujishige et al., 2014) and SHS (self-propagating high temperature synthesis (Gaggero et al., 2016)) are still in an embryonic state or are in the process of gradual upscaling.

In conclusion the Technology Readiness Levels of the different thermal techniques are:
TRL vitrification = 9
TRL thermal denaturation = 9
TRL thermal denaturation with microwave = 5 (or 7)
TRL recycling asbestos containing steel scrap in steel melting furnaces = 8
TRL thermo-chemical treatment = 7
TRL thermo-chemical conversion and DTO/P2F = 7
TRL ceramitization = 4
TRL SHS (self-propagating high temperature synthesis) = 5
TRL laser induced rapid melting = 3

5.2 Distance to market thermal ACW treatment techniques

Notwithstanding their technological readiness, up till now none of these thermal techniques have entered the Dutch market. There is still some distance to (this) market, which is mostly due to non-technical factors. The main one of these factors concerns the often somewhat difficult business case under Dutch market conditions for thermal treatment of asbestos waste. Generally speaking, these thermal techniques are costly, due to the types of (medium or large scale) installations that are required and the high amount of energy that is needed for fibre destruction (typically somewhere between 500 and 1.500 kWh/ton). Given these costs, thermal techniques in general cannot be applied profitably in a situation (in the Netherlands) in which ACM is accepted at landfill sites for gate fees in the order of 55 to 130 €/ton.

From 2017 onwards the Dutch National Waste Plan 3 (LAP3) has come into effect. Interestingly, LAP3 has a provision that if an alternative treatment technique is available, under certain conditions[28] a landfill ban for asbestos can come into effect. One of these conditions is that treatment of asbestos waste can be done at a maximum gate fee of 205 €/ton.

A gate fee of 205 €/ton will not lead to a viable business case for ***vitrification*** with its high energy requirements. E.g.: in France Inertam charges 1.000–2.500 €/ton (average price: 1.500 €/ton) (OVAM (a), 2016). So, the distance to the Dutch market for vitrification is still substantial.

[28] These conditions for the treatment techniques are: (1) smaller environmental footprint or reduced risks / improved public health; (2) there is a market for the end-product; (3) costs for the disposer do not exceed 205 €/ton; (4) the technique is functioning properly, can deal with 75% of the total waste supply and a plan is at hand to deal with 100% of the waste within two years.

For ***thermal denaturation***, however, the situation could be different. According to the Dutch patent holders, a viable business model is possible for this price (Interview Infestos / Twee "R"; see Appendix report), since the thermal denaturation operates at lower temperatures (1.000 °C) and therefore at lower costs. But there are other non-technical issues that still act as barriers for this technique to enter the Dutch market. They include:

- The nature of the technology, combined with the LAP3 requirement before a landfill ban can be proclaimed, that from the start 75% of the supply must be treated, calls for an installation of high capacity (100.000 ton/year). For investors to be willing to invest in an installation of this size, several securities must be in place.
- One of these securities concerns the availability of a stable supply of ACM (of a controlled quality), including sites for temporary storage (buffers; possibly at the landfill sites) and a functioning (and guaranteed) logistic chain from disposer via waste disposal sites to the treatment site.
- Another security concerns the acceptance (by the market and the authorities) of the end-product ('beststof') as a harmless substance that can be traded, exported and processed.
- According to the patent holders, several of these requirements (requirements that are mentioned by the patent holders are: separate collection of asbestos cement waste from other asbestos waste streams at source, the logistic chain, the role of waste disposal sites, the proclamation and enforcement of a landfill ban) can only be met through the active intervention of the authorities (which hasn't happened so far).

These non-technical issues lead to a situation in which there still is a little, but difficult to overcome distance to the Dutch market for thermal denaturation of asbestos waste.

For the technique of ***recycling asbestos containing steel scrap in steel melting furnaces,*** the main element of the business case lies in the recycling of asbestos containing steel scrap to asbestos-free homogeneous steel scrap in batches of circa 20 ton of known composition. The market value of this end-product makes the treatment already profitable under present market conditions (i.e. with a gate fee competitive to the one charged at landfill sites) (Interview Purified Metal Company; see Appendix report).
The initiators stress that also in this case investors require several securities. They include the security of a properly functioning installation, of feedstock, of a market for end-products, of a gate fee and of contractual and other legal conditions.
Having met these requirements, the initiators expect to have a fully operational installation running in one to two years (around 2020).

Experiences with former application of these techniques show the importance of public and administrative acceptance, which in turn appears to depend on risk perceptions and trust in quality assurance. Lack of transparent quality assurance (and the inspection thereof) at the thermal denaturation installation in Hockenheim, Germany, was one such learning experience.[29] Public opposition to experiments with asbestos destruction in steel melting furnaces in the Netherlands was another.[30]

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[29] See: https://www.baden-wuerttemberg.de/de/service/presse/pressemitteilung/pid/asbestentsorgung-in-hockenheim-abgeschlossen/
[30] See: https://www.rijnmond.nl/nieuws/122292/Asbestproeven-Nedstaal-gaan-definitief-niet-door

For ***thermo-chemical treatment*** to enter the Dutch market, there are still some tests to be done to ensure the guaranteed fibre destruction and the reusability of the end-product, especially as a clay substitute in the ceramic industry (e.g. for the production of bricks). Calculations – based on an installation with a processing capacity of 80 tons ACW/day – have shown viable business cases, both for ACW treatment with TCCT (gate fee of € 175,-) and for the TCCT-DTO/P2F-combination (gate fee of € 135,-) (including the gate fee for the energy rich 'sorter residue'). The latter figure indicates the 'balancing' effect of using the energy that results from burning energy rich waste streams. Both business cases are built on higher gate fees than the present gate fee for landfill, as well as on the availability of adequate storage capacity to ensure the regulated supply of ACW that the process requires.

In conclusion:
The distance to market for thermal techniques is largely dependent on non-technical factors.

- For vitrification the distance to market is big; even the maximum gate fee that would allow for a landfill ban to come into place, could probably not cover the high costs of the application of the technique.
- For thermal denaturation the distance to market is small but not easy to overcome; next to the possibility of a higher gate fee (made possible by a landfill ban), several requirements still have to be met concerning a guaranteed and steady flow of feedstock of the right quality, and acceptance by the market and the authorities of the resulting end-product.
- For recycling asbestos containing steel scrap in steel melting furnaces the distance to market is very small. As it seems, there is a proven technology and a solid business case, and no signs of lack of public and administrative acceptance at the presently designated location.
- For thermo-chemical treatment the distance to market is rather small, albeit a little bigger than for thermal denaturation. A definitive proof of operation and of the quality of the end-product is still required. Once this has been obtained, investment planning can start, for which, however, the possibility of higher gate fees (made possible by a landfill ban) and a steady flow of feedstock are essential requirements as well.

5.3 Sustainability aspects thermal ACW treatment techniques

An important positive sustainability aspect of thermal treatment of asbestos is that with the proper temperatures and processing time, complete fibre destruction is guaranteed, following elementary laws of physical chemistry. This process can be controlled and monitored on the basis of a few clear parameters (like core temperature and time), which allows for rather robust Quality Assurance (and easy inspection). Monitoring of the end-product (certification) will always remain necessary.

On the other hand, the relatively high amount of energy needed for thermal destruction of asbestos (in the order of 500 to 1.500 kWh/ton) makes for an important other pressing sustainability aspect: thermal techniques have a potentially large CO_2 footprint.

The latter picture may look somewhat different, however, if in the equation an ‘energy balance’ is included of the products of the process versus the products they replace. This hardly makes a difference where the end-product is an inert filler, like with vitrification. A case can be (and is) made when it comes to end-products that can replace clay, active fillers (in granulates) or even cement, since the production of such clay, fillers or cement itself also requires serious amounts of energy. The most serious claim for an energy balance that evens out the CO_2 footprint of the thermal treatment, however, concerns the recycling of asbestos containing steel scrap in steel melting furnaces. Indeed, almost all energy is used for the melting of steel, and this amount of energy more or less equals the amount that is used to recycle steel from steel scrap without asbestos (or to produce new steel from ore). The asbestos destruction almost occurs as a ‘side effect’ that hardly takes any energy itself.

An interesting variant of this ‘energy balancing’ approach can be found in the initiative in which thermo-chemical treatment of asbestos is combined with techniques to obtain fuel from non-recyclable plastics (‘P2F’) and to use energy from burning energy rich waste streams (‘DTO’). However, this combination of techniques drives up the number of process parameters that must be controlled (which is a risk-element).

Next to the ‘energy balance’, the circular use of asbestos waste is a positive sustainability aspect in itself. The same holds true for the prevention of risks as a result of fibre destruction. On the other hand there is some additional risk for occupational health and safety and for the environment (as compared to landfill), as a consequence of the extra[31] handling and logistics that these techniques require, like (pre-) separation of asbestos waste at source or at the plant, size reduction, shredding and grinding.
The advantage, from a sustainability point of view, of thermal denaturation over the other thermal techniques, is that for thermal denaturation no size reduction and grinding have to take place (interview Infestos / Twee “R”; see Appendix report). The ACW goes straight into the oven without further ado, and what comes out is a harmless substance.

All thermal treatment installation produce exhaust gases that must be treated by an after-burner, cooled down and led through a HEPA filter before the cleaned gases can be emitted. Treatment of less homogeneous asbestos containing waste streams will require a more elaborate flue gas cleaning installation.

In conclusion:
When it comes to the sustainability aspects of the different thermal techniques, the following can be said.
- (+) In general, they effect complete fibre destruction and result in mass and volume reduction.
- (+) The quality and effectiveness of the process can be controlled, monitored and inspected robustly on the basis of a few clear process parameters. Monitoring of the end-product will always remain necessary.
- (-) In general, thermal techniques have a potentially large CO_2 footprint (energy use in the order of 500 to 1.500 kWh/ton).

[31] As compared to the ACW landfill reference.

- (+) The CO_2 footprint is partially compensated by the use of the end-product (in the case of thermo-chemical treatment) as substitute for clay, or (in the case of thermal denaturation) to substitute active fillers or cement (the production of which also requires energy), and is largely compensated when the end-product is steel scrap (where the recycling of steel without asbestos in fact requires just as much of energy).
- (+) The CO_2 footprint can also be somewhat compensated (as in the case of the Dutch proposal for thermo-chemical treatment) by using the energy obtained from burning energy rich waste as part of the required energy for the destruction of asbestos.
- (-) The extra handling and logistics that are required for thermal treatment (like (pre-) separation of ACM waste streams, size reduction, shredding, grinding) require extra energy and produce some additional risks for occupational health and safety and the environment. This is to a lesser extent the case for thermal denaturation, where no pre-processing is required.
- (-) Due to the size and capacity of the installations, there will be room for one or at the most a few of them in the Netherlands, which implies that the asbestos-containing waste has to be transported to these installations (extra transport when compared to regional landfill).
- (-) All thermal techniques produce exhaust gases that must be treated and controlled before emission to the environment.

5.4 Area of application thermal ACW treatment techniques

From a technical point of view, thermal techniques are suitable to treat any type of ACW. At the temperatures at which asbestos fibres are destroyed, all other waste products generated by asbestos removal companies decompose as well.
From an economical point of view, however, most thermal techniques require specific types of ACM in order to have a viable business case.
Vitrification is most of all a suitable technique to treat highly problematic (toxic, radio-active) ACM, that justifies the high costs of the treatment.
The technique of ***thermal denaturation*** is mostly suited for the treatment of a constant and homogeneous stream of ACM, e.g. asbestos cement roofings or pipes, for optimum control of the process control and of the composition of the end-product, since this end-product needs to be certified for reuse.
The process of ***recycling asbestos containing steel scrap*** in steel melting furnaces requires a substantial percentage of steel scrap in the waste stream to get enough yield from the process (the non-‘steel scrap’ part of the waste ends up in slags that have hardly any economic value).
With ***Thermo-chemical treatment*** (combined with the DTO and P2F techniques) all types of ACM can be treated, but preferably no asbestos containing soil and no metals. The combined techniques are particularly suitable for ACW with high-energy waste, for instance asbestos containing floor cover and floor tiles.

In conclusion:
The areas of application of thermal techniques are:
- For vitrification: highly problematic (toxic, radio-active) ACM
- For thermal denaturation: a constant and homogeneous stream of ACM, e.g. asbestos cement (corrugated) sheets or pipes

– For recycling asbestos containing steel scrap in steel melting furnaces: asbestos containing steel scrap
– Thermo-chemical treatment (combined with the DTO and P2F techniques): all ACM except soil; preferably ACW with high-energy waste (and preferably no metals)

6. Assessment of chemical asbestos waste treatment techniques

6.1 Technology readiness level chemical ACW treatment techniques

There are several processes described for the chemical destruction of asbestos. Earlier attempts on a pilot scale to decompose asbestos in an **alkaline environment** have not been very successful (such as the (patented) TreSeNeRie process (OVAM (a) 2016)). Though the chemical structure of asbestos will be destroyed by strong alkaline solution, all kinds of technical problems were encountered during the pilot tests due to the aggressive alkaline solution in combination with high temperature and elevated pressure. Also, the process needs a high liquid-solid ratio. Thus, a significant amount of NaOH is needed for an industrial scale installation, with associated economic consequences. This was an important reason to stop the further development of the process. Therefore the TRL of a process based on alkaline destruction is low.

Better prospects provides the **acid destruction** of asbestos fibres, especially when waste strong acids from chemical industry can be used. In most of the described processes hydrochloric acid (HCl) is used, but sulphuric acid (H_2SO_4), phosphoric acid (H_3PO_4) or nitric acid (HNO_3) are used as well in several processes. Pawelczyk (Pawelczyk et al., 2017) and Trefler (Trefler et al., 2004) describe a process with phosphoric acid in which the end-product, a mixture of several phosphates, can be used as a fertilizer. Fluoric acid (HF) can be used (Sugama et al., 1998) and has the additional effect of attacking the Si bonds (amphibole destruction). Gaseous SiF_4 (corrosive and toxic) will be one of the reaction products.

