POLITECNICO DI MILANO

Faculty of Industrial Processes Engineering

Master of Nuclear Engineering

Radioactive waste management treatments: a selection for the Italian scenario

Supervisor: Prof. Mauro Mancini

Assistant supervisors: Prof. Marco Enrico Ricotti

Eng. Giorgio Locatelli

Student: Matteo Sardini 735727

Academic year: 2010/2011

Contents

Tables

Figures

Glossary

ANDRA: Agence Nationale pour la Gestion des Déchets Radioactifs

ANS: American Nuclear Society

APAT: Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici

ATW: Alpha Toxic Waste

BfS: Bundesamt für Strahlenschutz

BWR: Boiling Water Reactor

CANDU: Canadian Deuterium Uranium

CEA:

CFR: Code of Federal Regulations

CORA: Commissie Opberging Radioactief Afval

COVRA: Centrale Organisatie Voor Radioactief Afval

D&D: Decontamination and Decommissioning

DAW: Dry Active Waste

DbE: Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH

DGR: Deep Geological Repository

DOE: Department of Energy

DUPIC: Direct Use of Spent PWR Fuel in CANDU Reactors

EDF:

EDRAM: International Association for Environmentally Safe Disposal of Radioactive Materials

EIX: Electrochemical Ion Exchange

ENRESA: Empresa Nacional de Residuos Radiactivos SA

FBR: Fast Breeder Reactor

GCR: Gas Cooled Reactor

HEPA: High Efficiency Particulate Air

HLW: High Level Waste

HTGR:

HWGCR:

HWR: Heavy Water Reactor

IAEA: International Atomic Energy Agency

ILW: Intermediate Level Waste

INL: Idaho National Laboratory

ISO: International Organization for Standardization

JAEA: Japan Atomic Energy Agency

JNES: Japan Nuclear Energy Safety Organization

KHNP: Korea Hydro & Nuclear Power

KRWM: Korea Radioactive Waste Management Co. Ltd

LL: Long Lived

LLW: Low Level Waste

LWR: Light Water Reactor

MAGNOX: Magnesium Non-Oxidising

MOX: Mixed Oxide Fuel

NAGRA: Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle

NDA: Nuclear Decommissioning Authority

NEA: Nuclear Energy Agency

NORM: Naturally Occurring Radioactive Material

NRC: Nuclear Regulatory Commission

NUMO: Nuclear Waste Management Organization of Japan

NWMO: Nuclear Waste Management Organization

OCRWM: Office of Civilian Radioactive Waste Management

ONDRAF/NIRAS: Organisme national des Déchets Radioactifs et des Matières Fissiles Enrichies/Prioriteiten van de Nationale Instelling Voor Radioactief Afval en Verrijkte Splijtstoffen

PUREX: Plutonium and Uranium Recovery by Extraction

PWR: Pressurised Water Reactor

RD&D: Research, Development and Demonstration

R&D: Research and Development

RPV: Reactor Pressure Vessel

RWMC: Radioactive Waste Management Committee

SKB: Sveriges Radioaktiva Avfall

SL: Short Lived

SNF: Spent Nuclear Fuel

SSN: Servizio Sanitario Nazionale

TENORM: Technological Enhanced Natural Occurring Radioactive Materials

TRU: Transuranic

UNGG:

UREX: Uranium Extraction

VLLW: Very Low Level Waste

VVER: Vodo-Vodyanoi Energetichesky Reactor

VVFF: Vigili del Fuoco

WNA: World Nuclear Association

Executive Summary

Nuclear industry, as well as any industrial and – more in general – human activity, produces waste. Current deep attention for radioactive waste management is one of the most peculiar aspects of nuclear applications, from nuclear industry as well as the conventional one and research, medical, military fields. Therefore, deep studies and their consequent application are carried on and while some methods become more and more available, others strengthen or extend their applicability.

This work aims to analyse the state of art of these treatments, with reference to different waste feeds existing, starting from international applications of these ones and making a first selection on the basis of their current availability and thus a second filter to select the processes suitable for Italian scenario, till to provide a road map for the implementation of each available technique in Italy for each waste stream.

As IAEA points out, the difference between pre-treatment, treatment and conditioning is, however, country specific, but according to the IAEA Radioactive Waste Management Glossary, we can refer to the following definitions ([1] pg. 27):

- Pre-treatment: any operations prior to treatment, such as collections, segregation, chemical adjustment or decontamination;
- Treatment: operations intended to benefit safety and/or economy by changing the characteristics of the waste. Three basic treatment objectives are:
  - Volume reduction;
  - Removal of radionuclides from the waste;
  - Change of composition;

  Treatment may result in an appropriate waste form. If treatment does not result in an appropriate waste form, the waste may be immobilized.
- Conditioning: those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, enclosure of the waste in containers and, if necessary, providing an overpack.

After collection and following by segregation (if proper separation of waste streams is not part of the collection process), the main objectives of pretreatment are to ([2] pg. 22):

- Segregate waste into active and non-active streams in order to reduce the volume of radioactive waste to be processed;
- Separate an active stream into components or to convert the waste into a form so that it may be easily treated, conditioned, and packaged for storage and/or disposal.

Packaging of radioactive waste by the waste generator for storage or transport to further waste processing is an important pretreatment operation and it has to satisfy the transport regulation ([2] pg. 23, 24).

Treatment and conditioning processes are used to convert radioactive waste materials into a form that is suitable for its subsequent management, such as transportation, storage and final disposal. The principal aims are to:

- Minimise the volume of waste requiring treatments;
- Reduce the potential hazard of the waste by conditioning it into a stable solid form that immobilises it and provides containment to ensure that the waste can be safely handled during transportation, storage and final disposal.

While treatment processes such as compaction and incineration reduce the volume of waste, the amount of radioactivity remains the same, but concentrated in a reduced volume. ([3], pg. 1).

In some cases, chemical adjustments are needed to ensure waste compatibility with following storage, treatment or immobilization processes.

Physical adjustment, such as size reduction by dismantling of structures or components, cutting into pieces or shredding, is normally used for solid waste. The implementation options for this operation are on-site to meet transportation requirements or at a central waste processing facility to improve treatment performance.

Reaching a clearance level of contamination by decontamination techniques means to reduce the volume of solid waste. It's opportune, in this context, to specify what “clearance” and “exemption” mean: “clearance” is referred to the process by which the radioactive materials resulting from an authorized practice are withdrawn from any later control. Thus, the release implies the removal from the control, while “exemption” means that no regulatory control is applied to the practice in question right from the start ([4] pg. 9). The thresholds for exemption were published both in IAEA's "International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources" and in the Directive 96/29/Euratom and they have international consensus, but these values have limited applications in terms of quantities, e.g. 1 tonne of radioactive materials, and therefore their general application on usually superior amount is not suitable. With unconditioned removal from regulatory control, the materials have no restrictions for future use, whilst a conditioned removal implies several conditions to be respected in the future use.

As well as these technical factors, other aspects are considered, such as economical and social ones, that can bring to refuse the implementation of a new technology or an use of an obsolete one.

As IAEA underlines, the introduction of a waste management facility within a country generally requires public participation in order to gain public acceptance. The absence of a information programme can probably take to a failure of a development of a waste management facility in a designated area, due to an opposition of the local community or political decision-makers. And such an opposition can be avoided by involving them into the process of site and technology selection.

This social approach is the main argument of Aarhus convention (1998) that ensures the availability and accessibility of information and the right for the public to be involved in a decision making process. Therefore, to avoid or to reduce the negative perception of planned waste management facilities and installations, it can be useful to follow the requirements of this convention ([2] pg. 10).

Internationally, a principle called *polluter pays principle* is followed: those who generate the waste are responsible for paying the disposal costs, while special disposal funds financed by the nuclear utilities have been set up to pay for feasibility studies and operating costs.

But the foundation of the waste management optimization is the application of the so-called *waste hierarchy* (Figure 1).

The waste should be dealt with at the highest practicable level in the hierarchy, to reduce as much as possible the pressure on final disposal. In summary, the application steps of waste hierarchy are ([5] pg. 25):

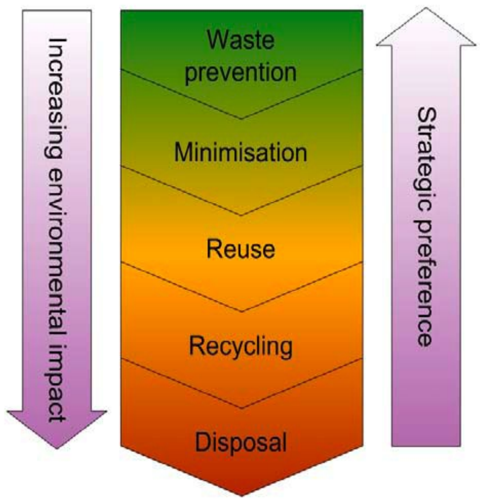


Figure 1: Waste hierarchy

- Not creating waste where practicable;
- Reducing waste arisings, both by activity and by mass;

- Minimising quantities of waste requiring disposal through decay storage, re-use and/or recycling, and incineration (when applicable);
- Disposal

Since the first step of this work is to analyse the international radioactive waste situation, an examination on several countries was carried out, with a national examples set heterogeneous enough to provide several informations about industrial, economical and social contexts very different each other. As it was said, this set of national examples includes different situations dues to their industrial history, their energetic policy – also relative to their geography – their population.

Therefore, European countries have been chosen to analyse the nuclear policy of the States just next to Italy (from some of them Italy gets electricity, such as France) and because one of the future possibilities for a radioactive waste disposal and/or waste processing facilities is a regional plant, where the waste from various country will be sent. Another reason is the implementation of centralised (regional or national) waste processing facilities that can be more economically convenient if some technology has high capital cost ([1] pg. 4, 5) and for which a regional cooperation between neighbouring countries can develop the knowledge of radiation technology and reduce potential hazards for the population ([2] pg. 11). About European disposal regulation, according to a Commission Directive, member States would be required to establish, implement and keep updated "national programmes" for the management of SNF and radioactive waste up to 2015 ([6]).

Other non-European countries have been chosen because of their strong experience with energy production by NPPs – also with very different histories, e.g. USA and South Korea – that have an important role for the development of new technologies and the implementation of well-proven treatments.

The main considerations after such an examination are the followings. First of all, it can be easily pointed out that NPPs are the main origin field for nuclear waste, so the number of NPPs existing in a country is an adapt sign to find a similarity between different contexts.

In addition, the military nuclear history of a country can have determined a particular waste production having non-negligible consequences in today waste management, i.e. by weapon-grade material production, reprocessing plants, navy reactors, military research.

Other obvious considerations can be the causes of a greater or smaller nuclear development, such as population, geography, politics.

Although an eventual Italian nuclear renaissance could foresee the use of French reactors (but after the last referendum in June 2011, such a nuclear renaissance is no more in program), France has a nuclear reality too different from Italian one to make an useful comparison about waste quantities: there are 19 nuclear sites with 58 nuclear reactors and 1 more reactor under construction, whilst in Italy the ancient nuclear sites for electricity production were only 4 and the eventual estimated new NPPs are always 4. Certainly, the experience gained by this deep exploitation of nuclear reactions, also regarding to radioactive waste management, can bring important developments in a international cooperation for the treatment of these waste (but this argument is valid also with other countries, of course). It doesn't have to omit the wide use of nuclear technology for military purpose and the relative waste production by i.e. submarine and ship reactors, plutonium production, nuclear warheads, and the fuel reprocessing facilities that doesn't exist in Italy.

In addition, France, as well as UK, has more big reprocessing facilities in operation where the SNF from other countries (included Italy) is sent. This activity is another main origin field of radioactive waste, especially HLW.

A similar incompatibility of the contexts is valid also with USA, with its nuclear power greater than the French one, Canada, that in addition uses widely a particular reactor type not used in Italy (CANDU reactors), UK, with its very large reprocessing plant of Sellafield and Japan, where, even if its particular seismic situation that can be a reference for Italy, there is a very high density of NPPs not comparable with Italy. Their useful contribution can be the studies for different disposal typologies, in addition to their research on treatments as said above, but always considering the differences between the waste production: some treatments need high waste input to be economically competitive and they maybe are not convenient in a smaller waste scenario, or others are suitable only for particular waste streams and not all waste typologies are present in Italy. A typical examples of this is the HLW coming from SNF reprocessing: if in Italy there was only such a plant, now in decommissioning, whilst in France, or in USA or in UK, there are more and larger of them where the SNF is normally sent, it's clear that the HLW existing in those countries is more than in Italy.

The same argument can be done for military nuclear material, not widely used in Italy but well implemented in those nations, with relative waste production.

The other European countries show more similarities with Italian framework.

Netherlands has less nuclear reactors than Italy with two nuclear site (and one of these shutdown): Borssele (1 PWR with 485 MWe) and Dodewaard (1 BWR with 58 MWe shut-down in 1997), in addition to its research centres. Even if the forecast for LLW/ILW amount over a period of 100 years are tripled between the prevision in 2000 and the one in 2008 ([7] pg. 3; [8] pg. 2), it can represent a good example for small amount waste management, a sort of opposite case of the nation described above, such as USA and France.

In Finland Loviisa (2 VVER producing 488 MWe each) and Olkiluoto (2 BWR producing 1.720 MWe total, and with the third reactor, an EPR, under construction) plants produce more electricity and an important contribution that this country can provide is the analysis about the planned deep geological repository in Olkiluoto – if such a disposal will be planned as a local one in Italy or as a regional one – and the experience about one of two EPR now under construction in Europe, a kind of reactor that can be used in an eventual Italian nuclear return.

More electricity is produced by nuclear fission in Belgium, with its 2 nuclear sites having 7 PWR total. An useful aspect of this PWR implementation is the skills gained with waste coming from PWR exploitation and decommissioning (of the old ones).

The most similar nuclear fleet to Italian one is in Switzerland, although with more power and without a MAGNOX technology, with 4 sites and 5 reactors (3 PWRs and 2 BWRs), so in Italy it can be expected a waste amount not too different – if the greater size of Swiss reactors can involve more waste, it's true that a GCR, as MAGNOX in Latina, produces considerably more waste than other technologies.

More reactors are currently in operation in Spain: 6 PWRs, 2 BWRs, that involves the expected increase of waste forecasts compared to Switzerland.

The greater presence of NPPs in Germany, the plants already decommissioned and the several studies on disposal options imply a good reference for efficient D&D operations.

Both Germany and Spain have some decommissioned reactors moderated by graphite – even if with very different technologies: 2 HTGR and 1 HWGCR for Germany, 1 UNGG for Spain; this is not a negligible aspect because one of the most problematic waste is just radioactive graphite from nuclear core: a contribution coming from the experience gained with these reactor decommissioning is suitable for D&D operations for Latina GCR.

So, with its particular nuclear situation but with a manageable waste amount due to small number of reactors in decommissioning or the same number of reactor in planning, Italy can look at the analogous scenarios, generally in Europe, to analyse the waste management with small quantities coming from NPPs; Switzerland, Finland, Belgium, Netherlands are good examples of these references. At the same time, it can take into account what happens in country with more nuclear power, such as Germany, Spain, eventually to share the knowledge of particular waste typologies (such as radioactive graphite, as said above) till to consider countries with large waste production, where a deep research on innovative treatments, a development for available techniques and studies for disposal solution are normally carried on.

About waste typologies coming from nuclear activities, NPPs operation gives rise to SNF; it contents more than 95% of its original energy, but with the actual open fuel cycle, this potential energy is considered as a waste. An implementing of a closed fuel cycle supplementing actual thermal reactors with fast reactors can exploit this energy with consequential waste reduction because the second ones can use as fuel the heavy and fissionable isotopes that accumulate in thermal reactors; so in this kind of a really closed cycle, the waste for disposal is only fission products with a small part of actinides and this reduces the heat load in the repository, increasing its capacity by about a factor of 5 ([9] pg. 2). There are three main approaches to SNF use and they change with the relative fuel cycle: thermal reactors without reprocessing, thermal reactors with reprocessing and fast reactors.

In the first case (*once through*), fuel is burned in thermal reactors and is not reprocessed and we have a SNF still rich in energy that is isolated in apposite canisters and then in underground repositories.

Ih the second possibility, fuel is burned in thermal reactors and after the plutonium is extracted using what is called PUREX processing.

In the third situation, recycled fuel prepared by pyrometallurgical processing would be burned in advanced fast neutron reactors (prototype technology).

From this study, it emerges a substantial difference in waste amount and typology using thermal reactors or fast reactors: a 1.000 MWe thermal reactor generates more than 100 tons of SNF a year, while a fast reactors with the same electrical capacity produce a little more than one ton of fission products, in addition to traces of TRU. Moreover, an AMLR fast reactor has a no significant quantity of long-lived TRU as waste so its radiation would decay to ore level (from which it came) in several centuries, rather than tens of thousands years ([10] pg. 6). With such a cycle, the need of highly radioactive materials transportation would exist only to ship it to disposal and to bring star-up fuel to a new reactor; in this way, commerce in plutonium would be effectively eliminated as well.

The other main source of waste from NPPs is the D&D phase. These activities have to decontaminate the plant's structures, with appropriate decontamination techniques on metal, concrete and other surfaces in order to facilitate access to working areas and the manipulation of components and equipment to be dismantled, reduce the radioactivity of plants and equipments to facilitate cutting, satisfy the standards on waste disposal or return this material to the public domain and to prepare the plant's structures for transport and future management. A basic IAEA principle about waste management says that "generation of radioactive waste shall be kept to the minimum practicable", which wants to lay emphasis on reuse or recycle of this waste within nuclear field or, for other less radioactive material, the removal from regulatory control ("clearance") for conventional reuse or recycle. As it was said above, some big components – like heat exchangers, steam generators, large tanks, etc... – have to be segmented in smaller pieces to insert them into containers for disposal. The problem of cutting and packaging of these kind of large components is that they can lock other works in the NPP because of their consuming time. Moreover, segmenting *in situ* suffers of the scarcity of space for the operations and of the high ambient dose in the containment the operators are subjected. Therefore, is not a rare choice to remove such components "in one piece" to cut and package them in a eventually available separate facilities out of the containment. Examples of this approach are the German MZFR project (The Multi-purpose Research Reactor Decommissioning Project) and Greifswald project. Regarding on (suspected) alpha contaminated areas, their decontamination to release from regulatory control involves a great engagement in terms of time consuming and labour intensity ([11] pg. 22, 23); the difficulties of these operation can be found in walls decontamination, where there is a problem about the good activity measurement at the very low levels required by authorities, the seepage of contamination into cracks and its reappearance on walls already declared "clean"; in this case, it can be envisaged to remove several centimetres of concrete before the wall can be declared "clean".

Regarding military field, the arising of radioactive waste has, on the one hand, the same origin of nuclear fuel cycle for NPPs and, on the other hand, has his particularity due to reactors for nuclear weapons production, their testing, submarines and craft with nuclear propulsion, manufacture of depleted uranium munitions and military research. Although the origin of nuclear exploitation was of military character, not all of these applications have an important influence on current Italian situation about radioactive waste – e.g. we can consider the difference from the large consequences due to the wide nuclear energy exploitation in military field, such as submarine reactors, nuclear weapons production in France, United Kingdom, United States, where, although their Non-Proliferation Treaty signature, there is a considerable radioactive waste amount coming from military activity during the Cold War.

The production of nuclear weapons releases carcinogenic and mutagenic materials such as plutonium, uranium, strontium, caesium and other dangerous chemical substances. Solid waste from submarine operations comes in a variety of forms, e.g. ion exchange resins or large bulky items such as old storage tanks or coolant pumps and small items such as contaminated tools, protective clothing and plastic sheeting; the replacement of devices from the core and from other plants forms a contribute of waste. Gaseous tritium light devices have been used for luminosity in a large number of instruments and dials.

From medical field, used nuclides are normally short-lived or medium-lived and with low or medium activity. After their use, these are treated as waste, temporally confined *in-situ* and then collected by the authorised firm for the disposal. Pharmacological and biomedical research uses radioactive materials as tracers, normally medium-lived and long-lived nuclides with low or medium activity usually mixed with other substances. Among this waste, it can find also contaminated animal carrions and unusable sources (as Co-60); moreover, according to Italian law, the radioactive sources must be declared to authorities (SSN, VVFF, APAT) and kept in authorised stores or returned to producers. The necessary condition to dispose of this waste is the conformity with at least one of these two condition:

- Activity concentration lower than 1 Bq/g and half-live lower than 75 days:
- Conformity with non radiological relevance:
  - Effective dose forecasted for any person of the population lower than 10 μSv/y;
  - Effective collective dose for one year not major than 1 Sv/person or a valuation analysis about the optimization of the procedure.

It can be useful to refer to the following scheme:

- Liquid waste:
  - residues of administered solutions;
  - washing waters (typically from glass washing);
  - serum or marked biological liquid;
- Solid waste:
  - bottle with seal cap, syringes and test-tubes, also with small volumes of liquid waste;

- solid waste from use of not-sealed radioactive sources (mono-use gloves, syringes, test-tubes, bottle, decontamination material and contaminated material);
- ion-exchange resins;
- used sealed radioactive sources (typically with medium/long-lived radionuclides).

As it's possible the presence of infective risks related to some pathogenic agents, the disinfection before management as "radioactive waste" is weighed up.

The waste from nuclear section of hospitals are an half-life below 75 days.

Regarding to waste from human body (after the assumption of radioactive medicinals or tracers), the dumping from the hospital wards in which nuclear therapy is used has to wait the descending below allowed level of radioactivity in decay tanks before draining in the normal sewer.

Conventional industry, such as food processing, chemical, steel also produces VLLW as a result of the concentration of natural radioactivity present in certain minerals used in their manufacturing processes. The waste is therefore disposed of with domestic refuse, although countries such as France are currently developing facilities to store VLLW in specifically designed VLLW disposal facilities ([12] pg. 1).

Also other industrial fields give a contribution in terms of radioactive waste: just for example, European fertiliser manufacturing contributes 90% of the alpha-active discharges in sea waters; scrap steel from gas plants may be recycled if it has less than 500,000 Bq/kg (0.5 MBq/kg) radioactivity (the exemption level) – this level however is one thousand times higher than the clearance level for recycled material (both steel and concrete) from the nuclear industry – and TENORM waste coming from coal ash, with 280 million tonnes arising globally each year (the largest stream), and carrying U-238 and all its non-gaseous decay products, as well as Th-232 and its progeny ([13] pg. 4, 5).

There is the presence of radioactive materials also in more common devices as used radioactive sources, some types of lightning rod, smoke detectors, contaminated metallic scrap.

As it was pointed out above, the problem of waste management has a double aspect: if the most radioactive material (i.e. HLW, SNF) arises with a relative small amount, other waste (i.e. LLW/ILW) has the trouble of its quantity.

For this purpose, clearance and recycle ([4] pg. 9) are key concepts concerning LLW/ILW production. The removal from regulatory control for reuse in conventional industry, i.e. clearance, or the recycle/reuse of the waste within the nuclear industry (when it's possible, of course) have as an important consequence the reduction of impact on the final disposal. The principle according to which "the generation of radioactive waste shall be kept to the minimum practicable" runs in this way. A typical example can be the choice of a reactor technology producing less waste than another: a GCR will have more waste amount than other reactor types to be managed in D&D phase.

The fuel cycle steps that can have a considerable influence in Italy are those included in back-end cycle, so after fuel exploitation, the phases of:

- Interim storage
- Reprocessing
- Vitrification
- Disposal.

Because of the absence of active uranium mines on Italian land and fuel fabrication facilities (activities characterizing the front-end cycle), the front-end cycle has not direct waste production in Italy.

But within those back-end operations, just interim storage and disposal (vitrified waste disposal) have indeed an importance for Italy, because reprocessing and vitrification are currently operated abroad. This is not a negligible aspect for HLW production: one of the main activity where liquid HLW is generated is just SNF reprocessing. Therefore, if there is a certain cost to send abroad the SNF for reprocessing – excluding in this way the possibility to reuse the energy contained in SNF (see above) – there is the advantage to dispose of only vitrified waste after its repatriation.

Another consideration is the different waste production (quantity and typology) between different technologies.

A first discrepancy exists with thermal reactors and fast reactors: the latter technology allows a waste production from fuel operation much less than the thermal one. This is due to the possibility to operate a full recycle of SNF coming from the nuclear core.

This is a obvious advantage of fast reactors, but they are not currently commercially available in a wide scale.

Therefore, a second discrepancy about waste arising is that between current reactor types.

In a scenario as the Italian one, a reuse/recycling of this type of decommissioning waste is suitable not only for IAEA's basic principle mentioned above, but also for practical situations such as economics and logistics: in Italy, where there is no actual repository, it is suitable to separate the material requiring treatment as radioactive waste from the great amount able to be normally reused and, also in the case where such a repository would be available, nevertheless the costs for conditioning and packaging into agreed containers usually can surpass the costs for segmenting, decontamination and clearance ([4] pg. 12).

The several examples analysed above ([11] pg. 36, 42, 43, 45-49, 52, 53, 58-62; [14] pg. 2) can function as reference cases to predict waste typologies and quantities coming from Italian NPPs decommissioning.

From there, the consideration is that the large amount of waste is formed by metals and concrete. They are present in any case, for every reactor technology.

These two waste stream have an substantial difference: metallic waste can be recycled as "cleared" waste or reused into nuclear industry whilst concrete is currently very difficult to treat due to its contamination, so a current, possible and considerable reduction of pressure on the final disposal can be provided only by metal recycling.

Radioactive waste typology from other fields can vary according to their origin.

The not-negligible difference for military nuclear waste between Italy and other countries with more military nuclear applications is not equally valid for waste from hospital and conventional industry, where the main radioactive waste arising concerns LLW/ILW as shown above.

LLW/ILW (with VLLW subcategory) have more available treatments than HLW. This aspect can be advantageous if we think about greater waste amount of LLW/ILW compared with the HLW one. This can involve more manageability of research and development phases for HLW treatments, because of its smaller arising; this signifies that some techniques currently not used for HLW have the possibility – due to a "not current critical" waste amount – to reach a full-scale utilisation. A similar reasoning can be valid for LLW/ILW, with the appropriate difference: several existing process are used for the great amount of this waste and, at the same time, others improve their implementation from research phase to full-scale use, with the consequence of a waste management optimisation.

Because of the great heterogeneity of LLW/ILW, a wide set of treatments exists. Certainly, some of these are at research phase, development phase or pilot scale, whilst others are fully exploited. This difference for implementation process is more evident when a waste stream has several possible treatments; some can be well-proven, some can be innovated and others will become available in the next years or the future.

Compaction and high-force compaction are already a regular part of LLW management and have realised a significant amount of volume saving prior to disposal. The current baseline treatment technology for most LLW generated from operations and decommissioning is high-force compaction (where applicable) followed by encapsulation (by grouting) prior to disposal. Compaction can be carried out by routing the waste in 200-litres drums and direct it to the super compaction suite. Both waste forms are ready for super compaction, which is then carried out. Typically the volume reduction achieved with super compaction is in the range of 4:1 to 10:1 depending on the waste stream characteristics, whilst with compaction is 5:1 Moreover, using blasting as a pre-treatment, followed by melting, can allow a wider envelope of material to be recycled ([15] pg. 51, 77, 83, 190, 192).

Thermal treatment of waste refers to the use of heat to stabilise and reduce the volume of waste. The most common example of this is incineration of VLLW/LLW, but other approaches exist such as pyrolysis, plasma arc processes, melting. These processes significantly reduce the volume of waste and remove some of the volatile and hazardous components of the waste ([16] pg. 24).

Cementation through the use of specially formulated grouts provides the means to immobilise radioactive material that is on solids and in various forms of sludges and precipitates/gels (flocks) or activated materials. In general the solid wastes are placed into containers. This process has been used for example in small oil drums and 500-litres containers for intermediate-level wastes and has been extended to ISO shipping containers for low-level waste materials. The technology is being used in the immobilisation of many toxic and hazardous wastes that arise outside the nuclear industry and has the potential to be used in many more cases ([3] pg. 3).

Since considerable quantities of waste exist that are very difficult to incorporate in glass by vitrification, Synroc technology can adapt to different waste compositions; it can incorporate into its crystal structures nearly all of the elements present in HLW and so immobilise them. Those species which are not suitable for transmutation can then be immobilised in Synroc. The waste suitable for Synroc is HLW (containing Am, Cm, Cs, Sr, Tc, Pu), rare earths, calcined waste as well as ILW ([17] pg. 1, 5; [18] pg. 8, 23, 30, 37).

Generally, one process can be suitable for at least 3-4 waste types, some used both for LLW/ILW and HLW, others more specific and therefore suitable just for a defined radioactivity category.

An important difference for the treatments described above is the characteristic of their end-product. As it will be shown in the proposed road maps, the end product can take different ways, depending on its suitability for conditioning before final or interim disposal. The analysis provided above regards all technologies existing, concerning pre-treatment as well as treatment, immobilisation and conditioning phases, “interconnected” just in a kind of flow charts.

If some processes preview further treatments to adapt the end-product for pre-disposal conditioning, others have as output a waste already appropriate for it. Beyond the immobilisation techniques, such as cementation, bituminisation, vitrification, cold crucible vitrification, that just by definition produce an output directly for conditioning and then for disposal, other treatments usually have the immobilisation step in their flow chart before conditioning; however there are some of them that have directly a conditioning step before disposal.

Decontamination techniques – that sometimes are considered as a suitable pre-treatment just to separate "decontaminable" part from the rest of the waste (e.g. ion exchange membranes, ion-specific filtration, membrane filtration, reverse osmosis for liquids, oil filtration specific for oils and lubricants or phytoremediation for contaminated land) – can be seen as volume reduction process, because they reduce the amount of waste to be sent to further treatments or to disposal. An obvious consequence of these operations is the production of secondary waste (waste part other than the end-product), usually EW or VLLW and easily conditionable.