In the Netherlands several chemical industries produce major amounts of waste acid. Neutralisation and subsequent discharge into the surface water is the common procedure. Therefore, the use of waste acid for asbestos destruction has environmental advantages (interview Deltalinqs; see Appendix report). Pilot test (lab scale) have been carried out which proved that, besides neutralizing the waste acid by the cement in asbestos cement, complete fibre destruction was effected for chrysotile. The process has to be accommodated however for the destruction of amphiboles.
The developers are aware that upscaling of the process to an industrial scale, including the use of other waste streams for the destruction of asbestos, will still cost a lot of effort.

The process requires at least a **medium sized installation** with an estimated capacity of 15.000 – 50.000 tons/year, a buffer amount of asbestos containing material as well as waste acids to be used. Such an installation will not be transportable.

The process can be accommodated in such a way that CO_2 capture is possible as well. Several processes for the sequestration of CO_2 by carbonation are described in literature. Some processes use direct mineral carbonation from the gaseous phase. At natural conditions the CO_2 capture/carbonation process is slow (Bodor et al., 2013; O Conner et al., 2000; Veetil et al., 2014; Trapasso et al., 2012; Yoon and Roh, 2012; Pan et al., 2012; Radvanec et al., 2013).

Weak acids are used in commercial processes as well, such as those based on oxalic acid (Turci et al., 2010, Rozalen and Huertas, 2013). As reported by Rozalen and Huertas, the reaction time for destruction of chrysotile takes about 9 days for oxalic acid and even longer (30 days) for sulphuric acid. This means that oxalic acid also reacts as a chelate for the Mg-ions, which speeds up the transformation reaction. The EcO Insight[32] process (US patent) uses waste organic acids from agro-food industry. Reaction speed can be increased at elevated temperature/pressure conditions. For a complete destruction of the asbestos a temperature of 200 °C and a pressure of 6 bar is needed. As is usual for U.S.A. patented processes, hardly any process details are available. No information about the end-product and the reusability is provided Another process describes the use of whey (Balducci et al., 2012, Alimenta, 2017). This process is based on a double-phase immersion of asbestos cement products in the acid by-products (whey) of cheese making processes. The first phase makes the cement soluble, while the second one, at 180°C, is supposed to completely destroy the asbestos fibres.

The complete degradation of amphibole asbestos (for all acid processes), chelating additives as citric acid, oxalic acid or EDTA are needed. As long as complete degradation is not thoroughly proved, the TRL for the technique for the destruction of amphibole fibres is regarded as low.

A general disadvantage of chemical methods is that the end-product must be neutralized and, if possible, converted into a **reusable end-product**. If this is not possible, this will lower the TRL value.

In conclusion:
TRL strong acids (chrysotile) = 3 - 5
TRL strong acids and chelating additives (amphibole asbestos) = 2 - 4
TRL weak acids = 3 - 5
TRL alkaline process = 2 – 4
TRL carbon capture / mineral carbonation = 2 – 4

6.2 Distance to market chemical ACW treatment techniques

Proven technique: Though several chemical treatment processes have been applied in the past, most of them failed for several reasons, including technical and economic aspects, the limited applicability of the end-product and/or health and safety aspects. However, new approaches of this principle in combination with the detoxification and/or neutralisation of other waste streams and improved technology give prospects for possible solutions to these problems. At the moment the results of recent pilot scale tests are awaited, including tests on the reusability of the end-product and its capability to overcome practical problems, such as the purity of the chemicals used and the capability for complete destruction of amphibole asbestos types. If the pilot phase has been successfully completed the process should be scaled up to a semi industrial size which will be substantial step to decrease the distance to market.

[32] www.eco-insightusa.com

Financial risk and securities, business case: The technical process has to be supported by a parallel process of finding funding, partners in industry. The process needs at least a medium size installation which should be supported by a well-balanced business case (interview Deltalinqs; see Appendix report).

Public and administrative acceptance: Public acceptance will depend strongly on the location that is chosen. If the installation is located close to a an asbestos landfill or chemical plant (industrial area), no major problems are expected. Administrative acceptance will probably require an environmental impact study in which all process, environmental and safety aspects have to be evaluated. This will include the use of chemicals, transport et cetera.

In conclusion: There is still quite a distance to market, given the number of technical and non-technical requirements that still have to be fulfilled:
- The technique is proven for the destruction of chrysotile in asbestos cement on a pilot scale but not yet on an industrial scale, which results in a considerable distance to market.
- Complete destruction of amphiboles has to be proved.
- For acid destruction using waste acids a business case still needs to be established, and the adequate financial support must still be found. Therefore, also from a business-economic point of view there is a considerable distance to market.
- So far there is no indication of lack of public and administrative acceptance.
- The actual planning and construction process, including environmental impact studies and requests for permits, is in its earliest stages.

6.3 Sustainability aspects chemical ACW treatment techniques

Regarding sustainability, chemical treatment has stronger and weaker points. Its strong points are that it can be combined with other waste streams from industry, such as acid waste, alkaline waste or CO_2. This can be advantageous from the points of view of saved disposal costs, low energy consumption (an exothermic process has to be cooled) and environmental benefits. A strong point is the complete fibre destruction of chrysotile. However, far as the other asbestos types are concerned, complete fibre destruction still has to be proved. More in general, a weaker point is that chemical treatment processes have an asymptotic decay of the reaction rate (depending on reactive surfaces and concentration of reactants) and can be subject to disturbances from irregular ACW composition. Also, working with strong acids requires strict health and safety measures; reaction products must be neutralized to obtain a reusable end-product. As described in literature, waste streams from agro industries can be used as well, but the reusability of the end-products raises questions. Reusability of the end-products will also depend on the purity of the chemicals used and the absence of toxic impurities (chemical by-products) in the end-product.

The use of an alkaline process has additional safety risks caused by high pressure, high temperature, high pH and possible corrosion of the pipe linings of the reactor. Therefore, the sustainability is regarded as low.

In conclusion:
The sustainability aspects of chemical treatment are:
(+) low energy use: exothermic process, has to be cooled
(+) complete fibre destruction for chrysotile
(+) combines the detoxification/neutralisation of two or more industrial waste streams
(+) CO_2-capture/carbonation has a beneficial effect on the CO_2 footprint of the process
(+) can be located at or close to industrial plants (no transport of industrial acids);
(-) asymptotic decay of the rate of reaction and risks of process disturbances by irregular ACW composition or supply require strict process control
(-) pre-processing of ACW is required
(-) the reusability of the end-product still has to be proved
(-) occupational health and safety as well as environmental aspects: chemical processes have their intrinsic risks; this is especially the case for alkaline processes (strong alkaline chemicals at elevated temperature and pressure) and processes based on destruction with HF
(-) All acid or alkaline reaction products must first be neutralized to obtain a reusable end-product; the end-product must not be contaminated with toxic (by-) products; for acid destruction of amphiboles chelate forming additives are needed

6.4 Area of application chemical ACW treatment techniques

Chemical destruction of asbestos has only advantages if combined with other waste streams such as waste acids from chemical industry. For process control the asbestos waste should be homogeneous to some extent (e.g. asbestos cement, friable asbestos et cetera). Chemical treatment techniques are not suited for very heterogeneous ACM. Complete destruction of amphiboles, using chelating additives, should be proven. This is especially important for the destruction of asbestos cement products which, besides 10-15% chrysotile, may contain 5-10% crocidolite as well.

In conclusion:
- Chemical treatment can be applied for the denaturation of a homogeneous stream of ACM which contains **chrysotile** asbestos, such as asbestos cement or friable asbestos.
- For the decomposition of **amphiboles** chelating additives are needed. Effective fibre destruction is still to be proved.

7. Assessment of mechanical asbestos waste treatment techniques

7.1 Technology readiness level mechanical ACW treatment techniques

Mechanical asbestos waste treatment (i.e. high energy milling system) has, after laboratory scale trials in 2003 and 2011, been applied on pilot/semi-industrial scale in South Africa (2015 and 2016) and planned in New Zealand (2018) (EDL, 2017).

The tested installation, based on the Mechano-Chemical Destruction technique (MCD), is developed by Environmental Decontamination Europe LTD (EDL), a New Zealand based company (interview with EDL; see Appendix report). The patented MCD technique is a continuous (high energy) ball milling system. The (modular) ball milling system consist of a cascade of milling units (from coarse to ultra-fine fraction) and can in terms of capacity easily be scaled up.

The MCD process has been developed for the destruction of toxic and carcinogenic substances. The process demonstrated its effectiveness during tests held between 2004 and 2012 by destroying a range of organic contaminants in soil (e.g. (persistent) organic contaminants like PCB's, Pesticides and Dioxins) (EDL, 2017).

Treatment of ACM is the next step in the development of the MCD process. The available technical data, quality assurance data and data related to the quality of the end-product (available so far) show a technique that is proven on pilot/semi-industrial scale. The results of full-scale (industrial scale) tests carried out on asbestos containing waste (March 2018), are currently worked out and will give more insight in pre-treatment of ACW, process parameters, emission control, practical data like energy consumption, quality and reusability of the end-product and finally which fine-tuning is needed for market introduction.

The technology ready level of the MCD technique is classified, status from early 2018 with sight on full-scale tests, as TRL 8 – 9.

In conclusion:
TRL Mechano-Chemical Destruction technique (MCD) = 8 – 9

7.2 Distance to market mechanical ACW treatment techniques

Although the ultimate proof for the industrial scale still has to be delivered, the distance to market for the MCD technique is relatively small. A combination of technical and non-technical factors play a role here.

The technique itself is rather mature. Moreover, the process installation is modular and scalable, and has a low to medium capacity (approximately 25.000 tons/year). As a consequence, the installation has a short construction time. Because of the low process temperature and the effectiveness of the process in destroying organic contaminants (including asbestos bags and asbestos contaminated remediation materials) the cleaning of exhaust emissions does not require a large and comprehensive post-treatment installation. On the other hand, the process places high demands on the pre-treatment of the ACM. Firstly, the ACM must be crushed to fragments that are not larger than 10 mm in length and width. Secondly and most importantly, the crushed ACM needs to be dried to less than 1 % (w/w) moisture content, otherwise the high energy milling process will not work efficiently and effectively. This implies a well-designed and controlled pre-treatment process, both for normal process conditions and for breakdown conditions, including maintenance and repair.

On the financial side the risks are relatively small, because of the low capital investments (approximately € 6 million, excluding air emission equipment). Energy consumption is not extremely high. Available data suggest the energy use (including pre-treatment (crushing and drying)) can be estimated at 60 – 70 kWh/ton. A rough estimate of the costs of energy per ton, based on Dutch large consumer electricity tariffs, lies in the order of € 10 per ton.

Given these investment and cost estimates, businesses using this technique are expected to be highly competitive in terms of gate fees to most other treatment techniques (excluding landfill).
There are no indications of lack of administrative or public acceptance.

In conclusion:
The distance to market of the mechanical treatment technique (MCD process) is relatively small. The technique is proven on a pilot/semi-industrial scale and has also proved to be effective for other (organic) contaminants.
Before market introduction the proof on industrial scale still has to be delivered. The pre-treatments demands are strict (dimensions of crushed ACM and moisture content). On the other hand, the installation has a short construction time.
Because of the relatively low capital investments and relatively low energy consumption, a positive business case is expected. The technique can probably be operated profitably for a gate fee that is considerably lower than the maximum gate fee mentioned in LAP3 (€ 205 per ton).

7.3 Sustainability aspects mechanical ACW treatment techniques

The positive sustainability aspects of mechanical treatment of ACM are its simplicity and robustness (simple quality assurance: dimensions and moisture content of the influx and process time (residence time in the process reactors)), the complete fibre destruction that is realised and the reusability of the end-product (which is yet to be proved on industrial scale). Facilities for cleaning of the exhaust dust and gasses and other environmental control techniques (possibly also including noise) are relatively simple, also because the process takes place, as much as possible, in a closed system.

The relative low energy consumption (and potential CO_2 footprint) of the milling process (including the pre-treatment, i.e. crushing and drying) is another strong point. Because of reusability of the end-product, energy is saved for winning and producing raw materials like cement and fillers in the conventional way.

Because of the modularity of the MCD treatment installation, a complete system fits into one or more standard sea container(s). This means the installation is easily transportable, also close to the source of ACM, which has positive consequences for the amount of ACM transport kilometres (and consequent risks).

A weaker point concerns the (potential) occupational health and safety and environmental risks of the pre-treatment handling (i.e. crushing and milling) of the ACM before fibre destruction has taken place. To a lesser extent this is also the case for the handling of the ultra-fine end-product after the destruction has taken place. Strict containment and control measures are required here.

In conclusion:
The sustainability aspects of mechanical treatment are:
(+) The simplicity and robustness of the process (less quality control parameters), complete fibre destruction, reusability of the end-product (cement/filler), the relatively low energy consumption for the treatment process, the relatively simple environmental control techniques and the modularity/mobility of the installation (less transport kilometres for ACM).
(-): The process requires drying, which takes 25% of the total energy consumption of the treatment process; also, measures will have to be taken to safeguard the process from the health and safety and environmental risks of handling the ACM and ultra-fine end-product.

7.4 Area of application mechanical ACW treatment techniques

Although the mechanical treatment technique (MCD process) can destruct all types of ACM and even toxic and carcinogenic substances, a homogeneous feed of asbestos cement will make the process more controllable and produce a qualitatively better and certifiable end-product.

In conclusion:
The preferred area of application of mechanical ACW treatment techniques is a homogeneous stream of asbestos cement.

8. Assessment of biological asbestos waste treatment techniques

8.1 Technology readiness level biological ACW treatment techniques

The principle of biological degradation of asbestos by fungi (and/or lichens and bacteria) was described first in 2003 by Torino University, Italy. Certain types of fungi were found ‘eating’ on naturally occurring serpentine minerals. Based on this principle several research groups carried out successful lab test as well as pilot scale tests on biological degradation (interview Arcadis, interview Deltares; see Appendix report). Interesting results were presented, especially on the remediation of soils contaminated with chrysotile fibres. For the destruction of amphibole asbestos types research is going on. Most promising is the in situ degradation of asbestos in soil using certain types of fungi. Pilot tests on asbestos contaminated sites have been carried out in 2017 and will be upscaled to “real life” contaminated sites in 2018 (interview Arcadis). In fact the same biological degradation process can be applied to asbestos cement or other ACM, but this requires pre-treatment, special designed bio-reactor vessels and optimum conditions. Lab experiments have been successful and pilot tests will be carried out during 2018 (interview Deltares).

It is to be expected that the reaction speed for biological degradation will decrease asymptotically, caused by several factors such as the availability of free fibre surface, availability of fungi et cetera. Therefore the completeness of **destruction of the asbestos fibre structure** must be controlled using state of the art analytical techniques. Though complete destruction of chrysotile fibres has been proved in pilot tests, there are still uncertainties about the effectiveness when the method is used on contaminated sites in real life.

In conclusion:
TRL biological treatment of asbestos in soil (free fibres in situ) = 5 – 6
TRL biological treatment of asbestos cement and other ACM (in bioreactor) = 1 – 3

8.2 Distance to market biological ACW treatment techniques

Important advantages of biological in situ remediation of asbestos contaminated soil are: low investment costs, no complicated pre-treatments required. Another important advantage is a great saving on the remediation costs. Complete excavation of the soil, with far-reaching consequences for the environment, can be avoided. There are some input requirements, though, since at this moment the effectiveness of the process is only proved for free chrysotile fibres (not in matrix). The biological process is slow which means that the contaminated site cannot be used and requires site management for a longer period. The biological degradation of asbestos in soil is a complex mechanism which is influenced by fungi, bacteria, soil type and other local conditions and the progress of the remediation process must be monitored periodically using state of the art analytical techniques.[33] In

[33] Interestingly, when using these analytical techniques on older existing asbestos contaminated sites, situations were encountered where biological asbestos degradation had already been taking place for years, sometimes even up to the point that no unaffected fibres were found.

spite of these complicating factors the distance to market is regarded as relatively small because the impact will be very low ('doesn't hurt to try')
Regarding the low TRL for biological treatment of asbestos cement products the distance to market is big. The impact of biological processes on the environment is expected to be low which can be a promoting factor for **public acceptance**.

In conclusion:
(+) Method can be used at semi industrial scale for the remediation of chrysotile asbestos fibres in soil at low cost; it will generate hardly any disturbance of the environment, which can be an advantage for public acceptance
(+) Investment costs are low and expensive traditional excavation can be prevented
(-) Completeness of asbestos fibre destruction is not yet proven in real life situations
(-) The biological remediation is slow

8.3 Sustainability aspects biological ACW treatment techniques

For asbestos fibres in soil additional risks from biological treatment are expected to be manageable and controllable by the selection of 'safe' fungi and bacteria. This is an important aspect in current laboratory research.The energy consumption for biological degradation in situ will be low, but the process takes time which requires management and protection of the site during treatment. The final result has to be "asbestos free" soil. It is to be expected that the reaction speed for biological degradation will decrease exponentially caused by several factors such as the availability of free fibre surface, availability of fungi et cetera. Therefore the completeness of **destruction of the asbestos fibre structure** must be controlled by adequate standardized analytical methods. The complete process should be monitored carefully (validation, QA-system, proof of clean soil).

For the biological degradation of asbestos cement bio reactors are needed. asbestos containing sheets must be transported and crushed to optimum size.

In conclusion:
(+) low energy consumption, process in situ; CO_2 footprint is expected to be low.
(+) no transport is required for remediation of asbestos in soil
(-): process for in situ remediation is sustainable but slow (month/years) which requires management/protection of the site during treatment.
(-) the asymptotical decrease in reaction speed requires careful control on completeness of asbestos fibre destruction
(-) standard analytical procedures should be optimized for the analysis of complex transition states of the asbestos degradation process.
(-) for asbestos cement and other ACM, bio reactors, transport and pre-treatment (crushing et cetera) is needed.

8.4 Area of application biological ACW treatment techniques

The most ready to use application is the biological decomposition of (chrysotile) asbestos fibres in soil. This process will probably work as well for asbestos cement and other ACM, but this will have some practical disadvantages such as required pre-treatments, low capacity, long process time.

The process is not suited for landfill sites were the mixed asbestos waste is buried in plastic bags, because the fungi and nutrition cannot reach the surface of the asbestos containing materials.

In conclusion:

- The biological degradation technique is mostly applicable for in situ cleaning **(chrysotile) asbestos contaminated soil**.
- Biological degradation of **asbestos cement products** or other ACM might be possible in the future but still requires much research.
- Biological degradation cannot be applied on mixed ACW buried in plastic bags on traditional landfill sites.

9. Summarizing overview of the assessment

9.1 Introduction

In this chapter the assessment of the different techniques is presented in overview tables and is discussed. When, in the course of this chapter, more scores on assessment criteria have been presented, also some attention is given to the growing overall picture. The final overall picture will be discussed in the next, concluding chapter.

9.2 Technology readiness levels

All techniques for asbestos waste treatment have been scored on the 9-points technology readiness (or TRL) scale (as described in paragraph 3.5.2). The resulting TRL's are summarised in Table 4.

Table 4. Overview TRL's

Technique	Technology readiness level (TRL)
Landfill (reference)	TRL landfill = 9
Thermal treatment	
– Vitrification	TRL vitrification = 9
– Thermal denaturation	TRL thermal denaturation = 9
– Thermal denaturation with microwave	TRL thermal denaturation with microwave = 5 or 7
– Recycling asbestos containing steel scrap in steel melting furnaces	TRL recycling asbestos containing steel scrap in steel melting furnaces = 8
– Thermo-chemical treatment	TRL thermo-chemical treatment = 7
– Ceramitization	TRL ceramitization = 4
– SHS (Self-propagating High temperature Synthesis)	TRL SHS =5
– Laser induced rapid melting	TRL laser induced rapid melting = 3
Chemical treatment	
– Treatment with strong acids	TRL treatment with strong acids = 3 to 5
– Treatment with strong acids and chelating additives (amphibole asbestos)	TRL treatment with strong acids and chelating additives (amphibole asbestos) = 2 to 4
– Treatment with weak acids	TRL treatment with weak acids = 3 to 5
– Alkaline process	TRL alkaline process = 2 to 4
– CO_2 carbon capture/mineral carbonation	TRL CO_2 carbon capture/mineral carbonation = 2 - 4
Mechanical treatment	
– Mechano-chemical treatment	TRL mechano-chemical treatment = 8 to 9
Biological treatment	
– Biological treatment of asbestos in soil	TRL biological treatment of asbestos in soil, in situ = 5 to 6
– Biological treatment of asbestos cement and other ACM	TRL biological treatment of asbestos cement and other ACM (in bioreactor) = 1 to 3

Several techniques can be considered technologically mature. This is particularly the case for a number of thermal treatment techniques. *Vitrification* and *thermal denaturation* techniques have already been operational on an industrial scale. All elements of the technique for *recycling asbestos containing steel scrap in steel melting furnaces* have been functioning on industrial or semi-industrial scale; the only last step is to have these techniques function in one integrated installation. Finally, the technique for *thermo-chemical treatment* will be going through a final test phase, after which it can be scaled up to industrial level. Other thermal techniques are in a lower developmental phase.

Another mature technique is the *mechano-chemical treatment*. The technique has been proven for the destruction of POP's and Dioxins and has proved effective for the treatment of ACW on a pilot/semi-industrial scale.

The mechanisms for the destruction of asbestos by chemical and by biological treatments are known for a longer time already. Still the different techniques based on these mechanisms have only reached pilot stages. New development activities in the Netherlands show possible new avenues, but require more tests and pilots before techniques can become operational.

9.3 Distances to market

The summarising overview of distances to market of the assessed techniques is presented in table 5.

Table 5. Overview distances to market

Technique	Distance to market	
	Distance	**Explanation**
Landfill (reference)	None	Steady business case, accepted
Thermal treatment		
– Vitrification	Big	Costs too high
– Thermal denaturation	Small	The introduction of a landfill ban could possibly result in a sufficient gate fee (the required gate fee is a threshold for introduction). Other necessary conditions are guaranteed feedstock and acceptance of end-product
– Thermal denaturation with microwave	Big	Technologically immature
– Recycling asbestos containing steel scrap in steel melting furnaces	Very small	Proven technology, solid business case, no signs of lack of acceptance at designated location
– Thermo-chemical treatment	Rather small	Proof of operation and of quality of end-product still required. Requires higher gate fee (possibly supported by landfill ban) and steady flow of feedstock
– Ceramitization	Big	Technologically immature
– SHS (Self-propagating High temperature Synthesis)	Big	Technologically immature
– Laser induced rapid melting	Big	Technologically immature
Chemical treatment		
– Treatment with strong acids	Big/medium	Proved on lab scale
– Treatment with strong acids and chelating additives (amphibole asbestos)	Big	Technologically immature

Technique	**Distance to market**	
	Distance	**Explanation**
– Treatment with weak acids	Big	Technologically immature US patent not transferable to EU market
– Alkaline process	Big	Technologically immature
– CO_2 carbon capture/mineral carbonation	Big	Technologically immature
Mechanical treatment		
– Mechano-chemical treatment	Small	Proved on a semi-industrial scale, requires low capital investments, favourable prospects for a positive business case
Biological treatment		
– Biological treatment of asbestos in soil in situ	Medium	Technologically immature, low entry barriers to market, favourable prospects for a positive business case
– Biological treatment of asbestos cement and other ACM (in bioreactor)	Big	Technologically immature

The closest to the market is the *technique for recycling asbestos containing steel scrap in steel melting furnaces*. It seems that all it takes for the technique to be on the market is the construction of the installation. Other thermal techniques (*thermal denaturation, thermo-chemical treatment*) are a little more distant to the market, mostly for non-technical reasons (the business cases require higher gate fees (could be made possible by a landfill ban), guaranteed feedstock and accepted end-products).

Although there seem to be no concrete plans yet on where and how to enter it, the distance of the *mechano-chemical treatment* to the Dutch market is considered to be small. This is due to the low investment requirements, the medium/high level of mobility/flexibility of the installation and the treatment's relatively positive business case (though in terms of gate fee no competition for landfill).

Interestingly, the distance to market of *biological treatment of asbestos in soil in situ* is considered to be 'medium'. Although the technique is still in its developmental stage, there is an apparent positive business case and the barriers to entry to the market appear to be very low.

For the other techniques the distance to market is deemed to be big. Most of them are still immature techniques; one of them (vitrification) is too expensive.

9.4 Sustainability aspects

The summarising overview of the sustainability aspects of the assessed techniques is presented in table 6.

Table 6. Overview sustainability aspects

Technique	Sustainability aspects	
	Energy use / potential CO_2 footprint	**Risks**
Landfill (reference)	Marginal / small	Remaining intrinsic risks of asbestos
Thermal treatment		
– Vitrification	1.300 kWh/ton / big	(+) complete fibre destruction, robust process (-) risks from extra handling and logistics; exhaust gases must be treated effectively
– Thermal denaturation	700 kWh/ton / big, somewhat balanced by reuse of end-product	(+) complete fibre destruction, robust process; (-) exhaust gases must be treated effectively
– Thermal denaturation with microwave	*No data*	*No data*
– Recycling asbestos containing steel scrap in steel melting furnaces	700 kWh/ton , fully balanced by reuse of recycled steel scrap	(+) complete fibre destruction, robust process (-) risks from extra handling and logistics; ; exhaust gases must be treated effectively
– Thermo-chemical treatment	1500 kWh/ton, balanced by 750 kWh/ton yield from burning energy-rich waste, somewhat balanced by reuse of end-product	(+) complete fibre destruction (yet to be proved) (-) risks from extra handling and logistics; exhaust gases must be treated effectively
– Ceramitization	*No data / big*	*No data*
– SHS (Self-propagating High temperature Synthesis)	*No data / big*	*No data*
– Laser induced rapid melting	*No data / big*	*No data*
Chemical treatment		
– Treatment with strong acids	Minor energy use (exothermic processes need standby cooling capacity); medium CO_2 footprint	(+) complete fibre destruction possible (yet to be proved on industrial scale); waste acids stream from industry can be used; (-) intrinsic risks from working with strong acids
– Treatment with strong acids and chelating additives (amphibole asbestos)	No data / (similar to treatment with strong acids)	(-) complete fibre destruction has to be proved (-) intrinsic risks from working with strong acids
– Treatment with weak acids	Process can be accelerated by applying elevated temperature and pressure; medium CO_2 footprint	(+) waste streams from agro-food industry can be used (such as whey) (-) very slow process at room temperature; complete fibre destruction to be proved
– Treatment with alkaline processes	Process works at elevated temperature and pressure; medium CO_2 footprint	(-) intrinsic risks for working with strong alkaline at high temperature/pressure conditions (-) poor reusability of end-product

Technique	Sustainability aspects	
	Energy use / potential CO_2 footprint	Risks
– CO_2 carbon capture/mineral carbonation	Process works at elevated temperature and pressure; medium CO_2 footprint	(-) intrinsic risks for working at high temperature/pressure (-) slow process
Mechanical treatment		
– Mechano-chemical treatment	Approx. 60 – 70 kWh/ton / the required drying takes 25% of the total energy consumption / small to medium CO_2 footprint, somewhat or fully balanced by reuse of end-product	(+) complete fibre destruction possible (yet to be proved on industrial scale) (+) modularity/mobility of the installation (-) risks from extra handling and logistics ACM and ultra-fine end-product
Biological treatment		
– Biological treatment of asbestos in soil in situ	Low energy use; small CO_2 footprint	(+) marginal impact on environment (-) completeness of asbestos destruction is not yet proven in practical situations (asymptotic decrease of reaction speed).
– Biological treatment of asbestos cement and other ACM (in bioreactor)	Pre-treatments (breaking / crushing), transport and bioreactors (mixing vessels) will use energy; small to medium CO_2 footprint	(-) for asbestos cement and other ACM, bio reactors, transport and pre-treatment (crushing et cetera) is needed.

Fibre destruction is a crucial sustainability aspect, given its important impact on risks and reusability of the end-product and, most probably, on public and administrative acceptance. Thermal and mechano-chemical treatments have the benefit of guaranteed fibre destruction under the right (easy to control) process conditions. Still, monitoring of full fibre destruction in the end-product will always remain necessary. Chemical and biological treatments result in an asymptotic decrease of the processes speed (depending on reactive surfaces, concentration of reactants) and can suffer disturbances from irregular waste ACW composition.