Secondary waste arises also from PVA dissolution, oil filtration and liquid concentrates volume reduction system (but for both they are EW or VLLW), whilst geopolymerization, DB-MHR haven't of it ([1] pg. 36, 37, 42, 44-46).

Volume reduction systems by pressure, such as hot isostatic pressing or compaction, generally acts on already treated waste, just to optimise the disposal space without further treatments, whilst volume reduction by destructive techniques, such as incineration, can involve consequential processes – e.g. ashes after incineration have several options between potential treatments before their disposal – and generally they have high capital cost, but their have however a large employment.

HLW has more specific treatments suitable for its higher radioactivity level, except for pyrolysis that, as said above, is one of the treatment with widest-range applicability, and calcination followed by vitrification, that can be used also for liquid LLW/ILW but originally developed for HLW.

We can underline that these latter operations aim only to immobolise the waste, while pyrolysis makes a volume reduction and partitioning and transmutation, with their different potential approaches, regard an innovative implementation of fuel cycle and therefore that preview a different waste arising. The importance of these applications is really clear for next reactors generation, because they virtually reuse what now is considered as a waste to extract further energy.

Certainly, the other important raison to implement partitioning and transmutation is the possibility to reduce the radiotoxicity time of the waste.

In any case, it need to point out again, a final disposal recourse is unavoidable, both for LLW/ILW and HLW treatments.

Starting now with a selection process, non-currently attractive methods will be rejected on basis of economical, technical and social aspects. This selection aims to point out all currently applicable treatments at international level prior to the disposal. Therefore, all the methods at research, pilot, demonstration phase or non suitable with the criteria of above, are beyond from the scope of this section, although they have a good potential development for future use. Widely used immobilization methods, suitable for LLW/ILW as well as HLW, such as cementation, compaction, Synroc (more recent), are not now reported and they are described above, whilst more specific immobilization techniques, such as vitrification, are considered because of their suitability for particular waste feeds.

Even if a treatment can be applied to different waste streams (as shown in the previous section), it's might be not the suitable method for all of these.

It is thought that complete dissolution, chemical separation and corrosion facilities do not currently exist on a significant scale whereas overseas melting LLW treatment facilities exist in countries such as Sweden, Germany and the United States.

Depending on the requirements for disposal, including price, there are other options for treatment which are not currently in commercial use. These processes include drying, wet oxidation, and melting ([5] pg. 134).

This can be seen as an advantage in terms of implementation: a singular capital cost, even if it's high, will provide a process adapt for a set of wastes for which different techniques implementations, with relative costs for each, can be avoided ([19] pg. 30-37; [5] pg. 75; [1] pg. 46, 47; [20] pg. 44, 45). Other examples of wide range treatments are incineration, drum drying or hot isostatic pressing, with the same consideration of above ([5] pg. 71-74; [1] pg. 30,31, 33). Moreover, sometimes their use as only available solution, maybe waiting for new development of more innovative approaches, justifies their high cost or can take to the decision to go on with their exploitation in spite of their low public acceptance. Most likely, in view of the new research fields and relative developments, a process both highly expensive and with low public perception – e.g. incineration – won't be considered for the construction of new waste treatment facilities, but just to continue its operational life.

But more peculiar treatments are developed and therefore currently employed. Just for example, it's the case of liquid waste, with its largest set of specific treatments, such as alkaline hydrolysis, electrochemical ion exchange (in development phase also for contaminated land), ion exchange membranes, ion-specific filtration, reverse osmosis, super-absorbent polymers (currently suitable for oils also). Other waste feeds that have treatments with particular specificity are resins (pelletization), combustibles (PVA dissolution), filters (liquid cartridge filter shearing and shredding and PVA dissolution), sludge (oil solidification), oils (oil solidification, oil filtration, super-absorbent polymers, contaminated land (thermochemical/advanced thermochemical process, that has reached an exploitation scale just for organic surfaces, whilst is in development phase for other waste types).

For these treatments, a mobile technology implementation can be hoped for – also thanks to their mobile implementation availability for many of these ([1] pg. 15) – to serve several sites with radioactive waste, avoiding its transportation and to optimise their employment on a campaign basis. The advantage of this approach is its flexibility according to power plants situations and the possibility to adopt new technologies as they will be developed.

On the other hand also a central facility can be economically advantageous, if it can receive waste from sites of a regional area. The main characteristics of plants such as e.g. cold crucible vitrification, incineration, hot isostatic pressing, PVA dissolution, pyrolysis, are generally their high capital cost and high level of technical expertise required, therefore these aspects lead to prefer a centralised waste processing plant. But to compensate their considerable implementation investment, these facilities would to receive radioactive waste not only from local national nuclear sites, but also from sites in a designed regional zone (both national or international). For this purpose, a strong international cooperation (e.g. about studies, research...) and regulation harmonisation (about radioactive waste categories, transport) is needed, particularly in Europe, where several countries in a relative small space use or have used nuclear energy, with consequent radioactive waste arising.

A problematic waste management aspect remains: the way to treat asbestos, concrete and graphite. In these cases, also well-proven applications, such as pyrolysis or thermochemical treatments, are not developed for these waste typologies, because of their particularity ([19] pg. 35, 39; [21] pg. 64, 65; [22] pg. 8).

HLW has several treatments options, some created just for this kind of radioactivity levels, such as calcination, vitrification, and then developed also for LLW/ILW, or pyrolysis and hot isostatic pressing, usually applied both for HLW and LLW/ILW ([19] pg. 33, 37; [21] pg. 58; [1] pg. 17). Partitioning and transmutation are the most innovative and potentially the best HLW management implementation, but their optimised employment requires an advanced fuel cycle that is not currently developed ([23] pg. 3). They are the only treatments that can reduce the radiotoxicity of HLW and, therefore, its confinement time.

To sum up, we think it's important to point out an interesting IAEA's approach to treatment technologies implementation.

There are two options for a scenario with a small number of plants (that typically will not produce sufficient volumes of waste to justify the large expenditures required for some high efficiency technologies). The most common is the use of regional, centralized, off site processing facilities which accept waste from many nuclear plants. These may be used for any individual country, or they may support a consortium of countries.

The second solution is the use of mobile systems which can be transported among multiple nuclear sites for processing campaigns. Typically such a system might be at an individual site for one to three months, but in some situations the mobile system may remain at an individual site for several years (e.g. the use of a supercompactor to recover some of the storage capacity of a ten-year accumulation of drummed and stored waste) ([1], pg. 16).

Depending on the national situation, centralized waste management can be done by a major waste generator, by a service organization, or by a specialized waste management organization. In countries where the national regulatory system is not very well developed, the waste management organization should be a State organization or a public company. In special cases the service of a foreign organization, inside or outside the country, specialized in waste management can be considered. It may also be possible to use the services of companies which are normally working with the equipment containing sealed radioactive sources and which have capacities for managing disused sources ([2], pg. 37).

A possible implementation of radioactive waste management in Italy is provided by a flow chart for each waste stream (here just few examples of these are reported), with the suitable treatments for it, the end products of these and the relative immobilisation options before the storage/disposal, according to Table 1 containing the waste feeds existing in Italy. Of course, some methods provide for further treatments if the end product of first ones is not suitable for storage or disposal.

Table 1: Treatments according to waste feed existing in Italy

WASTE STREAM	**TREATMENTS**
Asbestos	Treatments under development
Ash	Pelletization
Concrete	Treatments under development
Contaminated land	Thermochemical/Advanced thermochemical process; Pyrolysis
Evaporator concentrates	Cold crucible vitrification; Crystallization; Drum drying; Pelletization
Filters	Incineration; Liquid cartridge filter shearing and shredding; PVA dissolution; Pyrolysis
Graphite	Treatments under development
Liquid HLW	Calcination; Pyrolysis; Vitrification
Liquid waste	Alkaline hydrolysis; Calcination; EIX; Incineration; Ion exchange membranes; Ion-specific filtration; Reverse osmosis; Super absorbent polymers
Metallic waste	Incineration; Pyrolysis
Oils	Incineration; Oil filtration; Oil solidification; Super absorbent polymers

WASTE STREAM	**TREATMENTS**
Plastic waste	Incineration; Pyrolysis
Radioactive sources	Conditioning (grouting, cementation) or decay for those ones with half-life <100 d. [2], pg. 34, 35, 40, 41
Resins	Drum drying; Hot isostatic pressing; Incineration; Pelletization; Pyrolysis
Sludge	Drum drying; Hot isostatic pressing; Oil solidification
Uranium waste	For U-contaminated metals: Immobilisation; Minimisation/recycling

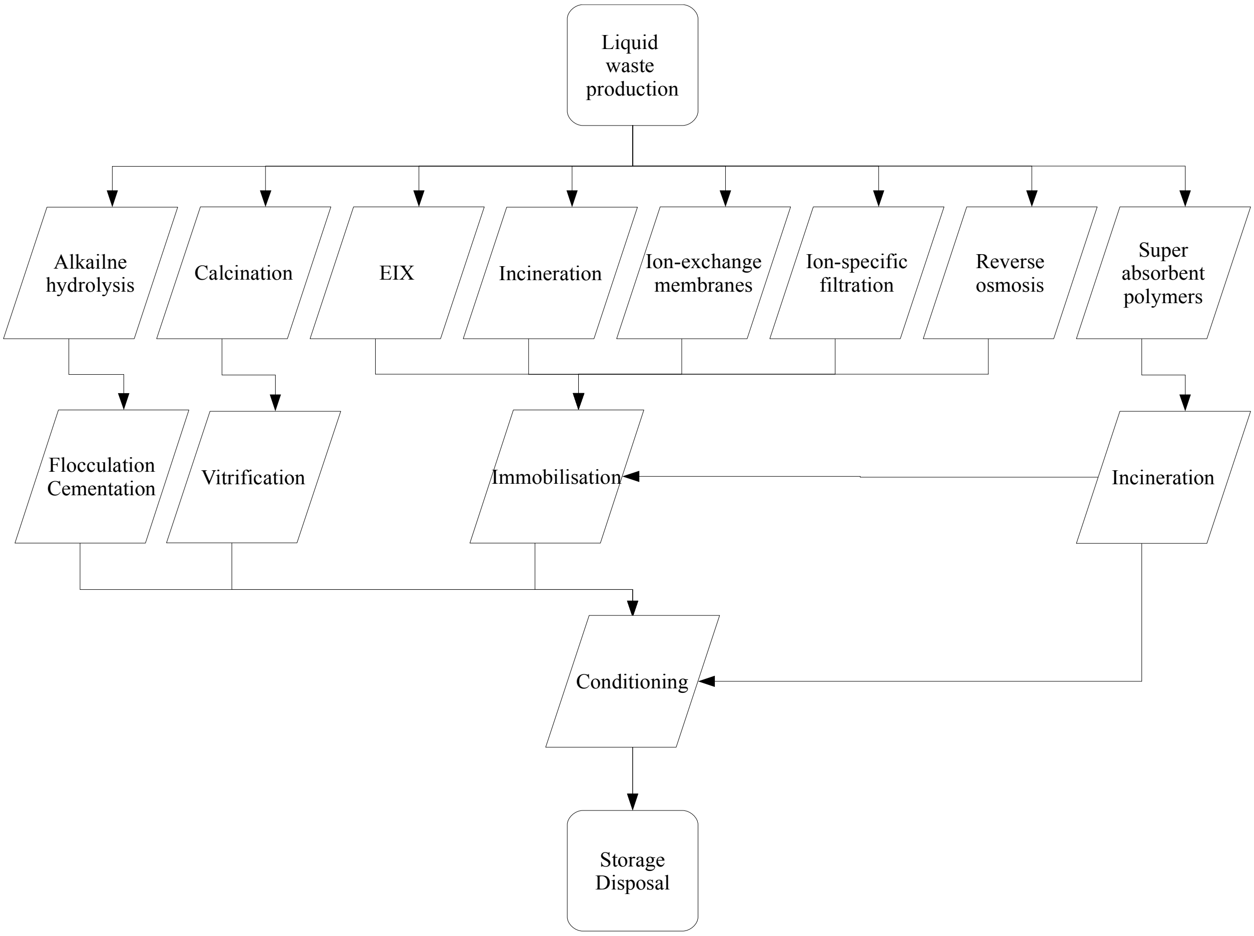


Figure 2: Diagram of the processes for liquid waste

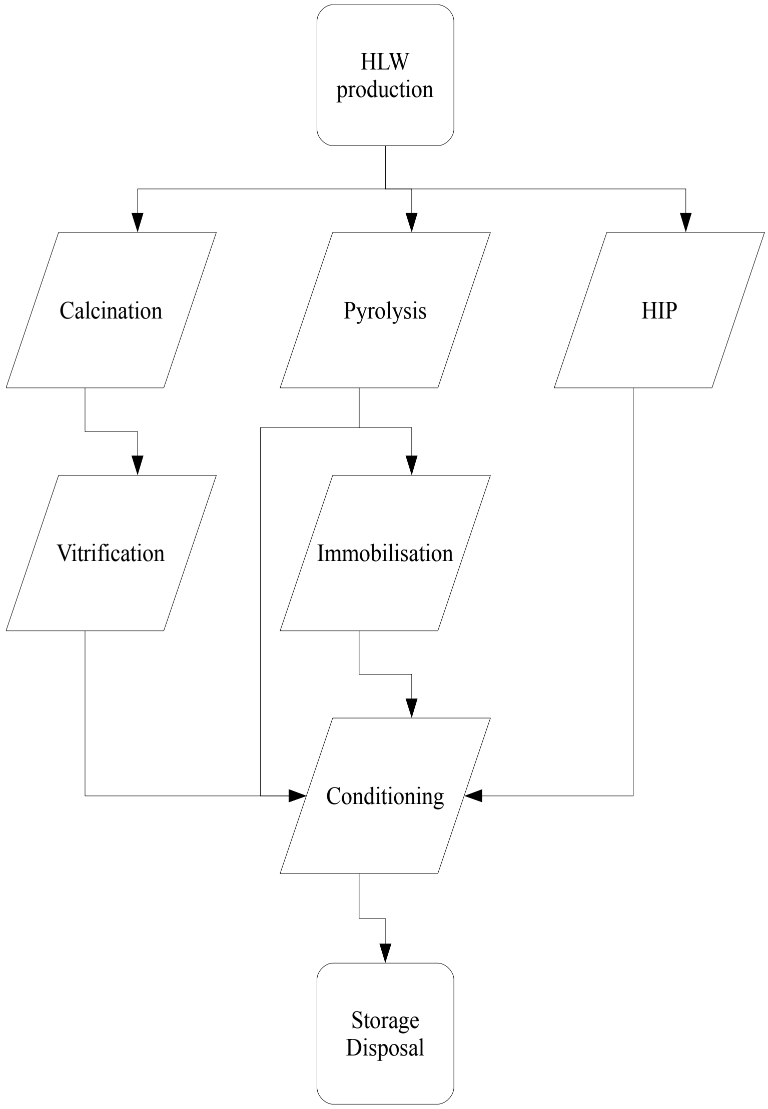


Figure 3: Diagram of processes for HLW

Abstract

Radioactive waste management represents one of the most relevant aspect of nuclear engineering and in the last years, an improved attention for this field provided the basis for a development of several solutions.