The energy use and potential CO_2 footprint is one of the main – negative – sustainability aspects of the thermal treatment techniques. Attempts are made to shrink this potential footprint by providing an end-product that replaces a product with an energy-intensive regular production and by innovative combinations of burning energy-rich waste. These attempts go hand in hand with more economically oriented attempts to develop a viable business case, given the high price of energy. And so, the thermal techniques that succeed in bringing down their potential CO_2 footprint are simultaneously the techniques with the smaller distances to market: most of all the technique for *recycling asbestos containing steel scrap in steel melting furnaces*, and to a lesser extent *thermal denaturation and thermo-chemical treatment*. The inherent lower energy use of the mechanical and biological treatments, makes that their potential CO_2 footprint is smaller in any case. Still there is a comparison to be made with the energy use for producing the products their end-products can replace.

As said before, high energy use leads to a high *potential* CO_2 footprint. The actual CO_2 footprint also depends on the type of energy used (green or grey). However, the lower the energy consumption, the easier it becomes to switch to green energy sources (e.g. solar power).

Handling and logistics of ACM are linked to (potential) occupational health & safety and environmental risks. With the exception of thermal denaturation (occasional opening of asbestos bags) and in situ remediation of asbestos contaminated soil, all treatment techniques more or less need a form of pre-treatment (size reduction), preferably in closed systems. The mechano-chemical technique needs size reduction as well as drying. Further attention is drawn to the ultra-fine end-product of the mechano-chemical technique. In a certain configuration the thermo-chemical treatment technique uses pre-separation for an optimal processing route. Chemical treatment techniques have their intrinsic handling risks (strong acids and alkaline chemicals).

These occupational health and safety aspects should not be underestimated. The Threshold Limit Value for respirable asbestos fibres in The Netherlands is 2000 fibres/m^3 of air, which is considerably lower than in most other EU-countries. It is required by law that all handling (transport, pre-treatments et cetera) of ACM is described in a protocol and that measures to prevent possible exposure are validated by the appropriate standard methods. Some processes can have their specific H&S issues such as the generation of fine dust particles which may have toxic properties (e.g. forms of respirable silica) or chemicals used in the process (e.g. strong acids, chemical additives). All such processes require described protocols for safe handling, validated by measurements based on personal sampling.

Techniques that use smaller installations, or in situ remediation of asbestos contaminated soil, generate less transport kilometres and less transport risks. Smaller installations can be located near the place where the ACM is removed and are cheaper to purchase, which allows for multiple installations spread over the country (e.g. at landfill sites or waste treatment installations).

9.5 Areas of application

Finally, all techniques have been evaluated on the types of ACW that they can (technically, profitably) treat. The summarising overview of these areas of application is presented in table 7.

Table 7. Overview areas of application

Technique	Area of application
Landfill (reference)	All ACW
Thermal treatment	
– Vitrification	Highly problematic (toxic, radio-active) ACM
– Thermal denaturation	Constant and homogeneous stream of ACM, e.g. asbestos cement roofings or pipes
– Thermal denaturation with microwave	-
– Recycling asbestos containing steel scrap in steel melting furnaces	Asbestos containing steel scrap

Technique	**Area of application**
– Thermo-chemical treatment	All ACM (except soil and preferably no metals); and high-energy waste as alternative fuel for the thermo-chemical conversion process
– Ceramitization	-
– SHS (Self-propagating High temperature Synthesis)	-
– Laser induced rapid melting	-
Chemical treatment	
– Treatment with strong acids – Treatment with strong acids and chelating additives (amphibole asbestos)	Homogeneous stream of ACM Homogeneous stream of ACM
– Treatment with weak acids	Homogeneous stream of ACM
– Alkaline process – CO_2 carbon capture/mineral carbonation	Homogeneous stream of ACM Homogeneous stream of ACM
Mechanical treatment	
– Mechano-chemical treatment	Homogeneous stream of asbestos cement
Biological treatment	
– Biological treatment of asbestos in soil in situ	(Chrysotile) asbestos contaminated soil
– Biological treatment of asbestos cement and other ACM (in bioreactor)	Asbestos cement and other ACM

The table shows that all techniques have an own type of feedstock that they can handle effectively and (under the right conditions) profitably. In many cases the technique itself could most probably also handle other types of ACW, but this would affect the business case in a negative way.

A closer look shows that most techniques, and particularly the techniques that were identified above as more mature and closer to market, have a specific area of their own (a niche) in which they could have particular added value:

- *Recycling asbestos containing steel scrap in steel melting furnaces:* asbestos containing steel scrap
- *Thermal denaturation:* a constant and homogeneous stream of asbestos cement roofings or pipes
- *Thermo-chemical treatment:* ACW and high-energy waste (alternative fuel)
- *Mechano-chemical treatment:* (different amounts, due to the easily scalable technique, and more local) homogeneous stream of asbestos cement
- *Biological treatment of asbestos in soil: (*chrysotile) asbestos fibres in soil *in situ.*

10. Conclusions

The aim of this assessment project has been to (1) develop an assessment method for asbestos waste treatment techniques, and (2) to employ this method to perform an assessment of all presently available asbestos waste treatment techniques.

The assessment method
As described in chapter 3 of this report, the assessment method has been developed from two directions. On the one hand – in a bottom-up direction – a first basic set of parameters that were used in the OVAM study was discussed with an international group of experts, was analysed and was enriched.

However, instead of using multi-criteria analyses to identify the most high-ranking techniques on the basis of these parameters (as was done in the OVAM study), in the present study four well-understandable and highly relevant parameters have been postulated (all four of a largely qualitative nature), that allow for a transparent weighing process (by policy makers) for the final appraisal of the techniques. The overall parameters are:
– Technological readiness level
– Distance to market
– Sustainability aspects
– Area of application

And so, in a more top-down direction, these four overall parameters were linked to the basic parameters. For this purpose, also a distinction was made between (a) technical parameters, (b) non-technical parameters that are reasonably objectifiable and (c) non-technical parameters that are hardly objectifiable. In this way, all relevant aspects of the techniques are included in a logically ordered assessment.

Assessment of the technique
With the use of this assessment method, all presently known and available techniques have been assessed. This has led to the following conclusions.

Thermal techniques
– Closest to (the Dutch) market appears to be the technique for *recycling asbestos containing steel scrap in steel melting furnaces*. The technology is mature, the business case appears to be sound and there are no indications of lack of administrative and public acceptance at the designated location.
– Several other techniques are (a little) more distanced to the (Dutch) market, but could possibly move fast forward (possibly in a few years' time) if the conditions are right. These conditions are of a technical nature, a non-technical nature or both.
– The distance to market of the *thermal denaturation* technique is mainly a matter of non-technical issues. In order for this technique to obtain a viable business case, a steady flow of asbestos cement feedstock is required, which in turn requires buffering capacity and logistic guarantees, as well as acceptance (by authorities and market) of a certified end-product.

- There are similar requirements for the *thermo-chemical treatment technique* to enter the market, but for this technique also some final technical tests must be passed. Therefore, its distance to market is a bit bigger still, given both the technical and non-technical conditions that have to be met.
- All thermal techniques require larger, static installations and relatively much energy. Consequently they have a relatively large potential CO_2 footprint, although it must be taken into account that the end-products can be substitutes for products whose regular (new) production also entails CO_2 emissions. For that reason, for example, the potential CO_2 footprint of recycling asbestos-containing steel scrap is small.
- Due to the size and capacity of the installations, there will be room for one or at the most a few of them in the Netherlands, which implies that the asbestos-containing waste has to be transported to these installations (extra transport when compared to regional landfill). In addition, the processes for recycling asbestos-containing steel scrap and thermo-chemical treatment require pre-treatment of the waste. For all this, measures are necessary to protect employees, residents and the environment against the risks of exposure to asbestos. This is somewhat different for thermal denaturation; no pre-processing is required here, as the asbestos-containing waste, including the packaging in polythene bags, goes straight in the oven.

Mechanical techniques

- Something rather similar is the case for the *mechano-chemical treatment technique*. The technique is rather mature but some final tests are still taking place. To enter the Dutch market, also a number of practical issues must be addressed, ranging from meeting pre-processing requirements to location and permit arrangements. On the other hand, the mechano-chemical treatment technique is more mobile and flexible and less capital intensive than many of the other techniques, which may allow for a relative fast entrance on the market.
- The mechano-chemical treatment technique uses less energy and has a relatively modest potential CO_2 footprint. The scalable and mobile nature of the installation means that it can be placed close to places where asbestos containing waste originates or at regional landfill sites. This may lead to less transport of asbestos-containing waste. However, pre-processing of this waste is required (drying and size reduction), which will also require the necessary protective measures.

Biological techniques

- There is still a serious (medium) distance to market of *biological techniques* for in situ treatment of soil that is contaminated with (chrysotile) asbestos fibres, due to its technological immaturity. However, soon as this technique is somewhat more under control, an immediate positive business case can be expected and the barriers to entry to the market appear to be very low.
- Energy consumption and potential CO_2 footprint of biological techniques are minimal. However, the safety of working with fungi, bacteria and any additives must be guaranteed.

Chemical techniques

- Although the historical record of chemical asbestos waste treatment techniques is rather poor, a new development drive has come into Dutch trials, also from an interest of making use of industrial acid waste streams. Given the number of technological and non-technological issues that still have to be overcome, however (including some relating to sustainability aspects), the distance to market is big.

Other assessed techniques for asbestos waste treatment are either still in an embryonic stage, are in a standstill after less successful pilot studies, or are in the slow process of being scaled up.

A further look into the areas of application of these techniques indicate that several of them may have their own markets or niches of asbestos waste that they can treat most effectively and profitably:
- Recycling asbestos containing steel scrap in steel melting furnaces: asbestos containing steel scrap
- *Thermal denaturation:* a constant and homogeneous stream of asbestos cement roofings or pipes
- *Thermo-chemical treatment:* ACW and high-energy waste (alternative fuel)
- *Mechano-chemical treatment:* (differing amounts, due to the easily scalable technique, and more local) homogeneous stream of asbestos cement
- Biological treatment of asbestos in soil: (chrysotile) asbestos fibres in soil in situ.

Discussion
This study shows that there are several techniques for asbestos waste treatment that may present themselves on the Dutch market in the next years to come. Some of these techniques will, once they are available, hardly or not require specifically adapted conditions to fit their needs. For example, *recycling asbestos containing steel scrap in steel melting furnaces* and *biological treatment of asbestos in soil* both appear to have strong economic drivers. Businesses offering such treatments may possibly require certain specifically adapted administrative and logistical conditions, but can probably realise steady business operations under present market conditions.

Some other techniques are however more dependent on market conditions that are (made) favourable to their needs, like the possibility to compete with higher gate fees (as a result of a landfill ban) and probably also certain logistical requirements like a regulated buffering capacity. For this, government intervention is required. For the decision making on whether or not such interventions are opportune, in fact the Dutch National Waste Plan (LAP) 3 has given the conditions: (1) smaller environmental footprint or reduced risks/improved public health; (2) there is a market for the end-products; (3) costs do not exceed 205 €/ton; (4) the technique is functioning properly, can deal with 75% of the total waste supply and a plan is at hand to deal with 100% of the waste within two years.

This report has aimed to provide insight into most of the conditions that are set in LAP3. Still, the final decision requires interpretation and weighing. How are the environmental footprint and the risks aspects of landfill compared to those of the different techniques discussed above, given their qualitatively different nature? And really how solid are the business cases for these new techniques, and how big is the risk of becoming dependent on their continuous operations while disturbing present institutional arrangements for dealing with asbestos waste streams and their checks and balances?

This final choice is of a political nature and includes the weighing of values. Hopefully, with the help of this report, this weighing can be done in a transparent and underpinned way.

Annex 1: Analysis sheets

Analysis sheet: Landfill

Table 1: Technical parameters

Parameter	Value	Q[34] or scale	Source no.
Treatment Mechanism	Dumping asbestos waste in landfill sites[35]	Q	1, 2
Type of process	No particular treatment; everlasting dumping site protection	Q	3
Process time	Dumping itself: minutes Time until destruction: if destruction occurs at all: centuries or longer	*Scale*: mins / hrs /days / months / years / centuries	3
Process temperature	Not applicable	^{o}C	3
Energy requirements	Marginal Energy for vehicles on dumping sites	kWh/ton	3
Input requirements / acceptance criteria	None All asbestos waste types are accepted.	*Options:* chrysotile / 'pure, friable' asbestos / asbestos cement/ asbestos containing scrap metal / asbestos containing soil / all ACM / other (to be explained)	3
Pre-processing (energy) requirements	Double bagged in conformity with certification scheme [4] (Big bags or container depot bags)	*Options:* pre-separated / reduced in size / grinded / milled / dried / none / other; plus kWh/ton	1, 2, 3, 4
Additives (chemicals) or other	None	Options: reactive chemicals / inert substances / other	
Fibre destruction	None	*Options:* full destruction / asymptotical reaction / none / other	1, 2, 3
Mass / volume reduction	None		
Reusability of end-product	Asbestos is 'filler' of 'landscape'. 'Landscape' can be used at the surface.	*Options:* None / inert filler / building material (civil engineering) / active substance (cement, clay) / clean soil / other	1, 3
Installation type / size	'Dumping site' is fixed and large scale (but is not an installation).	*Options:* On site / mobile / temporary / fixed medium scale / fixed large scale / other	3
Installation capacity	> 100.000 tons/y	< 1000, 1000 – 10.000, 10.000 – 100.000, > 100.000 tons / year	3

[34] Q = qualitative
[35] In Belgium friable asbestos is encapsulated into concrete before landfilling. This process is not applied in the Netherlands and is also not included in this analysis sheet.