The aim of this work is the selection of suitable treatments for radioactive waste management in Italy. To reach such a selection, we start with a overview about international situation for nuclear waste, analysing the different sources, amounts, treatments methods, social and economical impacts; thus we recall the classification of these waste and the typical waste arising from NPPs operation and decommissioning and from other conventional fields, such as military, hospital and industrial; Section 4 concerns all treatments, whether they be well-proven, in development stage, at pilot scale or in research phase; here (and in the following sections) are considered all kind of operation on the waste (pre-treatment, treatment, immobilisation, conditioning) and a description of disposal options, available, innovative and abandoned. A first selection of methods is provided in Section 5, where there is a first choice for currently available treatments on the technical, economical, social basis. A further filter operation is provided in Section 6, where just treatments suitable for Italian scenario are considered and where a flow chart of operation for each waste typology is provided.

This work is founded on official documents from international authorities, national waste management companies, technical reports, mainly of these last years, to provide a valid road-map with state of art operations suitable for current Italy scenario.

Sintesi

L'industria nucleare, così come ogni altra attività industriale e, più in generale, umana, produce rifiuti. Ma in campo nucleare vi è una particolare attenzione per la gestione di questi ultimi, poiché uno degli aspetti più problematici dello sfruttamento dell'energia nucleare è proprio quello legato ai rifiuti radioattivi. Diversi studi vengono quindi portati avanti per consolidare trattamenti già utilizzati o per estenderne la loro applicabilità o, ancora, per renderne disponibili altri attualmente in fase di ricerca e sviluppo.

Lo scopo del presente lavoro è quello di proporre una selezione di trattamenti adatti per uno scenario come quello italiano partendo da una panoramica sulla situazione internazionale circa la gestione dei rifiuti radioattivi, passando per un'analisi di tutti i processi subiti da ogni tipologia di rifiuto (divisi prima di tutto per categorie di radioattività e successivamente per composizione del rifiuto) fino a eseguire una prima operazione di "filtro" in cui vengono scartati quelli attualmente non disponibili per poi fare un'ulteriore cernita dove vengono presi in considerazione solamente quelli adatti per l'attuale panorama italiano.

Dunque, questo lavoro si sviluppa come segue:

- Capitolo 2: analisi della situazione internazionale circa i rifiuti radioattivi in diverse nazioni, per comprendere i diversi scenari ed approcci;
- Capitolo 3: classificazione dei rifiuti radioattivi e loro analisi conseguente alla loro origine;
- Capitolo 4: analisi dei trattamenti attualmente esistenti per le differenti tipologie di rifiuti prodotti da attività nucleari, ognuno coi relativi vantaggi e svantaggi;
- Capitolo 5: primo filtro, ovvero una selezione dei trattamenti attualmente disponibili;
- Capitolo 6: secondo filtro, ovvero una cernita dei trattamenti adatti per lo scenario italiano con relativa presentazione di una road-map per ogni tipologia di rifiuto presente in Italia, le possibilità di una sua implementazione.

Più in dettaglio, il capitolo 2 contiene un insieme di tabelle riportanti i dati circa le quantità e la fonte di provenienza dei rifiuti, i trattamenti operati, gli aspetti economici e sociali; i paesi scelti rappresentano un gruppo alquanto eterogeneo per quanto riguarda lo sfruttamento dell'energia nucleare nazionale – si va infatti da Stati altamente nuclearizzati come Francia fino a quelli con pochi siti nucleari quali i Paesi Bassi – in cui identificare anche un riferimento valido per l'Italia.

Il capitolo 3 esplicita le categorie di rifiuti radioattivi internazionalmente riconosciute e ne analizza la relativa produzione durante la fasi di *decommissioning* di centrali di diversa potenza. Considera inoltre ciò che proviene da altri ambiti quali quello militare, ospedaliero e dell'industria convenzionale, sorgenti non trascurabili di questo tipo di scorie.

Il capitolo 4 analizza tutti i tipi di trattamento attualmente esistenti – senza distinguere tra pre-trattamento, trattamento vero e proprio, immobilizzazione, condizionamento – coi relativi vantaggi e svantaggi e le opzioni per lo stoccaggio temporaneo o finale. Una prima suddivisione viene fatta tra LLW/ILW (categorie che subiscono generalmente gli stessi processi) e HLW, mentre una seconda, per quanto riguarda i LLW/ILW, viene fatta in base alla composizione del rifiuto.

Il capitolo 5 fornisce il primo filtro di cui sopra, ovvero vengono accantonati i trattamenti non disponibili attualmente in base ad un insieme di ragioni tecniche, economiche e sociali, con la stessa suddivisione del capitolo precedente, così da sottolineare cosa resta valido per una dato tipo di scoria.

Nel capitolo 6 si ha un ulteriore filtro che conduce alla proposta di una road-map in cui i trattamenti validi per la situazione italiana vengono riportati in dei diagrammi di flusso, uno per ogni tipologia di rifiuto.

Il lavoro si basa su documenti ufficiali di autorità internazionali, società nazionali per la gestione dei rifiuti radioattivi, rapporti tecnici degli ultimi anni così da fornire una proposta allo stato dell'arte riguardo le tecnologie disponibili.

1 Introduction

Nuclear industry, as well as any industrial and – more in general – human activity, produces waste. But in the current nuclear field, a particular attention for its waste management exists, because one of the most problematic aspect of energy production by nuclear reaction is the relative radioactive waste production. Therefore, deep studies and their consequent application are carried on. Obviously, with the fast scientific and technological development some methods become available while others strengthen or extend their applicability.

This work aims to analyse the state of art of these treatments, with reference to different waste feeds existing, till to provide a road map for the implementation of each available technique in Italy.

Therefore, this work will be developed as follows:

- Section 2: analysis of the international situation about the radioactive waste in several nations, to realize the different scenarios and the different approaches;
- Section 3: classification of radioactive waste and their analysis as regards their origins;
- Section 4: explication of existing suitable treatments for the different waste streams produced by nuclear activities, with their advantages and disadvantages;
- Section 5: first filter, that is a sorting of currently available methods;
- Section 6: second filter, that is a grading of treatments suitable for Italian scenario with relative road maps for each waste typology present in Italy with implementation options and the way to be carried out..

Although differences between pre-treatment, treatment, immobilisation and conditioning processes definitions exist, the overall set of operations on radioactive waste will be expounded in section 4, selected in section 5 and 6 and finally ordered in following conclusions with relative considerations.

According to the IAEA Radioactive Waste Management Glossary, we can refer to the following definitions ([1] pg. 27):

- Pre-treatment: any operations prior to treatment, such as collections, segregation, chemical adjustment or decontamination;

- Treatment: operations intended to benefit safety and/or economy by changing the characteristics of the waste. Three basic treatment objectives are:
  - Volume reduction;
  - Removal of radionuclides from the waste;
  - Change of composition;

  Treatment may result in an appropriate waste form. If treatment does not result in an appropriate waste form, the waste may be immobilized.
- Conditioning: those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, enclosure of the waste in containers and, if necessary, providing an overpack.

As IAEA points out, the difference between pre-treatment, treatment and conditioning is, however, country specific ([2] pg. 22-24, [1] pg. 27).

Collection involves the receipt of the waste from the waste generating processes and is followed by segregation if proper separation of waste streams is not part of the collection process.

The main objectives of pretreatment are to:

- Segregate waste into active and non-active streams in order to reduce the volume of radioactive waste to be processed;
- Separate an active stream into components or to convert the waste into a form so that it may be easily treated, conditioned, and packaged for storage and/or disposal.

Treatment and conditioning processes are used to convert radioactive waste materials into a form that is suitable for its subsequent management, such as transportation, storage and final disposal. The principal aims are to:

- Minimise the volume of waste requiring treatments;
- Reduce the potential hazard of the waste by conditioning it into a stable solid form that immobilises it and provides containment to ensure that the waste can be safely handled during transportation, storage and final disposal.

While treatment processes such as compaction and incineration reduce the volume of waste, the amount of radioactivity remains the same, but concentrated in a reduced volume. ([3], pg. 1).

In some cases, chemical adjustments are needed to ensure waste compatibility with following storage, treatment or immobilization processes.

Physical adjustment, such as size reduction by dismantling of structures or components, cutting into pieces or shredding, is normally used for solid waste. The implementation options for this operation are on-site to meet transportation requirements or at a central waste processing facility to improve treatment performance.

Reaching a clearance level of contamination by decontamination techniques means to reduce the volume of solid waste.

Packaging of radioactive waste by the waste generator for storage or transport to further waste processing is an important pretreatment operation and it has to satisfy the transport regulation ([2] pg. 23, 24).

As well as these technical factors, other aspects are considered, such as economical and social ones, that can bring to refuse the implementation of a new technology or an use of an obsolete one.

As IAEA underlines, the introduction of a waste management facility within a country generally requires public participation in order to gain public acceptance. The absence of a information programme can probably take to a failure of a development of a waste management facility in a designated area, due to an opposition of the local community or political decision-makers. And such an opposition can be avoided by involving them into the process of site and technology selection.

This social approach is the main argument of Aarhus convention (1998) which requires the parties concerned to ensure the availability and accessibility of information and provides the general public with the right to be involved in a decision making process. Therefore, to avoid or to reduce the negative perception of planned waste management facilities and installations, it can be useful to follow the requirements of this convention ([2] pg. 10).

Internationally, a principle called *polluter pays principle* is followed: those who generate the waste are responsible for paying the disposal costs, while special disposal funds financed by the nuclear utilities have been set up to pay for feasibility studies and operating costs.

But the foundation of the waste management optimization is the application of the so-called *waste hierarchy* (Figure 4). The waste should be dealt with at the highest practicable level in the hierarchy, to reduce as much as possible the pressure on final disposal. In summary, the application steps of waste hierarchy are ([5] pg. 25):

- Not creating waste where practicable;
- Reducing waste arisings, both by activity and by mass;
- Minimising quantities of waste requiring disposal through decay storage, re-use and/or recycling, and incineration (when applicable);
- Disposal.

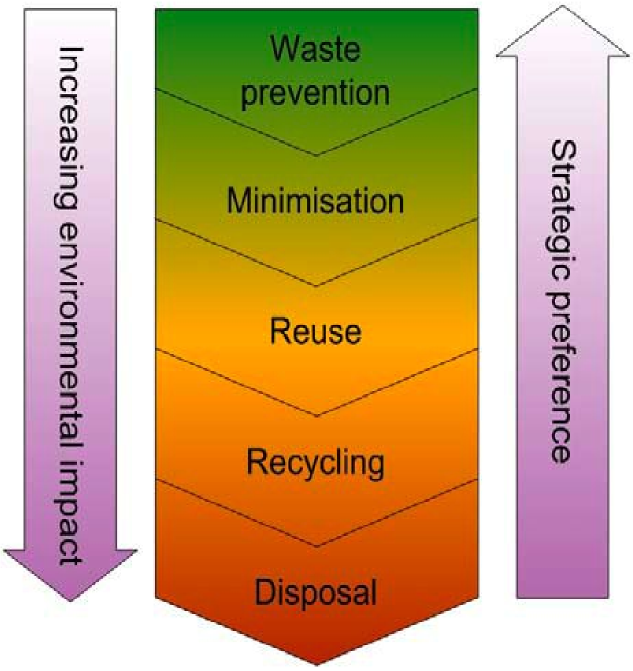


Figure 4: Waste Hierarchy

Two clear diagrams relating to the different phase of radioactive waste management are shown in Figure 5 and Figure 6 ([2] pg. 20, 21). In Figure 5 the several steps with local and central implementation options are described, while in Figure 6 the operations on waste before and after treatment are reported.

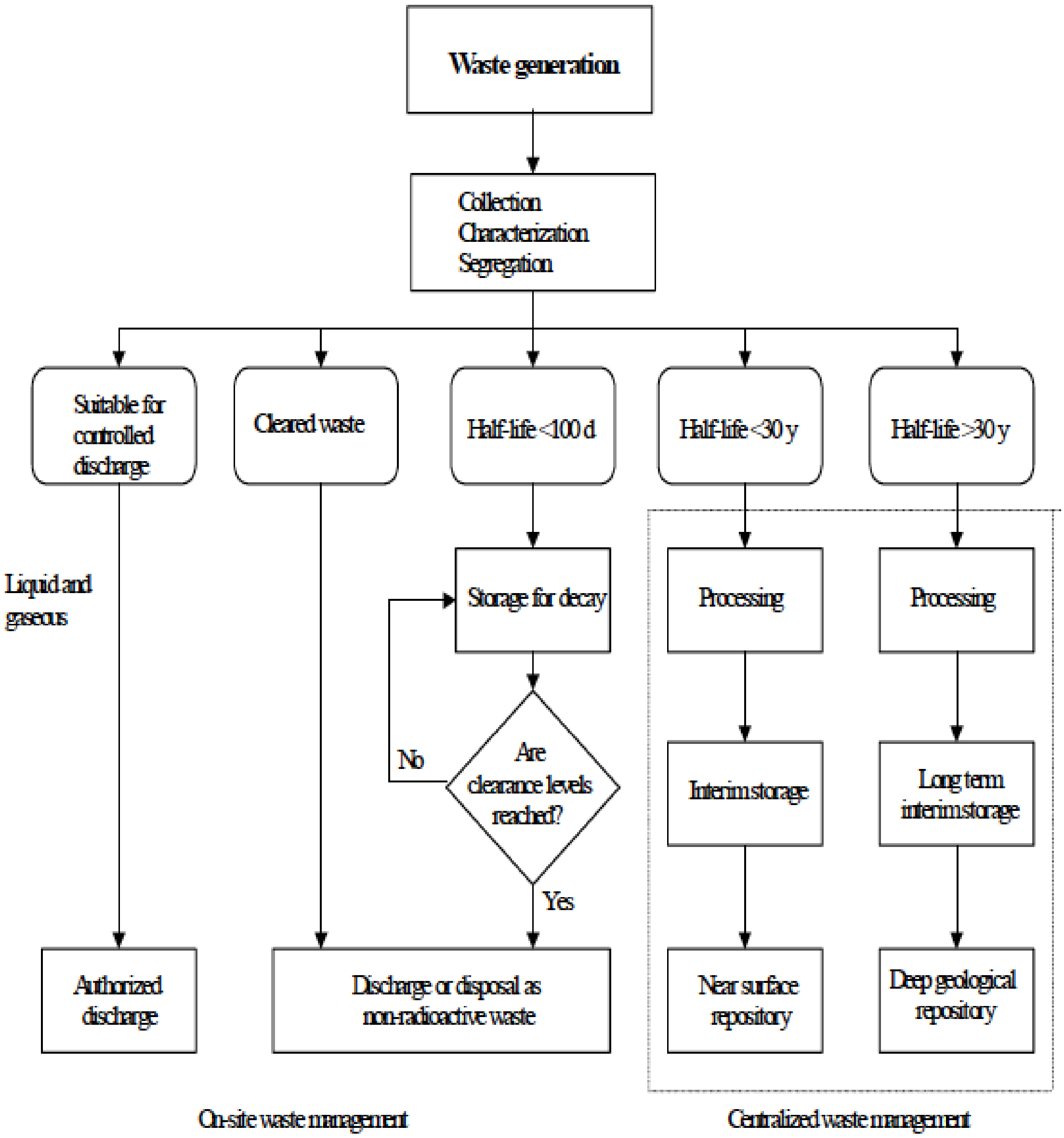


Figure 5: Local and central waste management

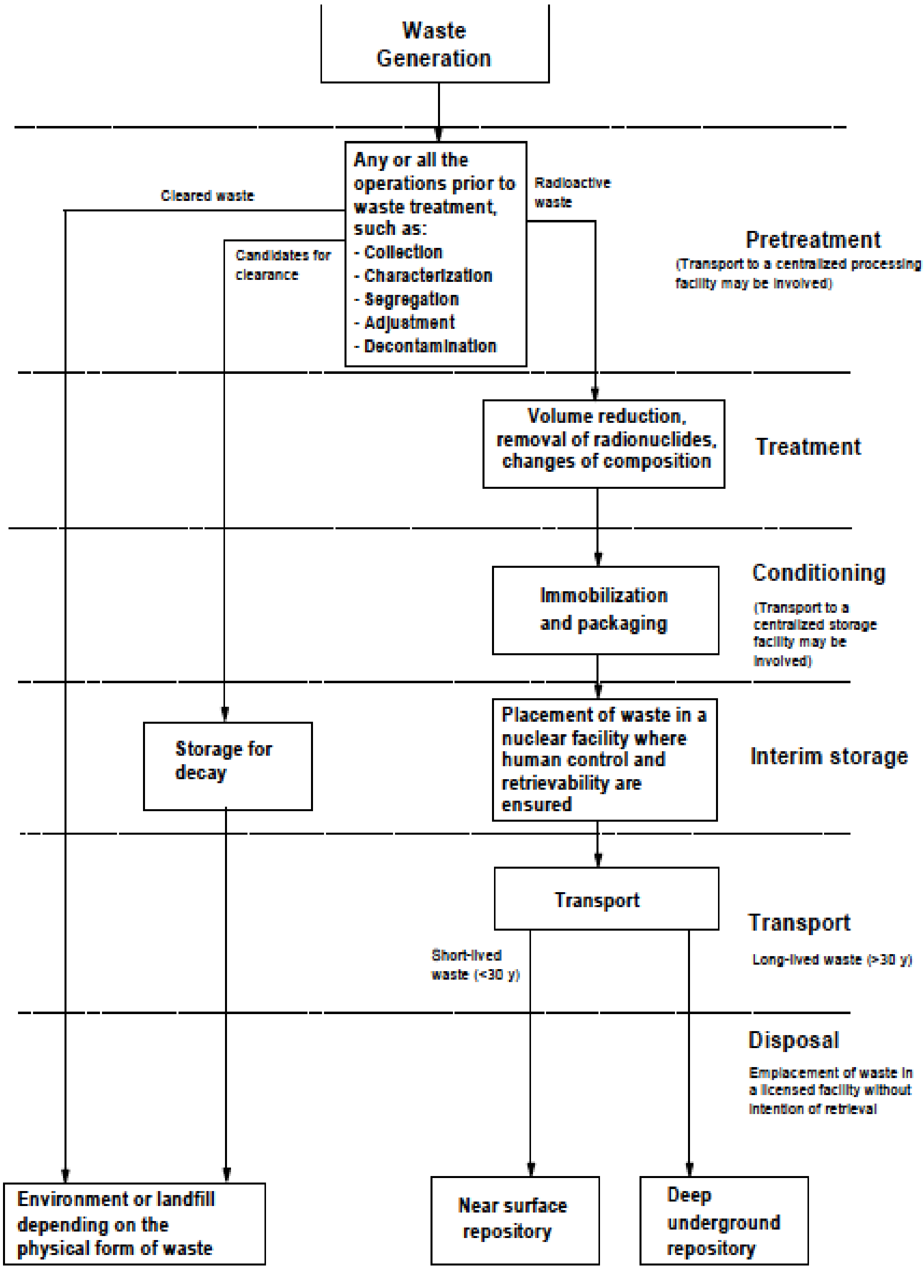


Figure 6: Waste management steps

In summary, the aim of this work is to identify the current available process for radioactive waste existing in Italy, considering the initial phases of waste management, such as, e.g., volume reduction by compaction, till the final ones, such as conditioning and disposal. As pointed out above, it will be provided by a series of "filters" starting with the overall set of technologies now used or in development internationally and concluding with the appropriate ones for Italian situation.

2 An international view

In this section, we present the international situation about the radioactive waste, referring to available data regarding quantities, typologies and treatment/disposal national policies. We consider 12 different cases, i.e. countries: Belgium, Canada, Finland, France, Germany, United Kingdom, Spain, United States, Sweden, Switzerland (members of EDRAM), Netherlands, South Korea.

The scope is then to understand if some of these national policies would be considered feasible in a scenario like the Italian one. We think that such a national examples set would be heterogeneous enough to provide several informations about industrial, economical and social contexts very different each other.

Here are reported the tables relative to each country (in brackets, the national enterprise for radioactive waste management) with the available data about the amount of the different kind of waste, the main origin field, the actual and foreseen treatments, the economical and social aspects with which the various radioactive waste management enterprises have to meet.

As it was said, this set of national examples includes different situations dues to their industrial history, their energetic policy – also relative to their geography – their population.

A possible aim of this section is to identify a kind of a reference scenario for Italy, by recognising a national context with these similar aspects.

Therefore, European countries have been chosen to analyse the nuclear policy of the States just next to Italy (from some of them Italy gets electricity, such as France) and because one of the future possibilities for a radioactive waste disposal and/or waste processing facilities is a regional plant, where the waste from various country will be sent. Another reason is the implementation of centralised (regional or national) waste processing facilities that can be more economically convenient if some technology has high capital cost ([1] pg. 4, 5) and for which a regional cooperation between neighbouring countries can develop the knowledge of radiation technology and reduce potential hazards for the population ([2] pg. 11). About European disposal regulation, according to a Commission Directive, member States would be required to establish, implement and keep updated "national programmes" for the management of SNF and radioactive waste up to 2015 ([6]).

Other non-European countries have been chosen because of their strong experience nuclear applications – also with very different histories, e.g. USA and South Korea – that have an important role for the development of new technologies and the implementation of well-proven treatments.

2.1 Belgium

Table 2: Belgium (ONDRAF/NIRAS)

AMOUNT AND SOURCE
From 2001 till 2070: 70.500 m³ of category A waste: • 18.700 m³ from routine production; • 51.800 m³ by dismantling operations; 8.900 m³ of category B waste: • 3.900 m³ now existing; • 5.000 m³ expected to 2070, from repatriation of waste from SNF reprocessing (some 100 m³), cleaning up of nuclear liabilities and decommissioning activities; Between 2.100 and 4.700 m³ of category C waste: • 195 m³ of vitrified waste from decommissioning of Eurochemic now existing; • 20 m³ of cemented waste from the operation of Pamela facility (pilot plant Mol for the production of waste suitable for storage) now existing; • 29,4 m³ of vitrified waste from COGEMA (now AREVA NC) now existing; • around 1.840 m³ from reprocessing of all current and future SNF ***or***; • 4.700 m³ if the reprocessing will be completely abandoned; Source: [24];
TREATMENTS
Volume reduction: • Combustible solid waste: reduced to ashes in an industrial incinerator, the ashes are poured into a 200-litre steel drum, the product obtained is a pellet with a maximum thickness of 40 cm; • Non-combustible solid waste: compressible waste is collected in the same type of steel drum, then compacted; non-compressible waste is cut up into pieces; • Liquid waste: by flocculation process, by which formed flakes produce residual sludge which is filtered and dried, while the purified water is checked prior to being discharged; by heat treatment, that consists in bringing the liquid waste to the boil, which leads to a residue in the form of radioactive sludge and steam, which is condensed then discharged after checking; certain organic or aqueous low-active liquid waste are treated in the same incinerator as the combustible solid waste, but not mixed; Stabilization and containment: • Solid waste: contained in cylindrical steel 400-litre drums resistant to corrosion (height: 1,07 m; diameter: 0,77 m), it is then stabilized by means of a matrix of cement, mortar or concrete, which is poured into the drums (1 ton); • Sludge (from liquid waste treatment): dried and mixed in a homogeneous way with bitumen and poured into steel drums of 200 or 400 litres; Storage:

- Conditioned LLW is stored in two buildings (1.929 m^3+14.300 m^3) with reinforced concrete walls 25 cm thick;
- Conditioned ILW is stored in a building (4.650 m^3) with reinforced concrete walls 80 cm thick;
- Conditioned HLW is stored in two buildings (250 m^3+600 containers of vitrified HLW and 1000 m^3 of cemented or bituminised ILW/HLW) with reinforced concrete walls between 1,2 and 2 metres thick;
- SNF, from SCK·CEN's BR3 reactor (10 MWe), is stored in a special building which can house 2 tons of fissile materials;
- Low-level radium and plutonium-bearing waste after processing/conditioning, are stored in a building with two separate storage rooms each measuring 2000 m^3;
- Final disposal: the studies currently being carried out by ONDRAF/NIRAS are at the Research & Development stage; none of these solutions is in use to day;

Source: [25], [26], [27];

ECONOMICAL ASPECTS

Decommissioning costs of all Belgian sites are estimated to € 7,93 billions (2006 value);

Source: [28] pg. 4;

SOCIAL ASPECTS

36 technical tours were organised in 2009. In total 617 people participated in such a technical visit to the Belgoprocess (a subsidiary of ONDRAF/NIRAS) installations. Moreover 13,867 people received information on radioactivity's role in society and the management of radioactive waste materials in 2009, via *Isotopolis*, the Belgoprocess information centre;

Source: [29] pg. 41;

NOTES

Category A waste: LLW/ILW short-lived waste;
Category B waste: LLW/ILW long-lived waste;
Category C waste: HLW long-lived waste

2.2 Canada

Table 3: Canada (NWMO)

AMOUNT AND SUORCES
LLW/ILW: approximately 166,229 m^3 of stored volume (after processing by compaction and incineration as applicable and recovery of space occupied by backlogged wastes) of operational waste and reactor refurbishment waste is expected to be generated from the committed nuclear program; SNF: 2.200.000 (rounded) used nuclear fuel bundles; Forecasts: 2064: 3,6 million used fuel bundles, referring scenario: the existing reactors would be shut down after their respective 25, 30 and 40-year average lifetimes; 2094: 7,2 millions used fuel bundles, referring scenario: existing nuclear reactors are assumed to be refurbished with a set of new pressure tubes and other major components and operated for an additional 30 years (25 years effective full power); refurbishment of all existing operating reactors results in an estimated total fuel inventory of approximately 5,5 million bundles; additional nuclear capacity is hypothetically assumed to be added in the form of two new 4 unit generating stations, this operation would result in the production of approximately 1,7 million fuel bundles; Source: [30] pg. 11, 12, 14, 27, 31, 35, 36 ; ; [31] pg. 36
TREATMENTS
LLW/ILW: compaction and incineration; SNF: temporary storage of used nuclear fuel in water-filled basins and also dry storage facilities; implementation of process for siting in DGR in sedimentary rocks or crystalline rocks; Source: [32] pg. 27, 28; , [31] pg. 38
ECONOMICAL ASPECTS
Development of the facility for the long-term management of Canada's SNF project, included the construction of a repository deep underground and creation of a centre of expertise: $ 7 to $ 8 billion (€ 5 to 6 billion); Liability for nuclear decommissioning and LLW/ILW management: $ 5,186 billion (€ 3,4 billion); Source: [33] pg. 12; [34] pg. 113;
SOCIAL ASPECTS
The NWMO's mission is to develop and implement, collaboratively with Canadians, a management approach for the long-term care of Canada's used nuclear fuel that is socially acceptable: ensure that any community that is selected to host this facility is both informed about the project and willing to host it; assist the potentially interested host community to consider carefully and thoroughly the project's potential benefits and risks when deciding whether to express interest and willingness to host the project; involve surrounding communities, regions and other jurisdictional levels potentially affected by the project and the transportation of used nuclear

fuel in the identification and assessment of public health, environmental, social, economic and cultural effects of the project as part of a broader regional assessment; involve First Nations, Métis and Inuit who are potentially affected by the implementation of this project;

Source: [33] pg. 8, 14-18;

2.3 Finland

Table 4: Finland (POSIVA OY)

AMOUNT AND SOURCE
SNF: 641 canisters containing a total of 941 tU of spent fuel from Loviisa 1-2; 1.219 canisters containing a total of 2.555 tU of spent fuel from Olkiluoto 1-2; 960 canisters containing a total of 2.054 tU of spent fuel from Olkiluoto 3 (under construction); canister's dimension: outer diameter 1,05 m, length 4,8 m (for Olkiuoto BWR fuel; 12 fuel assemblies/canister), 5,2 m (for Olkiluoto EPR – under construction – fuel; 4 fuel assemblies/canister)), 3,6 m (for PWR Loviisa fuel; 12 fuel assemblies/canister); LLW/ILW: 100÷200 m^3 of LLW/ILW generated annually during the operation of the plant units from Olkiluoto power plant; about 9 m^3 of LLW (solvent waste) generated by the operation of the power plant since 1977, from Loviisa power plant (end of 2008); Source: [35] pg. 38, 153, 518, 525
TREATMENTS
LLW/ILW: compaction for compressible waste; packing into stainless steel boxes, concrete boxes or waste drums for non-compressible waste; some metal components, such as pipes, can be cut and compressed into smaller volume before packing; big metal components, such as certain heat exchangers, are stored in a separate building which is located inside the enclosed power plant site until their radioactivity has decreased enough for releasing, recycling or disposal of the components; all operating waste is finally transported from the interim storages to a repository facility; spent ion exchange resins, evaporator bottom, sludge and sediment are treated in tanks in the liquid waste storage. Test runs of a liquid waste solidification plant, which is based on cementation; solvent waste are solidified by absorption; SNF: stored in power plant unit water pools for about four years, after this, the fuel is transported from the power plant unit to another storage which is located near the power plant units; damaged fuel rods are encapsulated individually in hermetically closed tubes and stored in power plant unit water pools; research about the optimization of cooling time; Research about: the transmission of radioactivity from waste into surrounding water of disposal; the assessment of long-term impacts; long-term corrosion tests of carbon steel and laboratory tests in concrete water and bedrock groundwater environments; samples for solubility tests of decommissioning waste metal will be taken (these studies will be continued over the TKS-2009 – POSIVA OY Annual Report); the treatment of low-level waste abroad will be examined, according to the Nuclear Energy Act; The following treatments will be used for OL-3 (EPR under construction): the filter cartridges packed into 200-litre drums without further treatment; ion exchange resins, evaporator bottoms and sludges treated with an “in-drum” drying method directly into the drum in order to minimise the amount of waste; ILW will be stored in an interim storage and disposal in an extension of the present repository ***or*** in a disposal in the present intermediate-level waste silo in the actual repository (now, the first option has been chosen); Source: [35] pg. 517-520, 522, 525
ECONOMICAL ASPECTS