Parameter	Value	Q[34] or scale	Source no.
Proven technique	Fully operational	Options: lab scale / pilot trials / upscaled / fully operational	

Table 2: Non-technical parameters (reasonably objectifiable)

Parameter	Value	Q or scale	Source no.
Logistical aspects	ACW must be double bagged and must be handled and 'laid down' with care.	Q	1, 3, 4
Quality Assurance (QA) aspects (robustness et cetera)	As long as the dumped asbestos material is not moved, the process is robust. Landfilled ACW does not produce gas nor leaches into groundwater.	Q	3
Risk aspects (in relation to transport, occupational H&S, residents and environment, end-product, other waste)	Measurements have never shown (release of) asbestos fibres in the air. Trickling water has and keeps a neutral pH value. For occupational health reasons dragging and blowing away of ACW must be limited to a minimum. In case of contamination, the landfill site has to be treated as a 'normal' asbestos contaminated site.	Q	3
Energy balance with replacement product	Not applicable	Q	
Costs in relation to energy use	< € 10/ton	*Costs (in actual market prices) in* €/ton *and/or (scale):* < € 10/ton; € 10 – 100/ton; € 100 – 200/ton; € 200 – 500/ton; > € 500/ton	3
Installation investments	- [2]: 'Capital costs are zero (waste disposed of at existing facility – existing landfill sites')	*(Claimed) investments in € and/or scale*: < 1 million € 1 million – 20 million; > € 20 million	2, 3
(Market) value of end-product	- ('Safe landscapes' have a market value)	*(Claimed*) value in €/ton And/or (options): avoided soil decontamination costs / < € 10/ton / > € 10/ton	3
Other costs	- Costs for land use - 'Raising funds (at Provincial level) for everlasting protection (by Provincial authorities): € 0,70/ton - € 1,40/ton - Protective foil: € 40/m^2 - Labour costs et cetera	Q	3

Table 3: Non-technical parameters (hardly objectifiable)

Parameter	Value	Q or scale	Source no.
Financial risks and securities; business case	Landfill costs including the costs of everlasting protection are covered by the gate fees. These amount from 55 to 130 € /ton (average 90 €/ton) (plus € 13/ton tax).	Q	3

Parameter	Value		Q or scale	Source no.
Public and administrative acceptance	Although there are known cases in The Netherlands where there is little acceptance of landfill sites by the neighbouring inhabitants, the landfill of ACW is not a relevant factor for this.		Q	3
Potential CO_2 footprint	Small	Options: Small / medium / large/ very large		
Actual market prices	55 to 130 € /ton (average 90 €/ton) (plus € 13/ton tax).	Actual price in €/ton		3

Table 4: Overall assessment

Parameter	Value	Q or scale	Source no.
Technology readiness level	9	Scale	See above
Distance to market	Already on the market on a large scale	Q	See above
Sustainability aspects	(+): marginal energy use and small CO_2 footprint; control of logistics and occupational health and safety and environmental risks; use of ACW as a 'filler' for landscapes (-): unreduced use of space, remaining intrinsic risks of asbestos as well as need for ongoing control and protection of site passed on to future generations	Q	
Area of application	All ACW	Q	

<u>Sources</u>

1. '*State of the art: asbestos – possible treatment methods in Flanders: constraints and opportunities'* (OVAM (a), 2016).
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Analysis sheet: Thermal processes

Table 1: Technical parameters

Parameter	Value	Q[36] or scale	Source no.
Treatment Mechanism	At certain (higher) temperatures asbestos fibres are unstable and naturally decompose. There are several underlying mechanisms of thermal treatment of ACM, sometimes chemically catalysed. With increasing temperatures overall evaporation of adsorbed water, dehydratation and crystallization take place [1]. This conversion process goes through different phases, in which different intermediate mineralogical stages are passed. At extreme temperatures, up to 1600 °C or even 2000 °C all (mineral) waste – including asbestos – is converted into a stable and homogeneous (silicate) glass. This latter process is called 'vitrification'.	Q	1, 3
Type of process	Several types of thermal treatment processes are distinguished (most of them semi-continuous): – Vitrification (very high temperatures to turn matter into glass, by plasma gun [4], conventional ovens or electric furnace (Joule heating (thermal process involving the use of high power currents made to flow through the material to be melted [5])/Geomelt vitrification process [6]) – Ceramitization (mixing with clay) (also: vitro-ceramitization, with other additives) – Thermo-chemical conversion (accelerated remineralisation process (expulsion of hydroxides) by using a fluxing agent (e.g. borax) [7] – Thermal denaturation (heating to approx. 1000 °C, either in an oven or by microwave (MODYAM: lower temperatures, only chrysotile) – Treatment of asbestos containing steel scrap in steel melting furnaces; in batches Others: – Self-propagating temperature synthesis (SHS) (a thermal method exploiting the highly exothermic and fast self-propagating high-temperature reaction between Fe_2O_3 and magnesium powder) [8] – Laser induced rapid melting (use of CO_2 laser irradiation for melting and decomposing [9]	Q	1, 3, 4, 5, 6, 7, 8, 9
Process time	The process time ranges from minutes to hours or even days	*Scale*: mins / hrs /days / months / years /	1, 3, 10

[36] Q = qualitative

Parameter	Value	Q[36] or scale	Source no.
	For denaturation: hours to days; Infestos/Twee "R" requires 75 hours (approx. 3 days) The treatment of asbestos containing steel scrap in steel melting furnaces will shortly be upscaled to industrial level; the exact melting time will be determined during the start-up phase (minutes or hours) [10]	centuries	
Process temperature	The ranges of decomposition temperatures of different asbestos types (at which the fibre structure is decomposed) are [11]: – $T_{decomposition}$ (chrysotile) = 450-700°C – $T_{decomposition}$ (crocidolite) = 400-600°C – $T_{decomposition}$ (tremolite) = 600 - 850°C – $T_{decomposition}$ (amosite) = 600-800°C – $T_{decomposition}$ (anthophylite) = 620 - 960°C – $T_{decomposition}$ (actinolite) = 950 - 1040°C Process temperatures: – Vitrification: 1100 – 1600 °C (or even up to 2000°C) – Ceramitization: 800 – 950 °C (vitro-ceramitization: 1300 -1400 °C) – Thermo-chemical conversion: 1200 – 1250 °C – Denaturation: 1000 – 1100 °C – Steel melting: 1500 – 1700 °C	°C	1, 3, 11, 12
Energy requirements	– Inertam (vitrification with plasma torch): 500 à 1.300 kWh/ton – ARI Technologies Inc. – Thermo-chemical conversion technology (TCCT): 1500 – 1600 kWh/ton (5,7 GJ/ton) – AM&P-groep – TCCT: approx. 1500 kWh/ton (natural gas) – AM&P-groep – TCCT + DTO/P2F[37]: approx. 750 kWh/ton and approx. 750 kWh/ton from energy-rich waste streams ('sorting residue') – For denaturation: 7 million m³ gas per year (equals 61,5/68,4 million kWh per year (= 615/684 kWh/ton)[38]	kWh/ton	3, 4, 11, 13, 14

[37] AM&P-Groep (the Netherlands) developed a ACW treatment concept (proof of concept) based on a combination of Thermo-chemical Conversion Technology (TCCT) and Dynamic Thermal Oxidation of energy-rich waste streams (DTO) and/or a combination of TCCT and depolymerisation (pyrolysis) of non-recyclable plastics (Plastic to Fuel process (P2F)). Both DTO and P2F are expected to provide a substantial part (up to 50%) of the TCCT energy consumption.

[38] Heat of combustion of natural gas; 31,65 MJ/m³ ('onderwaarde') / 35.17 MJ/m³ ('bovenwaarde') / Conversion factor: 1 kWh = 3,6 MJ / 1 m³ natural gas = 8,8 kWh ('onder waarde'); 1 m³ natural gas = 9,8 kWh ('boven waarde') (conversion efficiency (from gas to heath) is usually less than 100%)

Parameter	Value	Q[36] or scale	Source no.
	– PMC: 672 kWh/ton (incl. melting steel scrap; only a (very) small portion of the energy use is to be attributed to the asbestos destruction)		
Input requirements / acceptance criteria	– For vitrification: all ACM/acceptance criteria: none – For thermo-chemical conversion: all ACM (normally placed within asbestos bags) – logistical concept of AM&P-groep is based on 10 tons asbestos container bags [14] – For denaturation: non-friable asbestos material (ACW) (no soil); (MODYAM: only chrysotile) – For PMC: asbestos containing steel scrap in containers	*Options:* chrysotile / ‘pure, friable’ asbestos / asbestos cement/ asbestos containing scrap metal / asbestos containing soil / all ACM / other (to be explained)	3, 10, 14
Pre-processing (energy) requirements	– For vitrification: ‘powdered’ / particulate material (i.e. reduced in size (shredded)) – For ceramitization: other (grinding and mixing with clay) – For thermo-chemical conversion: reduced in size (TCCT (reduced in size (shredding)) / TCCT + DTO/P2F (sorting and segregating ACM in air-locked material and reduced in size (shredding); handling area, maintained at negative pressure)); no data available about pre-processing energy consumption [14] – For denaturation: none (double bagged (standard)) – For PMC: reduced in size (shredded) [12]	*Options:* pre-separated / reduced in size / grinded / milled / dried / none / other; plus kWh/ton	3, 12, 14
Additives (chemical or other)	For vitrification: inert substance (glass formers) For ceramitization: inert substance (clay) For thermo-chemical conversion: reactive chemical (fluxing agent (e.g. borax)) - less than 1% of the weight of the feedstock [7]	*Options:* reactive chemicals / inert substances / other	3, 6, 13
Fibre destruction	With adequate temperatures and processing times: full destruction	*Options:* full destruction / asymptotic decay of the reaction rate / none / other	3
Mass / volume reduction	- Vitrification: 30 – 50% (Inertam) or 80% (Geomelt) mass/volume reduction - Thermo-chemical conversion: volume reduction approx. 50% (asbestos cement) to more than 90% (friable asbestos) and mass reduction about 30 to 50%,	%	1, 3

Parameter	Value	Q36 or scale	Source no.
	- Other thermal techniques: > 15%		
Reusability of end-product	Reuseable products: – Vitrification: glass (e.g. Cofalit), can be reused in low grade construction applications (possibly substitute for quartz and basalt in building material) – Thermo-chemical conversion: end-product similar to coarse sand/gravel (low-grade construction applications, not suitable for use in high burden applications, because of its brittle nature) /AM&P-groep: clay substitute, ceramic products (e.g. bricks) – Ceramitization: ceramic materials, coatings / 'protective' surfaces in the building, mechanical and chemical industries' [3] – Denaturation: inert filler or even cement ('beststof') – PMC: not certain whether the asbestos waste is re-usable. The steel is (PMB's ('Purified Metal Blocks')); the slags can either be used as inert fillers or will be landfilled	*Options: None*[39] / inert filler / building material (civil engineering) / active substance (cement, clay) / clean soil / other	3, 7, 10, 12, 14
Installation type / size	Fixed medium to large scale installations	*Options:* On site / mobile / temporary / fixed medium scale / fixed large scale / other	3
Installation capacity	– Inertam (vitrification with plasma torch): 7.000 à 8.000 ton/year – Vitrification with electrical furnace: up to 100 ton/day. So: 30.000 tons/year – ARI Technologies Inc. - TCCT: the tested installation had a capacity of approx. 4500 – 5000 tons/year and is considered as the smallest installation which is commercial feasible) – Denaturation: expected Infestos/Twee "R": 100.000 tons/year – Denaturation by microwave (Japan [1]): 2 ton/day, or < 1000 tons/year – PMC: projected (incl. Steel scrap): 150.000 tons/year (approx. 3.900 tons/year asbestos)	*Scale:* <1.000 / 1.000 – 10.000 / 10.000 – 100.000 / > 100.000 tons/year	1, 3, 10, 12, 13
Proven technique	– Inertam (vitrification with plasma torch): fully operational – Vitrification with electrical furnace: fully	*Options:* lab scale / pilot trials / upscaled / fully operational	3, 7, 10, 14

39 Strictly speaking this option disqualifies a technique, given the requirements of LAP 3 (see footnote 28).

Parameter	Value	Q[36] or scale	Source no.
	operational (Japan) – ARI Technologies Inc. - TCCT: pilot trials – Thermal denaturation: expected Infestos/Twee “R”: pilot trials/upscaled (design of an industrial installation is ready) – Denaturation by microwave (Japan): lab scale/pilot trials – PMC: pilot trails/upscaled (design of an industrial installation is ready)		

Table 2: Non-technical parameters (reasonably objectifiable)

Parameter	Value	Q[1] or scale	Source no.
Logistical	Several thermal processes (denaturation, thermo-chemical conversion, PMC) are geared to incinerate packaging material (double bags) and other waste items as well. These processes have therefore no additional logistical requirements to the ones that are already in place for ACM waste landfill. Other thermal processes are less robust (MODYAM) and require controlled input streams.	Q	
Quality Assurance (QA) aspects (robustness et cetera)	Generally speaking for thermal processes: with adequate control of temperatures and process time (and depending on the type of process, also of the composition of input waste, e.g. for vitrification), the process is highly robust. For denaturation: Infestos/Twee “R” indicates it will take a sample of the core of each processed wagon to ensure complete denaturation. Also: control of composition of 1 bag per receiving load (in vacuum cabin) (For ceramitization: no specific data)	Q	3, 10, 15
Risk aspects (in relation to transport, occupational H&S, residents and environ-ment, end-product, other waste)	Process, especially pre-treatment (size reduction, shredding, grinding) and if the case pre-separation, in isolated space and with ‘negative’ pressure. For thermal denaturation, pre-treatment is not necessary, the ACM (in asbestos bags) goes straight into the oven. Within isolated space: work is to be regarded as work in asbestos contaminated area (‘working under asbestos conditions’). For vitrification: cooling water from plasma torch Exhaust gases must be treated in afterburners and filtered with HEPA filters. For thermo-chemical treatment the exhaust gases are routed through a secondary oxidizing unit, for the destruction of residual organic compounds, quench-coolers, caustic scrubbers and HEPA filtration before	Q	3, 10, 15