According to the current estimate, the final disposal of the SNF from the existing nuclear plant units and the OL3 unit under construction will cost about € 3 billion; the majority of the costs, over € 2 billion, is caused by the final disposal plant operation, which will take about 100 years. The final disposal costs are met by the nuclear power companies and the price of nuclear electricity covers the costs of nuclear waste management; Source: [36] pg. 13;
SOCIAL ASPECTS
Posiva Oy has during its activities in communities developed a system of information and communication, through meetings with the public and smaller discussion groups. The selection of Eurajoki is a sign of the authorities accepting the public opinion: a majority of the citizens in Loviisa and Olkiluoto in Eurajoki are positive towards a deep repository whilst the citizens in Kuhmo and Äänekoski were negative towards deep disposal; Source: [32] pg. 35-37

2.4 France

Table 5: France (ANDRA)

AMOUNT AND SOURCE
1.152.533 m^3 total of waste (31 December 2007): 2/3 from nuclear sector, 1/3 from research, hospitals, chemical industry, which: 43% from private research (pharmacological industries, etc...), 31% from public research, 6% from not-nuclear industry, 5% from hospitals, 15% from other sectors; The total amount of waste is subdivided (in volume) as follows: VLLW: 20,1%, 231.688 m^3 (89.331 m^3 already disposed of); LLW/ILW short lived: 68,8%, 792 695 m^3 (735.278 m^3 already disposed of); LLW long-lived: 7,2%, 82.536 m^3; ILW long-lived: 3,6%, 41.757 m^3; HLW: 0,2%, 2.293 m^3 (74 m^3 SNF); Other (for whom there is no defined management): 0,1%, 1.564 m^3; Estimated amount of waste: VLLW: 629.217 m^3 (2010), 869.311 m^3 (2030); LLW/ILW short-lived: 1.009.675 m^3 (2020), 1.174.193 m^3 (2030); LLW long-lived: 114.592 m^3 (2020), 151.876 m^3 (2030); ILW long-lived: 46.979 m^3 (2020), 51.009 m^3 (2030); HLW: 3.679 m^3 (2020), 5.060 m^3 (2030); Total: 1.804.142 m^3 (2020), 2.251.449 m^3 (2030); Source: [37] pg. 13, 14, 19; [38];
TREATMENTS
VLLW/LLW/ILW: compaction, incineration, immobilization by hydraulic binder, polymeric resins or bitumen for liquid waste; HLW: solidification for liquid waste, immobilization by glass matrix ; ANDRA has the project to build other 2 new installations for waste disposal: a near surface disposal for short-lived LLW (2019) and a deep disposal for HLW and long-lived ILW (2025); R&D about: partitioning and transmutation of long-lived elements, reversible disposal in deep geological formations; Source: [39]; [40]; [41]; [42]; [43]
ECONOMICAL ASPECTS
The total amount of future expenses (liabilities) for decommissioning and radioactive waste management, for the three major nuclear operators (EDF, AREVA, CEA), has been estimated by them at about 65 billions Euros (2004 value, i.e. undiscounted) corresponding to a discounted value of about 37 billions Euros (3% discounted rate). Still on the basis of the “polluter pays” principle and for other types of waste, ANDRA costs relating to either industrial operations are financed through bilateral conventions between the respective concerned waste producers and ANDRA;

Source: [44]
SOCIAL ASPECTS
The installations, such as Centre de l'Aube, de Meuse/Haute-Marne or de La Manche, are open to public visits. Conferences and brochure publications are also organised; Source: [37] pg. 20, 21, 32; [45] pg. 35

2.5 Germany

Table 6: Germany (DBE)

AMOUNT AND SOURCE
121.447 m^3 of radioactive residues with negligible heat generation; 1.914 m^3 of heat-generating radioactive residues existed (on December 31, 2008); Forecast (2040): 270.400 m^3 of radioactive waste with negligible heat generation, 64% of which would originate from NPP and the nuclear industry and 36% from state institutions. Furthermore, it is estimated that approx. 6.500 m^3 of radioactive waste will additionally arise in the 11 federal state collecting depots. Thus, according to the prognoses by the waste producers, a total volume of approx. 277.000 m^3 can be expected. After 2040, only small amounts of waste will arise; 29.000 m^3 of heat-generating waste in (this corresponds to approx. 17.200 tons of heavy metal from SNF) composed of: 20.600 m^3 of SNF, 3.400 m^3 of ends from the conditioning plant for SNF, 660 m^3 of vitrified HLW, 1.340 m^3 of technological waste and ILW vitrified from reprocessing at AREVA NC (former COGEMA) in France and Sellafield Ltd. (former BNFL) in Great Britain, 130 m^3 from SNF of research reactors, 2.000 m^3 of SNF from the Jülich Test Nuclear Power Plant (AVR) and the thorium high-temperature reactor in Hamm-Uentrop (THTR); no further waste being expected from 2030; Source: [46]
TREATMENTS

SNF: burnt to the extent that is possible and the ashes are compacted prior to being packed into storage casks using an high-pressure compactor; Non-SNF mixed waste: super-compacted and may be additionally dried; Moreover, many other moist radioactive wastes can be dried to improve their long-term stability; Liquid waste: such as evaporator concentrates are compacted into high-density solid product using a vacuum drying process; due to their high specific activity, ion exchange resins and filter aids have to be loaded into shielded casks in most cases; Activated metals: treated under water in the wet storage pools of the nuclear power plants using special tools or processed in dry condition in a shielded cell; The waste from decommissioning is stored temporarily at the place where it arises or in central storage sites for several nuclear facilities; The central interim storage facilities, originally intended as buffer storage, may become more important because of the stop to the reprocessing of SNF; Source: [47] pg. 6, 7, 18
ECONOMICAL ASPECTS
About the Morsleben Repository for Radioactive Waste (ERAM), the decommissioning costs will probably amount to at least 1.2 billion (+/- 30 %) €; the total costs until decommissioning works have been completed are estimated to amount to about 2.3 billion € (including operating costs); Source: [48] pg.46
SOCIAL ASPECTS
The involvement of the public is regulated in the Law on the Environmental Impact Assessment (UVPG) and in the Ordinance Concerning Procedures according to Atomic Energy Act (AtVfV); citizens who had raised objections against the project may lodge a complaint against the license granted for the storage of nuclear fuels in an interim storage facility with the competent court within one month after public announcement of the license; neighbours may also lodge a complaint against the construction permit for an interim storage building; Source: [49]

2.6 Spain

Table 7: Spain (ENRESA)

AMOUNT AND SOURCE
LLW/ILW: 37.200 m^3 and 666 m^3 of ILW from reprocessing in France of SNF; SNF: 3.272 tU in the nuclear power plant pools, which, added to the 98 tU at the Individualised Temporary Storage facility at Trillo NPP, make a total of 3.370 tU; HLW: 13 m^3 of vitrified waste, and also small quantities of fissionable materials (U and Pu) recovered; Forecasts: LLW/ILW: 176.300 m^3 (at NPP's shutdown); SNF: 10.000 m^3 (6.673 t); HLW/ILW: 2.800 m^3 from reprocessing or dismantling of the NPP's; Source of forecasts: 72% from NPP's decommissioning; 20% from NPP's operation; 3% from radioactive installations; 1% from nuclear elements manufacturing; 4% others; Source: [50] pg. 24-26
TREATMENTS
LLW/ILW: crushing, transfer, leaching, electrolysis, preparation and injection of mortar for the aggregates which will allow certain wastes from incidents and others of a similar nature to be stabilised inside the concrete containers used for the final conditioning of waste packages, thus optimising occupation of the available volume; incineration of compactable NPP wastes; compacting, stabilisation for the VLLW; SNF: stored on site in the plant pools; HLW: maintenance and updating of the separation and transmutation in support of the short and long-term management; Source: [50] pg. 55, 116, 119, 121,
ECONOMICAL ASPECTS
Costs for waste management from 2005 till 2070: 13.023.156.000 €, subdivided as follows: LLW/ILW management: 1.626.687.000 €; SNF/HLW management: 6.244.70.000 €; Decommissioning: 2.614.791 €; R&D: 358.802.000 €; Structural: 2.123.352.000 €; Others activities: 54.825.000 €; Source: [50] pg. 163
SOCIAL ASPECTS

Setting up of information and participation mechanisms facilitating the political and social consensus required for decisions on the location; a large majority of people associate the issue with the nuclear power plants and consider it to be an important problem entailing risk, although in general those who have had access to information on what is done with radioactive waste consider its management to be good or very good;

Source: [50] pg. 76

2.7 Sweden

Table 8: Sweden (SKB)

AMOUNT AND SOURCE
LLW/ILW: 31.000 m^3 from operations; SNF (included discharged fuel and current reactor cores): 5.000 tU from BWRs and 1.500 tU from PWRs; Forecasts: LLW/ILW: about 212,000 m^3 of short-lived waste and about 8,700 m^3 of long-lived waste from the nuclear power plants; SNF: 12.000 tU, equivalent to around 6.000 canisters, equivalent to 25.100 m^3; Source: [51] pg. 42, 406, ; [52] pg. 17, 40
TREATMENTS
LLW/ILW: disposed of in final repository (for short-lived and long-lived waste); HLW: stored for about 30 years in central interim storage; SNF: encapsulated in canisters according ti IAEA's recommendations and stored in interim storage (water pools); R&D programme about: Partitioning and transmutation; Deep boreholes; Source: [51] pg. 29, 120, 204, 211, 212, 406; [32] pg. 67
ECONOMICAL ASPECTS
Till 2010, the incurred costs were the following: SKB’s central functions and RD&D: 9,180 SEK M; Transportation system: 3,560 SEK M; CLAB: 7,040 SEK M; Encapsulation plant 13,190 SEK M; Final repository for SNF: 9.42 SEK M; Facilities below ground 14,550 SEK M; Final repository for long-lived LLW/ILW: 1,500 SEK M; At-plant near-surface repositories for VLLW: 50 SEK M; Final repository for operational LLW/ILW: 910SEK M ; Interim storage facility for operational and decommissioning LLW/ILW: 130 SEK M; Final repository for short-lived decommissioning LLW/ILW: 2,750 SEK M; Decommissioning of reactor plants: 15,860 SEK M; Total reference cost (excluding external economic factors and allowance for unforeseen factors and risk): 78,140 SEK M (8.384.641.042,267 €); Source: [52] pg. 36;
SOCIAL ASPECTS

The purpose of a research in the area of socioeconomic impact (and also about macroeconomic effects, decision processes, public opinion and attitudes – psychosocial effects, global changes) is to gain better knowledge and understanding of how the local community's economy and population structure is affected by the establishment of a large new facility. This knowledge can in turn make valuable contributions to SKB's, the concerned municipalities' and other stakeholders' assessments of how the establishment of the deep repository will affect the community's economy and demographic development;

Source: [51] pg. 392

2.8 Switzerland

Table 9: Switzerland (NAGRA)

AMOUNT AND SOURCE
3.375 m^3 from NPPs; 1.318 m^3 from power plants, plasma furnace and containers with HLW from reprocessing; 1.439 m^3 from medicine, industry and research; Forecasts (50-year NPP operation): LLW/ILW: 7.260 m^3 (conditioned) 24.400 m^3 (packaged) from the NPPs (from cleaning systems and mixed waste, included post-operational phase before decommissioning); 340 m^3 (conditioned), 1.560 m^3 (packaged) of activated components from reactor; 28.265 m^3 (conditioned), 28.265 m^3 (packaged) from NPP decommissioning; 45 m^3 (conditioned), 140 m^3 (packaged) from centralised interim storage facility operations; 620 m^3 (conditioned), 655 m^3 (packaged) from centralised interim storage facility decommissioning; 4.270 m^3 (conditioned), 9.170 m^3 (packaged) from medicine, industry and research operations; 23.000 m^3 (conditioned), 23.000 m^3 (packaged) from medicine, industry and research decommissioning; 2.220 m^3 (conditioned), 2.220 m^3 (packaged) from the future SNF encapsulation in repository; ATW: 10 m^3 (conditioned), 40 m^3 (packaged) from the NPPs (from cleaning systems and mixed waste, inc. post-operational phase before decommissioning); 200 m^3 (conditioned), 1.320 m^3 (packaged) from reprocessing; 325 m^3 (conditioned), 920 m^3 (packaged) from medicine, industry and research operations; HLW/SNF: 115 m^3 (conditioned), 730 m^3 (packaged) from reprocessing; 1.135 m^3 (conditioned), 6.595 m^3 (packaged), SNF; Total volumes: LLW/ILW: 66.020 m^3, 97,3%(conditioned), 89.410 m^3, 90,3% (packaged); ATW: 535 m^3, 0,8% (conditioned), 2.280 m^3, 2,3% (packaged); HLW/SNF: 1.250 m^3, 1,9% (conditioned), 7.325 m^3, 7,4% (packaged); Source: [53] pg. 29
TREATMENTS
LLW/ILW: retention and transport of radionuclides in the preferred host rocks, on the repository near-field large amounts of cement-based materials are used that could efficiently retain radionuclides; a project was carried out to investigate the influence of gas generated from the waste on the hydraulic conditions in the repository vicinity; incineration in plasma furnace; HLW/SNF: encapsulation, vitrification; Research about: a method for mineralisation of waste containing organic materials with a cost study for potential realisation of a treatment plant; the possibilities for melting metallic radioactive wastes; developing cement recipes for waste conditioned; finally, the simulations – that were

carried out to provide input to an investigation of the fundamental feasibility of realising a combined repository in Opalinus Clay – show that, given sufficient distance between the disposal zones for LLW/ILW and SF/HLW/ ILW, no interference between the thermal effects from the HLW repository and the gas pressure build-up in the L/ILW repository that would impact on safety is to be expected; anaerobic corrosion of carbon steel in bentonite saturated with Opalinus Clay porewater; corrosion rates by observing the evolution with time of the corrosion-driven formation of hydrogen gas. Recommendations were made for selection of the steel composition and for welding and handling the steel in order to avoid the possibility of fissure formation under the expected container environment conditions; alternatives to the steel reference material for the SF/HLW container were also evaluated, as copper or ceramic; Source: [53] pg. 12, 13, 29
ECONOMICAL ASPECTS
LLW/ILW programme: 420.735.792 CHF (324.118.393 €), subdivided as follows: Geoscientific studies: 162.164.307 CHF; Nuclear technology and safety: 37.287.576 CHF; Radioactive materials: 31.790.242 CHF; Facility planning: 19.615.151 CHF; Generic (non-site-specific) work: 81.106.980 CHF; General programme costs: 63.262.947 CHF; Fees and compensation: 25.508.589 CHF; HLW programme: 553.837.310 CHF (426.654.595 €), subdivided as follows: Geoscientific studies: 299.536.235 CHF; Nuclear technology and safety: 50.362.277 CHF; Radioactive materials: 21.830.262 CHF; Facility planning: 15.653.374 CHF; Generic (non-site-specific) work: 81.952.256 CHF; General programme costs: 49.357.891 CHF; Fees and compensation: 35.145.014 CHF; Project expenses for repository programmes: 974.573.102 CHF; Administration and general project expenses: 84.920.000 CHF; Total expenses for L/ILW and HLW programmes and administration and general project expenses: 1.059.493.102 CHF (816.192.033 €); Source: [53] pg. 26
SOCIAL ASPECTS
Nagra's responsibility is to prepare the scientific and technical background: public relations activities are aimed at maintaining contact with the public and providing them with comprehensive and accurate information, using the internet, brochures, films, media presence, guided tours, presentations and lectures, presence at regional events, street actions, discussion platforms and so on. Cantons and local communities, neighbouring countries, interested organisations and associations, political parties and the public are brought into the process by the SFOE. Parliament, and ultimately the Swiss people (optional national referendum), have the final say on the general licence for a repository; Source: [53] pg. 8

2.9 United Kingdom

Table 10: United Kingdom (NDA)

AMOUNT AND SOURCES
LLW: 3.200.000 m^3; ILW: 240.000 m^3; HLW: 1.100 m^3; Total: 3.400.000 m^3, 95% already existing, 5% from planned future operations; 52% from SNF reprocessing; 19% from NPPs; 13% from fuel fabrication and U enrichment; 8% from nuclear energy R&D; 6% from medical and industrial; 2% from defence; VLLW: around 18.000 m^3 annually (not including waste from British Energy and MAGNOX sites, contaminated land from Sellafield, undisclosed contaminated land from other sites); Forecasts (2129): LLW: 1.2 million m^3 (in a prevision of 2008), 1.4 million m^3 (in a prevision of 2009); VLLW (only): 1,8 million m^3 (with the same omissions of above); Source: [54] pg. 4, 6, 7; [55] pg. 1; [56] pg. 40; [57] pg. 10, [5] pg. 26
TREATMENTS
Evaporation, settlement, filtration and precipitation (for liquid waste), compaction (for solid waste), vitrification, ion exchange, cementation; Source: [58] pg. 64, 70, 82, 83, 85, 87, 96, 97, 109-111, 117, 127-129, 156, 157; [59] pg. 18, 19, 31
ECONOMICAL ASPECTS
Business Optimisation: £ 18 million; Spent Fuels: £ 439 million; Integrated Waste Management: £ 435 million (management of waste prior to delivering a Geological Disposal Facility); Manage Nuclear Materials: £ 137 million; Critical Enablers: £ 225 million; Support Costs: £ 723 million; Site restoration: £ 862 million; Total: about £ 2,840 billion, of which £ 1,690 million will be funded by Government and £ 1,150 million by income from commercial operations; planned expenditure on site programmes will be £2,634 million, while non-site expenditure (e.g.: skills development, R&D, insurance and pensions costs) is expected to be £ 206 million; Management and disposal of solid LLW: £ 9,87 billion; Source: [60] pg. 8, 9; [61] pg. 5

SOCIAL ASPECTS
In order to minimise the impact of decommissioning and clean-up on the local communities, through, NDA would to support three main drivers: • Enhancing the opportunity for local people to be involved in decommissioning work through education, retraining and skills development; • Supporting the diversification of local economies into other sectors – reducing the reliance of communities on nuclear sites for employment by increasing the number, variety and vibrancy of local businesses, promoting entrepreneurship and attracting new enterprises; • Increasing the attractiveness of areas near NDA sites as places to live, work and invest, with particular emphasis on achieving environmental, social, cultural and infrastructure improvements; Source: [62] pg. 6

2.10 United states of America

Table 11: United States of America (OCRWM)

AMOUNT AND SOURCE
LLW: 2.085.366 m^3 disposed of in 2008, from research, hospitals, clinics and NPPs; HLW/SNF: 70.000 MTHM, of which 63.000 MTHM of commercial HLW/SNF, 2.333 MTHM of DOE SNF (including naval SNF) and 4.667 MTHM DOE HLW; Source: [63] pg. 18, 19, 64; [64]
TREATMENTS
LLW: incineration, compaction; HLW: disposed of in interim storage, mainly at NPPs; 90% of commercial SNF would be put in TAD (Transportation, Aging and Disposal) canisters, the remaining 10% put in other types of canisters (dual purpose or uncanistered in truck casks); Research about the technical basis to ensure the continued safe performance of long-term dry storage systems; Source: [63] pg. 58; [65]
ECONOMICAL ASPECTS
The total cost of the whole nuclear waste management program through the year 2116 is calculated to be around $ 44 billion; of this sum, $ 29 billion relate to repository development, implementation and closure of the facility; Source: [32] pg. 103
SOCIAL ASPECTS
From time to time, the NRC conducts meetings or workshops to address specific enforcement issues; these meetings may be conducted in the Washington, D.C. Area, in the areas around the NRC's four regional offices or in the community near a nuclear power plant or other facility to make it easier for the public to participate; these meetings are listed on the NRC website; Source: [66]

2.11 Netherlands

Table 12: Netherlands (COVRA)

AMOUNT AND SOURCE
VLLW: about 1.000 m^3 generated annually from processing of some metal ores in the relatively stable form of slag and calcine; LLW/ILW: some 100 m^3 conditioned waste generated annually from NPPs and also 100 m^3 conditioned waste from hospital, research and industry HLW: about 10 m^3 produced annually from mainly SNF reprocessing; 125 actually existing from NPPs, medical and scientific research Forecasts (over a period of 100 years): LLW/ILW: about 188.000 m^3, including decommissioning (more dated prevision for LLW/ILW over the same period fixed the amount to 60.000 m^3); HLW: 40 m^3 from fuel elements and fissile residues; 110 m^3 of vitrified waste; 2.000 m^3 from decommissioning; 850-900 m^3 from reprocessing; 120 m^3 of other waste; for a total of about 3.200 m^3; Source: [67] pg. 4; [7] pg. 3; [8] pg. 2, 3
TREATMENTS
VLLW: no further conditioning is needed and it's stored in a dedicate building; LLW/ILW: resins conditioned by cementation and the others treated and conditioned at NPPs to create a stable product; compaction; organic/inorganic liquinds separation; incineration for biological waste and organic liquids; HLW: waste from reprocessing is stored in a engineered facility, where it is planned to store SNF from two research reactors; and also conditioning, compaction, incineration, shearing, cutting. A direct disposal is not yet feasible, but the facilities can store all nuclear waste (all types) that will be produced in 100 years; the retrievability of the waste allows for future disposal solutions or new techniques; R&D about salt and clay repositories; Source: [68]; [7] pg. 2, 3; [8] pg. 5,6
ECONOMICAL ASPECTS
The financial burden of a direct disposal facility is prohibitive also for the small amounts existing; however, there is the establishment of the capital growth fund for these proposes; extension of the interim storage period with COVRA from 100 to 300 years will cost about 90 million €; construction and maintenance of a repository in rock salt will cost about 280 million €, in clay this will cost about 400-800 million €, depending on several factors; maintenance of the facilities enabling the retrieval of the wastes costs 1.8 million € per year; Costs for retrievable repository are higher than those for a non-retrievable one, mainly due to a maintenance of accessibility; Source: [69]; [8] pg. 6
SOCIAL ASPECTS

The public acceptability for deep geologic disposal is low, influenced by the negative image of nuclear energy and the small volumes of waste available for direct disposal don't require an immediate final solution; Source: [67] pg. 9; [8] pg. 4, 7

2.12 South Korea

Table 13: South Korea (KRWM)

AMOUNT AND SOURCES
LLW/ILW: 60.000 drums of 200 litres, according to WNA, or 86.757 drums of 200 litres, according to KHNP, largely from NNPs; we take in account this last quantity for a conservative approach due a planned increase of nuclear power production in this country; SNF: 323.187 SNF bundle; Source: [70]; [71]; [72] pg. 7
TREATMENTS
LLW/ILW: volume reduction, stabilization of shape; currently, these wastes are safely stored in temporary storage facilities on four nuclear power sites; afterward, they will be permanently disposed of after construction of the LLW/ILW geological disposal facility, with vitrification on ILW from about 2006 to increase public acceptability; SNF: stored in the water pool, located inside the fuel building, for cooling down and radiation protection and in a dry-type spent fuel storage facility, also used to store those spent fuels cooled down for about some six years in the pool; reprocessing, either domestic or overseas, is not possible under constraints imposed by the country's cooperation agreement with the USA; however this is being appealed; R&D with DUPIC programme, using SNF from LWR; Source: [70]; [71]; [72] pg. 7
ECONOMICAL ASPECTS
A number of silos and caverns with a capacity for 800.000 drums would have a total cost amounting to 1.15 billion US$; 290 million US$ assigned to LLW/ILW facility area, as well as an annual fee of 300 million US$ paid to the local community; Source: [72] pg. 8
SOCIAL ASPECTS
The amount of money set apart for LLW/ILW facility area has the aim to compensate for the psychological burden of residents, to reward a community participating in an important national project, and to facilitate amicable implementation of radioactive waste management; Source: [72] pg. 8

2.13 Japan

Table 14: Japan (NUMO)

AMOUNT AND SOURCES
LLW: 67.622 200-litres drums generated in 2008 at commercial NPPs; 809 200-litres drums generated in 2008 at nuclear power reactor at R&D stage; 624.309 cumulative 200-litres drums stored in 2008; HLW: 40.000 canisters arising from nuclear power plant operation up to 2020; Source: [73] pg. 32, 33; [74]
TREATMENTS
LLW: Solid type hold in the 200- litres drums and kept in a storage facility; HLW: vitrification, cooling and deep geological disposal; R&D on: geological environment, disposal technology, safety requirements; Source: [75]; [76]; [73] pg. 32
ECONOMICAL ASPECTS
Approximately 3 trillion ¥ (28 billion €) for HLW programme; Source: [74]
SOCIAL ASPECTS
R&D on institutionalization and technology to communicate and correspond with the society: preparation of promotional materials, repository monitoring and record preservation to transfer information to future generation; Source: [76]

From this general view, it appear that the choice to implement a national SNF reprocessing system is not currently an habitual policy; the reasons of this may be several: the high cost of the technology, the risk of proliferation for military purposes (terrorist or not), the size of uranium resources proved to be larger than anticipated and their ubiquity on the Earth ([77]; [78]). Moreover, the actual technologies enable a safety management of radioactive waste by the interim or near-surface storages thanks to their experienced use in the past, especially for the country with a small part on electricity production from NPPs, while the deep ones are still under construction only in a few countries in the Europe and in the world (Table 15). However, it's clear that a final solution for radioactive waste is absolutely necessary, therefore the studies about new technologies of treatment and the analysis about different fuel cycle, e.g. fast reactor, are carrying on (Section 4).

To complete this general view on national management policies about radioactive waste, it carry on the following tables regarding the different type of disposal existing in different countries, their actual situation (Table 15) and the ways of SNF storage (Table 16).

It can be noted that the deep geological repositories form currently only a small part in the national policies, while the near-surface ones are more used. This situation has different causes: the social aspects about a deep repository, the absence of a long experience – as well as for the surface disposal – of these plants, the possibility to reach the waste to apply new techniques of treatment or new disposal solution.

For SNF, there is a large use of water-pool, shielded buildings and metal canisters.

Table 15: Definitive VLLW/LLW/ILW disposal facilities in different countries

COUNTRY	INSTALLATION	TYPE	SITUATION
Germany	Morsleben	Deep geologic	Closed
	Konrad	Deep geologic	In licensing
	Asse	Deep geologic	In decommissioning
Slovakia	Mochovce	Near-surface	Operation
Spain	El Cabril	Near-surface	Operation
United States	Beatty	Near-surface	Closed
	Maxey Flats	Near-surface	Closed
	West Valley	Near-surface	Closed
	Richland	Near-surface	Operation
	Sheffield	Near-surface	Closed
	Barnwell	Near-surface	Operation
	Carslbad	Deep geologic	Operation (TRU)
Finland	Olkiluoto	Cavern	Operation
	Loviisa	Cavern	Operation
France	La Manche	Near-surface	Closed
	L'Aube	Near-surface	Operation
	Morvilliers	Near-surface	Operation

Hungary	Püspökszilágy Bátaapáti	Near-surface Underground	Operation* Commissioning *currently, only as interim storage
Japan	Rokkasho Mura	Near-surface	Operation
Great Britain	Dounreay Drigg	Surface Surface	Operation Operation
Czech Republic	Dukovany Richard Bratrstvi	Near-surface Cavern Cavern	Operation Operation Operation
Sweden	Forsmark	Cavern	Operation
Argentina	Ezeiza	Near-surface	Operation
Belgium	Mol-Dessel	Near-surface	In licensing
Bulgaria	Novi Han	Near-surface	Operation
Canada	Kincardine	Deep geologic	Under investigation
Norway	Himladen	Cavern	Operation
Poland	Rózan	Near-surface	Operation
Romania	Baita-Bihor	Cavern	Operation
South Africa	Thabana Hill Vaalputs	Near-surface Near-surface	Operation Operation

Source: [50] pg. 31; [79]; [80]

Table 16: Centralised temporary HLW/SNF storage facilities

COUNTRY	INSTALLATION	TECHNOLOGY	STORAGE
Germany	Ahaus Gorleben	Metallic casks Metallic casks	SNF SNF and glass
Belgium	Dessel	Vault	Glass
United States	PFS	Metal-concrete casks	SNF
Russian Fed.	Mayak Krasnoyarsk	Pool Pool	SNF SNF
France	La Hague La Hague CASCAD	Pool Vault Vault	SNF Glass Glass
Holland	HABOG	Vault	SNF and glass
Great Britain	Sellafield Sellafield	Pool Vault	SNF Glass
Sweden	CLAB	Pool	SNF
Switzerland	ZWILAG	Metallic casks	SNF and glass