Parameter	Value	Q[1] or scale	Source no.
	exhaust tot the atmosphere. For the thermal denaturation process: risks of steam explosions in case the waste is heated too fast (a (very) wide heating period is applied). No risks of end-product (monitoring is required; (sample-wise) the end-product must be sampled and analysed to confirm the absence of asbestos fibres).		
Energy balance with replacement product	In case the end-product is steel scrap the energy consumption is hardly higher than when asbestos free steel scrap is melted. Compared to the recycling of asbestos-free steel scrap or the production of steel from ore the energy consumption is largely the same. For all other thermal techniques the energy consumption is somewhat compensated, a little bit more for active fillers, cement or substitutes for clay. Using energy obtained from burning energy rich waste, an option for thermo-chemical treatment, the balance shifts slightly in a positive direction.	Q	15
Costs in relation to energy use	The costs in relation to the energy use of thermal treatment techniques (rough estimation) can be classified in the range from € 10 to 100/ton. Costs calculations, based on the reported energy consumption per ton ACM (see energy parameter) and large user tariffs[40], show that the energy costs for vitrification and thermo-chemical conversion are almost the same (€ 50 to 100/ton ACM). The cost range for thermal denaturation is € 20 to 40/ton ACM. PMC requires € 35 to 55/ton steel scrap, of which a small part can be assigned to the destruction of ACM.	*Costs (in actual market prices) in* €/ton *and/or (scale):* < € 10/ton; € 10 – 100/ton; € 100 – 200/ton; € 200 – 500/ton; > € 500/ton	
Installation investments	– TCCT (27 tons ACW/day): € 3,87 million – TCCT (45 tons ACW/day): € 5,16 million – TCCT - AM&P-groep: 80 tons/day installation): € 8,5 million (CAPEX) – TCCT + DTO/P2F - AM&P-groep: 80 tons/day installation): € 12,4 million (CAPEX) – Infestos/Twee "R": € 23 million	*(Claimed) investments in* € *and/or scale*: < 1 million € 1 million – 20 million; > € 20 million	3, 14

[40] Business user tariffs 2017 (CBS, the Netherlands), including taxes, excluding VAT:
Natural gas - EUR 8,961/GJ (large business user) - EUR 15,282/GJ (business user)
Electricity - EUR 0,054/kWh (large business user) - EUR 0,079/kWh (business user)

Parameter	Value	Q[1] or scale	Source no.
(Market) value of end-product	– Market price of Cofalit (from vitrification at Inertam): € 10 / ton - TCCT: no market values are reported – TCCT - AM&P-groep: business cases are based on 'zero value' of the end-product (possibly in the long term a fee per brick in case of clay substitute) – For treated asbestos containing steel scrap the market value of the end-product mainly concerns the market price for recycled steel.	*(Claimed)* value in €/ton And/or (options): avoided soil decontamination costs / < € 10/ton / > € 10/ton	3, 14
Other costs	Not available	Q	

Table 3: Non-technical parameters (hardly objectifiable)

Parameter	Value	Q[1] or scale	Source no.
Financial risks and securities; business case	– Vitrification: business case appears to be related to high gate fees of nuclear and highly toxic waste. – Thermo-chemical conversion (ARI Technologies Inc.): no data – Thermo-chemical conversion (AM&P-groep): business case (TCCT) is built on higher gate fee than of landfill (therefore dependent on landfill ban), (delivery guarantee), gate fee > € 175, exclusive costs for (initial) buffering capacity. – Thermo-chemical conversion (AM&P-groep): business case (TCCT +DTO/P2F) is built on higher gate fee than of landfill (therefore dependent on landfill ban), (delivery guarantee), gate fee > € 135 exclusive costs for (initial) buffering capacity (including gate fee of energy-rich waste stream). – For thermal denaturation: business case is built on higher gate fee than of landfill (therefore dependent on landfill ban), gate fee > € 175 and (initial) buffering capacity. – For PMC: business case is related to economic value of steel, negative market value of AC steel scrap and equally costly/high energy level of production of steel from ore.	Q	3, 9, 14
Public acceptance and administrative acceptance	– Little data. – AM&P-groep claims: public acceptance is related to choice of location, suitable for heavy industry, the government could play a promotive role in using 'asbestos' bricks, housing associations have the intention to use bricks made from ACW of their asbestos remediation projects, independent test results can support applying the end-product as clay	Q	10, 14

Parameter	Value	Q[1] or scale	Source no.
	substitute. – PMC claims public acceptance is related to choice of location (not too close to inhabited areas, suitable for heavy industry), commitment of authorities and energy supply with the appropriate capacity at close range.		
Potential CO_2 footprint	Thermal destruction of asbestos waste needs a relative high amount of energy (500 to 1500 kWh/ton) and therefore has a (relative) large potential CO_2 footprint. The equivalent CO_2-emission[41] for the above energy consumption range: - (natural gas): 105 – 325 kg CO_2/ton - (electricity): 325 – 975 kg CO_2/ton Processing 1 ton of ACM by thermal denaturation (Infestos/Twee "R") is equivalent to a CO_2 emission of approx. 130 kg CO_2 (7 million m^3 natuaral gas per year and a production of 100.000 ton ACM/year) Processing 1 ton of ACM by thermal treatment is equivalent to: 2 - 7% (natural gas) or 7 - 22% (electricity) of the annual energy consumption (natural gas and electricity)[42] of an average NL household. Using thermal denaturation demands approx. 3% of the annual energy consumption of an average NL household.	*Options:* Small / medium /large / very large	16
Actual market prices	– Inertam (vitrification with plasma gun): € 1.000 – € 2.500 / ton; average € 1.500 / ton – For ceramitization: no data – Thermo-chemical conversion ARI technologies Inc. (TCCT): € 370 / ton (27 tons ACW/day) - € 270 / ton (45 tons ACW/day) – Thermo-chemical conversion AM&P-Groep: € 175 / ton (80 tons ACW/day) – TCCT + DTO/P2F - AM&P-Groep: € 135 / ton (80 tons ACW/day) (including gate fee for the 'sorter residue') – For denaturation: claim by Infestos/Twee "R": € 175 /	Actual price in €/ton	3, 10, 14, 17

[41] Source: www.milieubarometer.nl – Actuele CO_2-parameters – 2018 en verder: electricity 0,649 kg CO_2/kWh; natural gas 1,89 kg CO_2/m^3 (also see footnote 38: 1 m^3 natural gas is equivalent to approx. 8,8 – 9,8 kWh)
[42] Annual average energy consumption of private homes in the Netherlands (2016) is 1300 m^3 of natural gas and 2910 kWh (Source: CBS: Energieverbruik particulier woningen; woningtype en regio's). This energy use is equivalent to approx. 4500 kg CO_2 (55% natural gas and 45% electricity).

Parameter	Value	Q[1] or scale	Source no.
	ton; claim by AsbestEx-System GmbH: € 520 / ton. – Melting steel/PMC: business case is based on present gate fees for landfill of ACW (on average € 90 / ton plus taxes).		

Table 4: Overall assessment

Parameter	Value	Q[1] or scale	Source no.
Technology readiness level	– Vitrification: TRL 9 (Europlasma group / Inertam: vitrification with plasma gun in operation; vitrification with electrical furnace called 'best 'demonstrated available technology' by EPA) – Ceramitization: TRL 4 – Thermo-chemical conversion – ARI Technologies Inc.: TRL 7 – Thermal denaturation: TRL 9 – Thermal denaturation with microwave: TRL 5 (or 7) – Melting steel/PMC: TRL 8 – Self-propagating high temperature synthesis (SHS): TRL 5 – Laser induced rapid melting: TRL 3 All techniques are patented.	Scale	1, 3, 10, 14
Distance to market	Distance to market is small and depends largely on non-technical issues. – For denaturation to come on the market, the right conditions have to be in place in terms of gate fee (made possible by a landfill ban) and (at first) buffering / storing capacity (small distance to market but not easy to overcome). – For vitrification something similar applies, but probably with higher gate fees that can only be justified in cases of nuclear or highly toxic waste (big distance to market). – For thermo-chemical conversion a definitive proof of operation and of the quality of the end-product is still required. Once this has been obtained, investment planning can start. The possibility to compete with a higher gate fee (made possible by a landfill ban) and a steady flow of feedstock are essential (the distance to market is rather small but a little bigger than for thermal denaturation). – For steel scrap the distance to market is mostly determined by the installation's construction time (distance to market is very small).	Q	(see above)
Sustainability aspects	(+) complete fibre destruction, reusable end-products (+) the quality and the effectiveness of the process can be controlled, monitored and inspected robustly on the basis	Q	(see above)

Parameter	Value	Q[1] or scale	Source no.
	of a few process parameters. (+) compensation of the CO_2 footprint by the use of the end-product, somewhat for thermo-chemical conversion and thermal denaturation, and large for processing of steel scrap). (+) compensation of CO_2 footprint by using energy obtained from burning of energy rich waste (Dutch proposal for thermo-chemical conversion). (-) high energy use (500 to 1500 kWh/ton and a potentially large CO_2 footprint (-) the extra handling and logistic that are required for thermal treatment (pre-separation of ACM waste streams, size reduction, shredding, grinding) require extra energy and produce some additional risks for occupational health and safety and the environment. This is to a lesser extent the case for thermal denaturation, where no pre-processing is required. (-) all thermal techniques produce exhaust gases that must be treated and controlled before emission to the environment.		
Area of application	– For vitrification: all ACW (including highly problematic waste (toxic, radio-active) – For thermo-chemical conversion (combined with DTO and P2F techniques): all ACM except soil (preferable no metals (removed by pre-separation) and high-energy waste, including asbestos containing floor cover and floor tiles, for the DTO and P2F techniques to produce thermal energy for the thermo-chemical conversion process . The DTO and P2F techniques are a kind of pre-processing for asbestos containing floor cover and floor tiles. – For thermal denaturation: a constant and homogeneous stream of ACM (asbestos cement (corrugated) sheets or pipes (non-friable asbestos material (ACW) (no soil); (MODYAM: only chrysotile) – For steel melting/PMC: AC steel scrap	Q	(see above)

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Analysis sheet: Chemical processes

Table 1: Technical parameters

Parameter	Value	Q[43] or scale	Source no.
Treatment Mechanism	Chemical decomposition mechanisms can be divided into the following categories: • Acid* decomposition using strong acids (dehydration) • Alkaline* decomposition • Specific decomposition of amphibole asbestos using chelates (such as citrate (citric acid), oxalate (oxalic acid), ascorbate (ascorbic acid) and ethylene diamine tetraacetic acid (EDTA) • Acid* decomposition using weak acids • Carbon dioxide capturing / Mineral carbonation – The process is based on acid-base reactions in which carbonate acid is neutralized by a base (alkaline mineral) - ($Mg_3Si_2O_5(OH)_4 + 3\ CO_2 \rightarrow 3\ MgCO_3 + 2\ SiO_2 + 2\ H_2O$) - at natural conditions a slow process) *) *all acid or alkaline reaction products must be neutralized to obtain a reusable end-product*	Q	1, 3, 4, 7, 8 6 3 4 1, 3, 4, 5 14, 15 5, 9, 10, 11, 12, 13, 17
Type of process	Chemical decomposition of asbestos fibres	Q	all
Process time	Varies from hrs to days, depending on the chosen process and the type of ACM processed	*Scale*: mins / hrs /days / months / years / centuries	1, 4, 5
Process temperature	Varying from room temperature to 500 °C, depending on process. Some processes are exothermic.	°C	1, 5
Energy requirements	10 – 200 kWh/ton* *) Chemical processes for asbestos destruction can be combined with other waste streams from industry such as acid waste, alkaline waste or CO_2 which can have advantages for disposal costs, energy consumption and environmental benefits. Some processes can be exothermic (energy consumption for a standby cooling unit).	kWh/ton	1, 4, 5
Input requirements / acceptance criteria	Pure friable asbestos insulation materials as well as asbestos cementproducts. Not suited for very heterogenic asbestos containing materials (ACM) such as bagged building materials contaminated with	*Options:* chrysotile / 'pure, friable' asbestos / asbestos cement/ asbestos containing scrap metal / asbestos containing soil / all ACM / other (to be explained)	4

[43] Q = qualitative

Parameter	Value	Q[43] or scale	Source no.
	small amounts of asbestos and asbestos contaminated metal scrap.		
Pre-processing (energy) requirements	Grinded. Available free surface dominates reaction kinetics. Bagged products must be unpacked first.	*Options:* pre-separated / reduced in size / grinded / milled / dried / none / other; plus kWh/ton	
Additives (chemicals) or other	Acid for destruction of asbestos, for destruction of amphiboles chelate forming additives are needed.	*Options:* reactive chemicals / inert substances / other	
Fibre destruction	• Full destruction for pure chrysotile. • Complete destruction of amphibole asbestos fibres require additional use of chelates • For asbestos cement products the available surface (pre-grinding) dominates reaction kinetics and therefore the reaction time needed for complete decomposition. • An asymptotic decay of the reaction rate is expected. • Complete destruction of the asbestos fibres must be proved by 'state of the art' analytical techniques (see also quality assurance aspects).	*Options:* full destruction / asymptotic decay of the reaction rate / none / other	1, 3
Mass / volume reduction	No data	%	
Reusability of end-product	Inert filler for cement production, bulk chemicals and other low-grade end-products (after optimizing the chemical processes)	*Options: None[44]* / inert filler / building material (civil engineering) / active substance (cement, clay) / clean soil / other	4
Installation type / size	Fixed medium scale or fixed large scale	*Options:* On site / mobile / temporary / fixed medium scale / fixed large scale / other	1, 4
Installation capacity	10.000 - 100.000 tons/year depending on plant capacity	*Scale:* <1.000 / 1.000 – 10.000 / 10.000 – 100.000 / > 100.000 tons/year	
Proven technique	Pilot trial(s) (for chrysotile)	Options: lab scale / pilot trials / upscaled / fully operational	4

[44] Strictly speaking this option disqualifies a technique, given the requirements of LAP 3 (see footnote 21).

Table 2: Non-technical parameters (reasonably objectifiable)

Parameter	Value	Q[1] or scale	Source no.
Logistical	• If the process installation is built near chemical plant, transport of chemicals can be limited. Extra transport of asbestos waste is required in case of central locations (elsewhere and fewer than landfill sites). Transport of chemicals and/or asbestos products shall be reduced to obtain maximum safety.	Q	4
Quality Assurance (QA) aspects (robustness et cetera)	• Conversion rate of the asbestos as well as other crucial parameters (e.g. temperature, pressure, pH, concentration of reactants, irregularities in the ACM composition) must be monitored during the process. • Complete fibre destruction must be proved by 'state of the art' analytical techniques. • The need to develop a standardized analytical method (a combination of different analytical techniques) to demonstrate being "asbestos safe" or preferably "asbestos free"of the end-product was discussed at the meeting of the ISO Working Group TC146 / SC3 / WG1 .The intention is to pick this up as a new work item during the upcoming meeting (Sidney, 2018). • In time process certification can be considered	Q	1, 2, 4
Risk aspects (in relation to transport, occupational H&S, residents and environ-ment, end-product, other waste)	• A covered storage site is required to store a buffer stock of asbestos containing materials • Storage tanks of waste chemicals (acids, alkaline solutions et cetera) shall meet all requirements for occupational and environmental safety • All pre-treatments such as grinding, unpacking bags et cetera must be carried out in a closed system (screened room with 'negative' pressure) to avoid emission of airborne asbestos fibres • Transport of chemicals and/or asbestos products shall be reduced to obtain maximum safety. • There is a risk of corrosion of the pipe linings of the reactor	Q	4
Energy balance with replacement product	Research is aimed at producing reusable end-product (inert filler, bulk chemicals or other low-grade end-products). Reusable end-products contribute to energy compensation to a modest extent.	Q	

Parameter	Value	Q[1] or scale	Source no.
Costs in relation to energy use	€ 100 – 200/ton but will depend on choices made. Cost will be reduced if combined with other waste streams, such as industrial acid waste and/or CO_2 capture. Prevents required neutralization of acid industrial waste.	*Costs (in actual market prices) in €/ton and/or (scale):* < € 10/ton; € 10 – 100/ton; € 100 – 200/ton; € 200 – 500/ton; > € 500/ton	4, 5
Installation investments	No data	*(Claimed) investments in € and/or scale*: < 1 million € 1 million – 20 million; > € 20 million	
(Market) value of end-product	< € 10/ton (filler)	*(Claimed*) value in €/ton And/or (options): avoided soil decontamination costs / < € 10/ton / > € 10/ton	
Other costs	No data	Q	

Table 3: Non-technical parameters (hardly objectifiable)

Parameter	Value	Q[1] or scale	Source no.
Financial risks and securities; business case	• The business case is built on the combination of the asbestos destruction process with the disposal of other hazardous waste streams, such as industrial acid waste and/or CO_2 capture. • A chemical treatment process can be competitive with (more expensively prized) regular landfill. At this moment costs for regular landfill (gate fee) in NL vary from 55 to 130 €/ton depending from (average 90). The landfill rate depends on regional policy and policy views of the ministry.	Q	4
Public and administrative acceptance	Hardly any data, but it is expected to depend on the location chosen. A location close to an industrial plant using other waste streams, public acceptance might be easier. An environmental impact study is required.	Q	
Potential CO_2 footprint	Medium (if combined with waste acid stream.)	*Options:* Small / medium /large /very large	
Actual market prices	Process costs (acid treatment process) are estimated at € 125,-/ ton.	Actual price in €/ton	4

Table 4: Overall assessment

Parameter	Value	Q[1] or scale	Source no.
Technology readiness level (see table 1)	• Acid decomposition using strong acids: 3 - 5 • Alkaline decomposition: 2 - 4 • Specific decomposition of amphibole asbestos using chelates (such as citrate, oxalate, ascorbate and EDTA): 2 - 4 • Acid decomposition using weak acids: 3 – 5 • Carbon capture / mineral carbonation: 2 - 4	Scale	
Distance to market	Big/medium - Both technical issues (reusability of the end-product, the purity of the used chemicals, the destruction of amphiboles and the upscaling from lab to semi industrial size) and non-technical issues (drafting a business case, financing, environmental impact study and request for permits) still need to be solved.	Q	
Sustainability aspects	Low energy consumption (relative to thermal treatment), complete fibre destruction (chrysotile), processing 'waste with waste' (combination of (industrial) waste streams, risks of process disturbance by irregularities in ACM supply, chemical process with intrinsic risks (especially alkaline processes (NaOH) and strong and corrosive processes (HF)), necessity of neutralisation of the end-product and reusability of the end-product still has to be proved.	Q	
Area of application	Homogeneous stream of asbestos cement (chrysotile) or friable asbestos, process combined with acid waste.	Q	

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Analysis sheet: Mechanical processes

Table 1: Technical parameters

Parameter	Value	Q[45] or scale	Source no.
Treatment Mechanism	The mechanisms behind mechanical (mechano-chemical) treatment of ACM is the complete crystallographic transformation of asbestos (structural destruction by mechanical energy). The mechanical energy transferred to the ACM systems is partly converted into heat and partly utilised to cause fractures, compression and slips at macro-meso and microscopic levels, affecting the crystalline structure of the solid material [4]. The main stress types applied are compression, shear (attrition), impact (stroke) and impact (collision) [6]. The mechano-chemical process on a mineral grain follows ideally a sequence of the following events: plastic deformation, increase in internal stress (crystal lattice is permanently deformed), micro plastic deformation and fracture (division of the grain) [4].	Q	4, 6
Type of process	Mechanical (mechano-chemical) treatment of ACM means high-energy milling or ultra-grinding based on high-energy collisions between grinding media (rings, rollers, balls, hammers, etc.) and the asbestos containing powders [5]. A practical example of this treatment technique is Mechano-Chemical Destruction (MCD™) by Environmental Decontamination Europe LTD (EDL) – continuous ball-milling system (pilot scale/semi-industrial scale) [7, 8]. The performance of the process is optimized by fine-tuning of milling parameters such as [9]: • number, size and hardness of the balls; • hardness and construction of the rotating mixing rods; • balancing the multi-stacked reactor vessels for maximum capacity as well as complete destruction of asbestos **Note**: The practical information below relates to an important extent to EDL's MCD™ process. This process is demonstrated on a semi-industrial scale and, in terms of scale, it is well ahead of the large number of laboratory experiments that are reported in literature.	Q	5, 7, 8, 9
Process time	4 – 12 minutes (100% destruction)	*Scale*: mins / hrs /days / months / years / centuries	7, 8
Process temperature	Although ball milling can be performed at relatively low temperatures (i.e. 25°C to 150°C), the internal temperatures of milled matrices can exceed several	°C	7, 8

[45] Q = qualitative

Parameter	Value	Q[45] or scale	Source no.
	thousand degrees Celsius for very short periods of time (10^{-3}s to 10^{-4}s). This concept is often referred to as the 'hotspot' theory [7]. The low temperature of the ACM matrix (160 – 200 °C) is due to MCD mechano-chemical reaction, which uses the mechanical energy of ball to ball and ball to surface collisions to initiate crystalline fracture and amorphisation [8].		
Energy requirements	Information about the energy consumption, including the energy consumption related to pre-treatment (drying, size reduction and emission control), is one of the expected results of the March 2018 (ACM-) tests in New Zealand. The MCD™ reactor drums are driven by 55 kW motors. A full scale continuous system can be consisting of 10 reactors. Additional power will be required for crushing, drying and emission control systems [8]. EDL quantified the power requirements for a full scale contaminated soil processing plant (10 reactors: 2 towers of 5 cascading reactors). They expect an equivalent operational power consumption for a full-scale ACM treatment plan. The total power required for the reactors and ancillary apparatus is approx. 700 kW (10 reactors: 73%; drying 25% (soil); crushing: 1,5%; other: 0,5%). The expected power for drying ACM to a moisture content of 1% (w/w) is ≤ 15% [10]. The capacity of a full scale continuous system (10 reactors) is 10 tons of ACM per hour. The energy use is in the order of 60 - 70 kWh/ton.	kWh/ton	8, 10
Input requirements / acceptance criteria	MCD is an indiscriminate process capable of destroying all types of asbestos (screening of the input material). EDL's trials to date have focussed on asbestos cement products containing chrysotile and crocidolite. Asbestos cement roofing can be contaminated with organic material	*Options:* chrysotile / 'pure, friable' asbestos / asbestos cement/ asbestos containing scrap metal / asbestos containing soil / all ACM / other (to be explained)	7, 9

Parameter	Value	Q[45] or scale	Source no.
	like mosses and lichens. AC-sheets are mostly delivered in polythene bags. The reactor can deal with such pre-processed organic materials. This was proven before on projects (United Nations Development Programme (UNDP) and Global Environmental Facility (GEF)) dealing with contaminated soil ((persistent) organic contaminants like PCB's, Pesticides and Dioxins) [7] .		
Pre-processing (energy) requirements	Adequately pre-conditioning of double bagged (standard) ACM prior to feeding the material through the reactor stack. ACM would need to be dried to less than 1% (w/w) moisture and crushed to fragments less than 10 mm in length and width. Pre-processing will be fully automated in the final installation. The energy use for drying and crushing is in the order of 10 - 20 kWh/ton.	*Options:* pre-separated / reduced in size / grinded / milled / dried / none / other; plus kWh/ton	9, 10
Additives (chemicals) or other	No additives are used	*Options:* reactive chemicals / inert substances / other	
Fibre destruction	Laboratory scale trials carried out by the Italian National Research Council (2003 & 2011) revealed rapid asbestos degradation, reaching 100% destruction in 4-12 minutes. The results of these lab scale trials were replicated by EDL in pilot trials conducted in 2015 and 2016.	*Options:* full destruction / asymptotic decay of the reaction rate / none / other	4, 5, 7, 8, 9
Mass / volume reduction	Lab scale: mass reduction 20 - 60 %	%	4
Re-usability of end-product	The end-product of these processes are asbestos free powders which could be reused for the preparation of mortars with mechanical properties better than those obtained from lime-pozzolana conglomerates [5]. The reuse of post-milled powders in the mineral component in building materials has been investigated. Published evidence shows that asbestos-free milled powders are suitable for use in a variety of civil engineering applications, specifically	*Options: None*[47] / inert filler / building material (civil engineering) / active substance (cement, clay) / clean soil / other	5, 9, 10

[47] Strictly speaking this option disqualifies a technique, given the requirements of LAP 3 (see footnote 21).

Parameter	Value	Q[45] or scale	Source no.
	cements and mortars (exceptional high-grade cement additive, notably increasing the durability and strength of concrete). The powdered end-product has been used already in practice: • Production of pavers in Belgium (replacement of $CaCO_3$) • As a blend in paver stones • As EPC special cement product with Portland cement - EMC Sweden uses the product and it fit also in the Dutch "Beton-akkoord"[46]		
Installation type / size	Small and transportable plants (to be applied on industrial scale because of its advantages (fast and economic process, (extremely) limited gas and dust pollutions) [3]. The only full-scale ACM destruction technology using ball-milling. Further full-scale trials are being prepared and will commence in March 2018 [9]. The type / size of an MCD installation can be varied dependent the expected processing capacity, ACM type, pre-processing requirements et cetera. The MCD technology is adaptable, with the capability of setting bespoke systems dependent on the project. A complete 3-reactor system fits into a standard size sea container.	*Options:* On site / mobile / temporary / fixed medium scale / fixed large scale / other	3, 9
Installation capacity	MCD-installation has a capacity up to 10 tons of ACM per hour per multi-stack reactor – full scale continuous system consisting of 10 MCD reactors (approx. 25.000 tons/year – 300 days/year – 8 hours/day). The processing capacity can be further upscaled by: • adjusting the number of reactors in a tower; • increasing the overall number of towers in an operational plant; • bespoke tuning of milling parameters The March 2018 trials will give actual	*Scale:* <1.000 / 1.000 – 10.000 / 10.000 – 100.000 / > 100.000 tons/year	7, 8, 9

[46] A partnership between public and private parties aimed at making the concrete sector ('betonketen') more sustainable (https://mvonederland.nl/betonakkoord)

Parameter	Value	Q[45] or scale	Source no.
	information about the flow rate.		
Proven technique	The MCD-process has been demonstrated on a semi-industrial scale. The performance has been proven by state of the art analytical techniques.	*Options:* lab scale / pilot trials / upscaled / fully operational	9

Table 2: Non-technical parameters (reasonably objectifiable)

Parameter	Value	Q[1] or scale	Source no.
Logistical aspects	ACM will be sealed (bagged) and transported as per conventional methods. (Additional screening of the input material will be required to adequately understand asbestos composition (%)). These bags will be weighed and placed on a conveyor leading into a sealed warehouse where ACM drying, crushing, and conditioning takes place. The resultant material from pre-processing will feed directly into the MCD reactor tower, where fibrous asbestos degradation takes place. Collection of the end-product will be controlled to minimise dust emissions, and samples will be taken for analysis.	Q	7, 8, 9
Quality Assurance (QA) aspects (robustness et cetera)	MCD (EDL): Quality Assurance (QA) will be a part of the full MCD process, including pre-processing. Additionally, screening of the input material will be required to adequately understand asbestos composition (%). The system will comprise air emission/dust control, on-site air monitoring and noise /vibration control. The end-product will be sent for laboratory analysis (SEM, XRD), in accordance with country specific hazardous waste regulations. Re-processing will be carried out if required. After certification of the process re-processing should no longer be necessary. Due to the relative simplicity of the technology the process is robust. The installation is modular build-up and it concerns (relatively) closed system operation. In case one side of the rotor blade starts getting worn (after more than 1000 hours of operation) the direction of rotation of the reactor motor is changed. The reactors can be cleaned by flushing using water.	Q	8, 9
Risk aspects (in relation to transport, occupational H&S residents and environ-ment, end-product, other waste)	Gas and dust pollutions from mechano-chemical reactors are (extremely) limited, because operations are restricted in a close and limited environment and does not use thermal equipment. In continuous industrial reactors, which allow an airflow inside the system to accelerate the processes, a treatment of the exit gasses must be carried out in order to remove the suspended asbestos fibres and other fine dust particles [3, 4]. The overall level of risk associated with the processing of ACM can be adequately controlled using standard	Q	3, 4, 8, 9

Parameter	Value	Q[1] or scale	Source no.
	occupational H&S handling requirements. The only time at which any site worker will encounter untreated ACM would be when loading bagged bulk material into the enclosed pre-processing system for drying and crushing. Reactor design encapsulates all materials so in the event of any failure, ACM would be 'trapped' inside the reactor. No requisite for harmful additives or toxic solvents. Easy plant establishment and decommissioning of plant. Simple operation, i.e. not requiring complex start-up and shutdown procedures. The end-product shows no fibrous morphology, and therefore no carcinogenic risk factors. No hazardous forms of respirable silica will be formed. All silica is converted to an amorphous habit. Standard precautions measures will be taken to prevent exposure to respirable inert dust [8, 9]. The system will comprise: • Air emission / dust control • On-site air monitoring • Noise / vibration control		
Energy balance with replacement product	The avoided CO_2 emission depends on the type of material that can be replaced by the end-product. As substitute for cement the avoided CO_2 emission is in the range of 390 - 820 kg CO_2/ton[48]. For concrete mortar, a mixture of cement, gravel, fillers and additives the avoided CO_2 emission is in the range of 40 - 140 kg CO_2/ton. The production of 1 ton of MCD-end-product requires approx. 60 - 70 kWh or 40 - 45 kg CO_2 (based on: 1 kWh (electricity) is equivalent to 0,65 kg CO_2/kWh). The energy balance with the (example) replacement product seems to be positive.	Q	
Costs in relation to energy use	No data: The results of March 2018 MCD-trials will detail a range of information, including the cost of energy per ton. A rough estimate of the cost of energy per ton, based on the energy consumption mentioned above and an indication of the Dutch large customer electricity tariffs, is < € 10/ton.	*Costs (in actual market prices) in* €/ton *and/or (scale):* < € 10/ton; € 10 – 100/ton; € 100 – 200/ton; € 200 – 500/ton; > € 500/ton	9
Installation investments	From an economic point of view, the investment cost of an industrial ball milling plant can be derived from that of similar plants used in other environmental applications. This cost	*(Claimed) investments in* € *and/or scale*: < 1 million € 1 million – 20 million; > € 20 million	5, 8, 9

48 Source: https://www.rvo.nl/sites/default/files/2018/02/GER-waarden%2520en%2520CO2-lijst%2520-%2520februari%25202018.xlsx

Parameter	Value	Q[1] or scale	Source no.
	is orders of magnitude less than thermal or chemical based inertisation systems [5]. The overall capital expenditure of an MCD™ installation is approximately € 6 million. This would consist of a full processing unit, including a multi-stack reactor tower (exclusive of conditioning and auxiliary equipment, including air emission equipment).		
(Market) value of end-product	The market value of the previous mentioned applications of the end-product are: • Production of pavers in Belgium (replacement of $CaCO_3$): approx. € 5 à 10 per ton • Blend-in in paver stones: approx. € 25 à 30 per ton • End-product is added to Portland cement: approx. € 5 à 10 per ton	*(Claimed)* value in €/ton And/or (options): avoided soil decontamination costs / < € 10/ton / > € 10/ton	
Other costs	No information available about cost items like labour, maintenance and site protection.	Q	

Table 3: Non-technical parameters (hardly objectifiable)

Parameter	Value	Q[1] or scale	Source no.
Financial risks and securities; business case	MCD (EDL): There are limited financial risks related to the ACM destruction capabilities of the proven MCD technology. The scalability and effectiveness of the process is well documented, with continuing development demonstrating greater efficacy for ACM destruction. An operational plant can be modified following installation (within reason), to achieve optimal ACM destruction based on continuous monitoring and R&D. MCD provides the benefit of previous scrutinization for technology development, including cost benefit analysis over other technologies; conducted by the Global Environmental Facility (GEF)[49] and United Nations Development Program (UNDP)[50] for recalcitrant organic contaminants. ACM destruction can be achieved in shorter time frames, and using (significantly) less power, than comparable thermal treatment methods. The empirical and documented evidence of EDL's MCD process provides justification for proposed ACM	Q	8, 9

[49] https://www.thegef.org
[50] http://www.undp.org/content/undp/en/home.hmtl

Parameter	Value	Q[1] or scale	Source no.
	degradation project(s), based on both the expected commercial benefit as well as the positive environmental outcomes.		
Public and administrative acceptance	MCD (EDL): Public (and administrative) acceptance is expected for a number of reasons: • The final product is an inert powder which can be safely reused in civil engineering applications. • No legacy issues associated with the recycled ACM. • Destruction takes place in a closed system, at low temperatures. • Sustainable approach, with comparatively less energy and resources used to treat ACM.	Q	9
Potential CO_2 footprint	Based on the estimation made for the parameter Energy balance with replacement product the potential CO_2 footprint is estimated as small to medium. At request of UNEP, EDL are now investigating solar power to reduce the overall fossil-fuel requirement for on-site generated power, subject to site-specific conditions. Renewable power systems to offset the carbon footprint of any process is inherently beneficial for public and market acceptance. Therefore, EDL will consider the application of renewable energy sources (i.e. solar) for a full-scale operational plant for ACM treatment.	Options: Small / medium / large / very large (For the purpose of this study it would take too far to actually calculate the potential CO_2 footprint; therefore a rough scale is used, built on more concrete and precise basic parameters)	10
Actual market prices	MCD (EDL): The March 2018 trials will give actual information about the costs per ton ACM.	Actual price in €/ton	

Table 4: Overall assessment

Parameter	Value	Q[1] or scale	Source no.
Technology readiness level (see table 1)	MCD (EDL): estimated as TRL 8/9	Scale	(see above)

Parameter	Value	Q[1] or scale	Source no.
Distance to market	MCD (EDL): Distance to market is small and depends on technical and non-technical issues. The technique is proven, but the proof on industrial scale has still to be delivered and the pre-treatment demands are strict (size crushed and moisture content of ACM). The installation has a short construction time. The capital investments are relatively low, which is also the case for the energy consumption. A positive business case is expected (profitably operation is expected for a gate fee which is considerably lower than LAP3's maximum gate fee of € 205 per ton).	Q	
Sustainability aspects	(+) simplicity and robustness of the process (less quality control parameters), complete fibre destruction, re-usable end-product, modular, scalable and transportable installation and the relatively simple environmental control techniques (-) energy use (process and pre-process, including (intensive) drying of ACM, which takes 25% of the total energy consumption), occupational health and safety and environmental risks of pre-processing and ultra-fine end-product	Q	
Area of application	EDL'trials to date have focussed on asbestos cement products containing chrysotile and crocidolite. A homogeneous feed of asbestos cement makes the process more controllable and guarantees a qualitatively better and certifiable end-product.	Q	

Sources

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7. Mechano-Chemical Destruction (MCD™) of asbestos containing materials - Environmental Decontamination Limited, November 2017
8. Criteria list for asbestos waste treatment - MCD™ Technology, 19 February 2018
9. Notes on the exchange of information with Environmental Decontamination Europe Ltd, 12 March 2018

10. Letter from EDL addressed to the Bureau KLB projectteam entitled: Assessment Response - MCD™ Asbestos waste Treatment, April 2018

Analysis sheet: Biological processes

Table 1: Technical parameters

Parameter	Value	Q or scale	Source no.
Treatment Mechanism	Exposure of asbestos fibres to fungi (and/or lichens and bacteria) and/or other natural occurring environments. Some types of fungi produce organic acids and/or chelates which can leach out Mg (chrysotile) and/or Fe (crocidolite and amosite). If this reaction is completed, the typical chemical and crystalline structure of asbestos is decomposed in such a way that no carcinogenic activity remains.	Q	1, 2, 3, 4, 5, 6
Type of process	Biological degradation of asbestos fibres and asbestos fibres in a matrix of cement	Q	4, 5, 6
Process time	Month/years, depending on conditions on site (soil) or in special designed bio reaction vessels	*Scale*: mins / hrs /days / months / years / centuries	4, 5
Process temperature	Contaminated soil in situ: natural temperature Asbestos cement products in bioreactor: approximately 20 °C	°C	4, 5
Energy requirements	Contaminated soil in situ: no external energy needed AC-products in bioreactor: energy consumption (milling and continuous mixing) is low compared to thermal treatment methods	kWh/ton	4, 5
Input requirements / acceptance criteria	Chrysotile, friable Chrysotile as well as asbestos cement Soil contaminated with asbestos cement products as well as loose fibres and aggregates	*Options:* chrysotile / 'pure, friable' asbestos / asbestos cement/ asbestos containing scrap metal / asbestos containing soil / all ACM / other (to be explained)	4, 5

Parameter	Value	Q or scale	Source no.
Pre-processing (energy) requirements	Asbestos must be available for fungi/lichens/bacteria and/or a natural or an artificially created environment. In soil: as present, no or minor requirements Asbestos cement products: must be reduced to optimum size for availability to fungi and suitable pH value.	*Options:* pre-separated / reduced in size / grinded / milled / dried / none / other; plus kWh/ton	4, 5
Additives (chemicals) or other	Other: fungal cultures (and/or lichens and bacteria) with their nutrients	*Options:* reactive chemicals / inert substances / other	4, 5
Fibre destruction	Full destruction claimed for chrysotile fibres at optimum conditions Asymptotic decay of the reaction rate in a natural environment (soil)	*Options:* full destruction / asymptotic decay of the reaction rate / none / other	4, 5
Mass / volume reduction	No data	%	
Reusability of end-product	For soil in situ: clean soil Asbestos cement: low-grade inert filler (reusability of end-product: to be proved)	*Options: None*[51] / inert filler / building material (civil engineering) / active substance (cement, clay) / clean soil / other	4, 5
Installation type / size	For contaminated soil: in situ with added fungi and nutrients Asbestos cement and other asbestos containing materials (ACM): fixed small/medium scale (special designed bio-reactors)	*Options:* On site / mobile / temporary / fixed medium scale / fixed large scale / other	4, 5
Installation capacity	Soil in situ: 10.000-100.000 tons/year Asbestos cement: 1000 tons/year using optimum sized bioreactors	*Scale:* <1.000 / 1.000 – 10.000 / 10.000 – 100.000 / > 100.000 tons/year	4, 5 (estimation by Bureau KLB)
Proven technique	Lab scale / Pilot trials	Options: lab scale / pilot trials / upscaled / fully operational	

[51] Strictly speaking this option disqualifies a technique, given the requirements of LAP 3 (see footnote 21).

Table 2: Non-technical parameters (reasonably objectifiable)

Parameter	Value	Q[1] or scale	Source no.
Logistical	Soil in situ: no transport Asbestos cement using bioreactors*:* asbestos cement has to be transported to the site where the bioreactors are stationed or the (medium sized) bioreactors are transported to the location where the asbestos cement is remediated.	Q	4, 5
Quality Assurance (QA) aspects (robustness et cetera)	Conversion rate of the asbestos as well as other crucial parameters must be monitored during the conversion process Complete conversion must be proved by means of well documented analytical procedures	Q	4, 5
Risk aspects (in relation to transport, occupational H&S, residents and environ-ment, end-product, other waste)	Using fungi (and/or lichens and bacteria) outside laboratories is not risk-free. An important research aspect is the selection of 'intrinsically' safe fungi (high level of control based on the available asbestos mineral 'diet' – no chance of survival in case of absence of the specific diet). Soil in situ: Apart from site management/-protection for a longer period, no additional risks are to be expected because of the completely natural conditions ('doesn't hurt to try') Asbestos cement using bioreactors*:* AC sheets must be transported (transport risks) and must be broken into pieces to optimum size (H&S risks). H&S risks can be controlled by using standardized methods and control measures	Q	4, 5
Energy balance with replacement product	No data	Q	
Costs in relation to energy use	No claims yet, but costs will be relatively low (AC using bioreactors) to very low (soil in situ)	*Costs (in actual market prices) in* €/ton *and/or (scale):* < € 10/ton; € 10 – 100/ton; € 100 – 200/ton; € 200 – 500/ton; > € 500/ton	4, 5
Installation investments	Contaminated soil in situ: low cost (<1 million), Asbestos cement and other ACM in bioreactors: 1-10 million (too early to make a realistic estimate)	*(Claimed) investments in* € *and/or scale*: < 1 million € 1 million – 20 million; > € 20 million	
(Market) value of end-product	Contaminated soil: avoided soil decontamination costs: > € 10/ton. Asbestos cement and other ACM*:* < € 10/ton	*(Claimed*) value in €/ton And/or (options): avoided soil decontamination costs / < € 10/ton / > € 10/ton	4, 5 (estimation by Bureau KLB)
Other costs	No data	Q	

Table 3: Non-technical parameters (hardly objectifiable)

Parameter	Value	Q[1] or scale	Source no.
Financial risks and securities; business case	Relatively low: low investments costs (bioreactors), low or very low energy consumption	Q	4, 5
Public and administrative acceptance	Hardly any data. Will probably depend on location. The impact of biological processes on the environment is expected to be low, which can be a promoting factor for public acceptance	Q	4, 5
Potential CO_2 footprint	Asbestos in soil: small Asbestos cement products: medium	Options: Small / medium /large /very large (For the purpose of this study it would take too far to actually calculate the potential CO_2 footprint; therefore a rough scale is used, built on more concrete and precise basic parameters)	
Actual market prices	Too early for a reliable estimation	Actual price in €/ton	4, 5

Table 4: Overall assessment

Parameter	Value	Q[1] or scale	Source no.
Technology readiness level (see table 1)	Asbestos in soil (free fibres in situ): TRL 5 - 6 Asbestos cement and other ACM (in bioreactor): TRL 1 - 3	Scale	
Distance to market	Asbestos in soil (free fibres in situ): Distance to market is relatively small : it can be used at semi industrial scale at low (investment) costs, it will generate hardly any disturbance of the environment (public acceptance) and excavation can be prevented. On the other hand the completeness of asbestos fibre destruction is not yet proven in real life situations and biological remediation is a slow process. Asbestos cement and other ACM (in bioreactor): distance to market is big; early stage of developmental	Q	
Sustainability aspects	Asbestos in soil: the energy consumption is low, the CO_2 footprint is expected to be low/small and no transport is required. A careful control of the completeness of the fibre destruction (asymptotic decay of reaction rate) and optimization of the analytical procedures (analysis of the complex transition states) is needed. Asbestos cement and other ACM (bioreactors): (in addition to asbestos in soil) energy consumption and the CO_2 footprint is higher (medium) because of the pre-treatment (break into pieces/crushing). Transport is needed, for ACM to location where	Q	

Parameter	Value	Q[1] or scale	Source no.
	the bioreactors being in operation or bioreactors to the remediation locations.		
Area of application	Remediation of asbestos contaminated sites in situ (not suited for locations with bagged waste (e.g. landfill sites)). New approaches/rules of landfill might create new possibilities for biological degradation at landfill sites. Biological degradation of asbestos cement and other ACM might be possible in future but still requires much research.	Q	

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Annex 2: List of consulted persons

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List of experts that were interviewed

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Annex 3: References

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