Source: [50] pg. 38

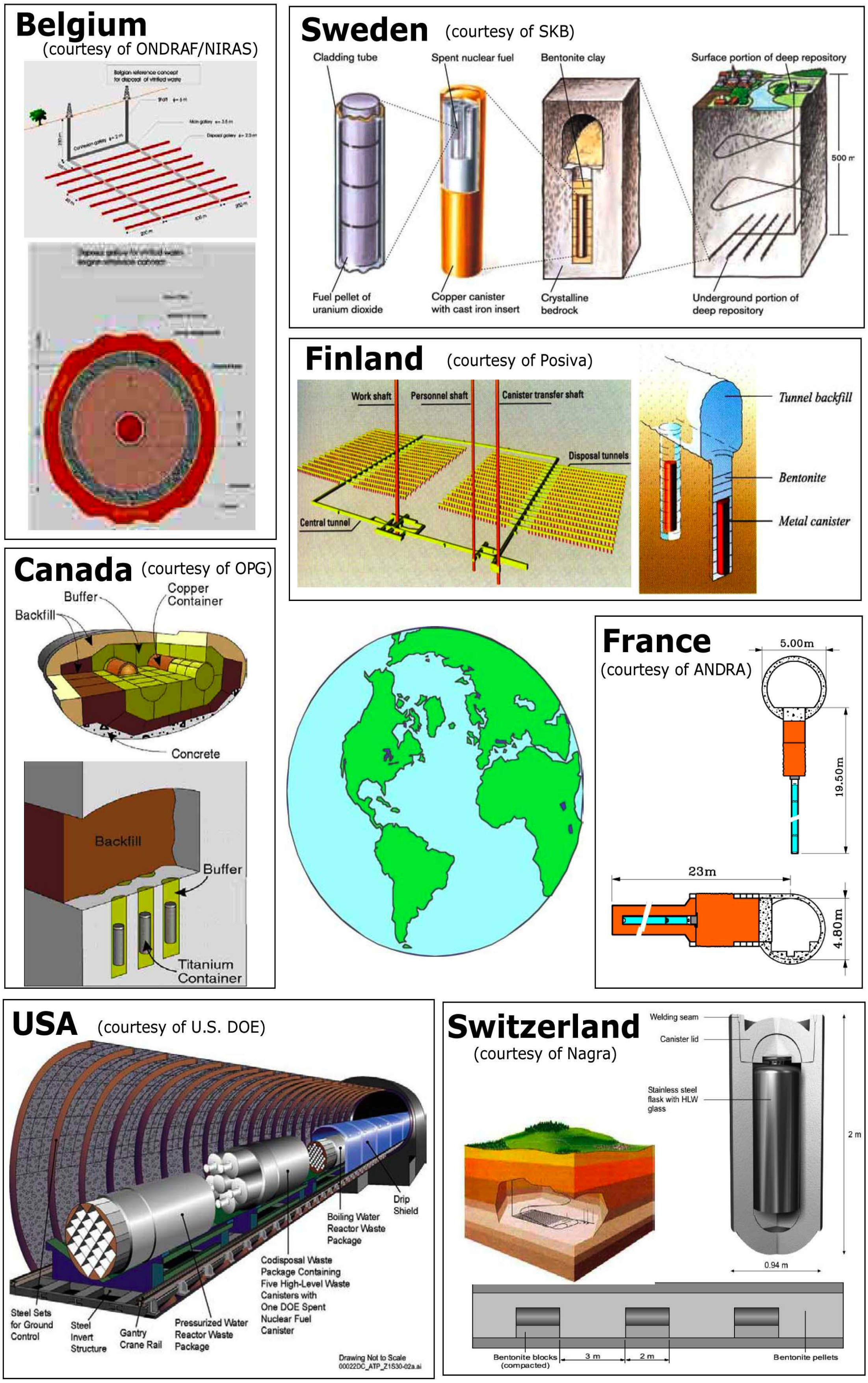


Figure 7: Repository design variants considered in feasibility studies by different national programmes

How we see in Figure 7, there several studies about the storage of nuclear waste, but all these consider the *multi-barrier concept*: a series of engineered and geological barriers that prevent an uncontrolled emission of radioactivity in biosphere.

We can see an example of the approach in Figure 8, where it's reported a part of a Finnish study (Posiva Oy in cooperation with Swedish SKB) about the safety concept.

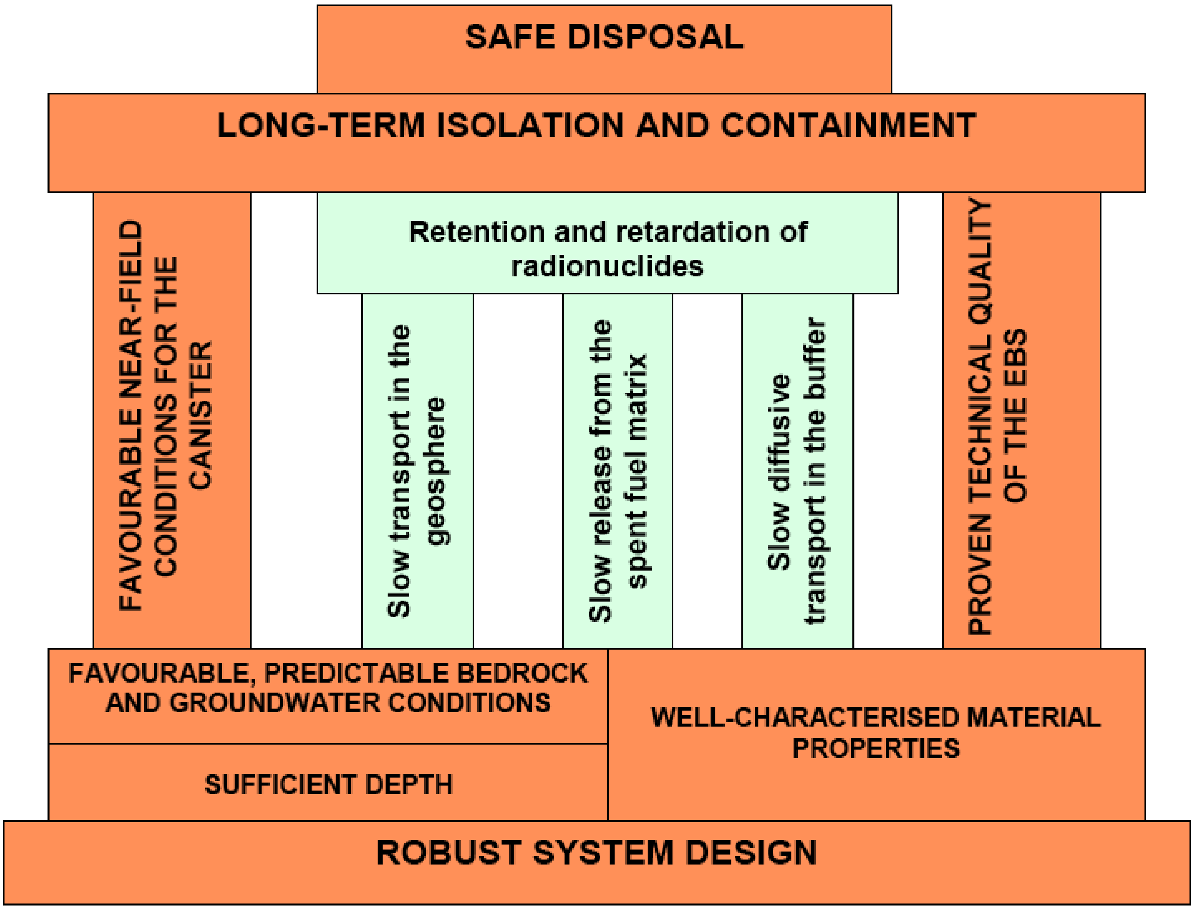


Figure 8: Outline of the safety concept for a Finnish repository for SNF in a crystalline bedrock. The safety concept is based on a robust system design: red pillars and blocks indicate the primary safety features and properties of the disposal system, green pillars and blocks indicate the secondary safety features that may become important in the event of a radionuclide release from a canister.

Source: [35]

This kind of approach could be the same also for a national context like the Italian one (or international one, if we want to consider an European framework for radioactive waste management).

2.14 Conclusions

After this presentation of different national nuclear situations, we can recognize some points of connection with some aspects of Italian scenario.

First of all, it can be easily pointed out that NPPs are the main origin field for nuclear waste, so the number of NPPs existing in a country is an adapt sign to find a similarity between different contexts.

In addition, the military nuclear history of a country can have determined a particular waste production having non-negligible consequences in today waste management, i.e. by weapon-grade material production, reprocessing plants, navy reactors, military research.

Other obvious considerations can be the causes of a greater or smaller nuclear development, such as population, geography, politics.

Although an eventual Italian nuclear renaissance could foresee the use of French reactors (but after the last referendum in June 2011, such a nuclear renaissance is no more in program), France has a nuclear reality too different from Italian one to make an useful comparison about waste quantities: there are 19 nuclear sites with 58 nuclear reactors and 1 more reactor under construction, whilst in Italy the ancient nuclear sites for electricity production were only 4 and the eventual estimated new NPPs are always 4. Certainly, the experience gained by this deep exploitation of nuclear reactions, also regarding to radioactive waste management, can bring important developments in a international cooperation for the treatment of these waste (but this argument is valid also with other countries, of course). It doesn't have to omit the wide use of nuclear technology for military purpose and the relative waste production by i.e. submarine and ship reactors, plutonium production, nuclear warheads, and the fuel reprocessing facilities that doesn't exist in Italy.

In addition, France, as well as UK, has more big reprocessing facilities in operation where the SNF from other countries (included Italy) is sent. This activity is another main origin field of radioactive waste, especially HLW.

A similar incompatibility of the contexts is valid also with USA, with its nuclear power greater than the French one, Canada, that in addition uses widely a particular reactor type not used in Italy (CANDU reactors), UK, with its very large reprocessing plant of Sellafield and Japan, where, even if its particular seismic situation that can be a reference for Italy, there is a very high density of NPPs not comparable with Italy. Their useful contribution can be the studies for different disposal typologies, in addition to their research on treatments as said above, but always considering the differences between the waste production: as we will see in Section 4, some treatments need high waste input to be economically competitive and they maybe are not convenient in a smaller waste scenario, or others are suitable only for particular waste streams and not all waste typologies are present in Italy. A typical examples of this is the HLW coming from SNF reprocessing: if in Italy there was only such a plant, now in decommissioning, whilst in France, or in USA or in UK, there are more and larger of them where the SNF is normally sent, it's clear that the HLW existing in those countries is more than in Italy.

The same argument can be done for military nuclear material, not widely used in Italy but well implemented in those nations, with relative waste production.

The other European countries show more similarities with Italian framework.

Netherlands has less nuclear reactors than Italy with two nuclear site (and one of these shut-down): Borssele (1 PWR with 485 MWe) and Dodewaard (1 BWR with 58 MWe shut-down in 1997), in addition to its research centres. Even if the forecast for LLW/ILW amount over a period of 100 years are tripled between the prevision in 2000 and the one in 2008 ([7] pg. 3; [8] pg. 2), it can represent a good example for small amount waste management, a sort of opposite case of the nation described above, such as USA and France.

In Finland Loviisa (2 VVER producing 488 MWe each) and Olkiluoto (2 BWR producing 1.720 MWe total, and with the third reactor, an EPR, under construction) plants produce more electricity and an important contribution that this country can provide is the analysis about the planned deep geological repository in Olkiluoto – if such a disposal will be planned as a local one in Italy or as a regional one – and the experience about one of two EPR now under construction in Europe, a kind of reactor that can be used in an eventual Italian nuclear return.

More electricity is produced by nuclear fission in Belgium, with its 2 nuclear sites having 7 PWR total. An useful aspect of this PWR implementation is the skills gained with waste coming from PWR exploitation and decommissioning (of the old ones).

The most similar nuclear fleet to Italian one is in Switzerland, although with more power and without a MAGNOX technology, with 4 sites and 5 reactors (3 PWRs and 2 BWRs), so in Italy it can be expected a waste amount not too different – if the greater size of Swiss reactors can involve more waste, it's true that a GCR, as MAGNOX in Latina, produces considerably more waste than other technologies.

More reactors are currently in operation in Spain: 6 PWRs, 2 BWRs, that involves the expected increase of waste forecasts compared to Switzerland.

The greater presence of NPPs in Germany, the plants already decommissioned and the several studies on disposal options imply a good reference for efficient D&D operations.

Both Germany and Spain have some decommissioned reactors moderated by graphite – even if with very different technologies: 2 HTGR and 1 HWGCR for Germany, 1 UNGG for Spain; this is not a negligible aspect because one of the most problematic waste is just radioactive graphite from nuclear core: a contribution coming from the experience gained with these reactor decommissioning is suitable for D&D operations for Latina GCR.

So, with its particular nuclear situation but with a manageable waste amount due to small number of reactors in decommissioning or the same number of reactor in planning, Italy can look at the analogous scenarios, generally in Europe, to analyse the waste management with small quantities coming from NPPs; Switzerland, Finland, Belgium, Netherlands are good examples of these references. At the same time, it can take into account what happens in country with more nuclear power, such as Germany, Spain, eventually to share the knowledge of particular waste typologies (such as radioactive graphite, as said above) till to consider countries with large waste production, where a deep research on innovative treatments, a development for available techniques and studies for disposal solution are normally carried on.

3 Waste typologies

In this section, a classification of radioactive waste is provided, according to international standards. The aim of this part is not only to show the criteria whereby the different categories are defined – by different national and international authorities, in some cases – but also to analyse all the possible sources for radioactive waste and their typology: NPPs are the clearest within these, but we will see that every human activity produces this kind of waste.

Therefore, there is a first part where it will be explained the typical waste stream from NPPs and a second part regarding other radioactive waste producers, such as military, hospital and industrial fields, every with its particular waste feed.

In the paragraph dedicated to nuclear plants, there is a distinction between the waste coming from the fuel and the one coming the other part of NPP. This choice is due to (and it points out) an important aspect about the nuclear waste from NPPs: the most dangerous part of the waste, in radioactivity terms, comes from the nuclear core, where the fuel is located, but its quantity is much less than the waste amount coming from the "not-core" part, that however has a lower radioactivity level. As it is shown in 3.2.1, the waste from fuel is formed not only by its exploitation but also by its whole life cycle, the so-called "fuel cycle" (Figure 11), a series of different steps from uranium mining to final disposal. Every oh these steps involves an inevitable waste production and the waste from nuclear core, i.e. fuel exploitation, will be added to the one from the other phases of the fuel cycle.

In the second paragraph, concerning the "out-of-core" and general decommissioning waste, we will talk about the D&D activities that have a considerable impact in terms of waste amount. For this purpose, some decommissioning cases, in Europe as well as in the world, are taken as reference for future decommissioning of Italian NPPs. Certainly, to take these decommissioning project as a reference for Italy, the choice was for NPPs with a power comparable to the Italian ones and with a similar technology. Therefore, typical waste stream from each plant technology will be listed and, where data are available, quantified.

In this context, the "clearance" concept is also explained as well as its importance to reduce the waste management problems and the pressure on final disposal.

Waste from other field will be described in 3.3 and divided by three main activity: military, hospital and industrial, all of these with a considerable waste production.

3.1 Radioactive waste classification

To understand the different typologies of waste that exist, it's convenient to refer to the following subdivision, according to IAEA's standards ([81] pg. 5, 6):

- **Exempt waste (EW)**: Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes;
- **Very short lived waste (VSLW)**: Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge. This class includes waste containing primarily radionuclides with very short half-lives often used for research and medical purposes.
- **Very low level waste (VLLW)**: Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control. Such landfill type facilities may also contain other hazardous waste. Typical waste in this class includes soil and rubble with low levels of activity concentration. Concentrations of longer lived radionuclides in VLLW are generally very limited.
- **Low level waste (LLW)**: Waste that is above clearance levels, but with limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities. This class covers a very broad range of waste. LLW may include short lived radionuclides at higher levels of activity concentration, and also long lived radionuclides, but only at relatively low levels of activity concentration.
- **Intermediate level waste (ILW)**: Waste that, because of its content, particularly of long lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal. ILW may contain long lived radionuclides, in particular, alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. Therefore, waste in this class requires disposal at greater depths, of the order of tens of metres to a few hundred metres.

- **High level waste (HLW)**: Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal of HLW.

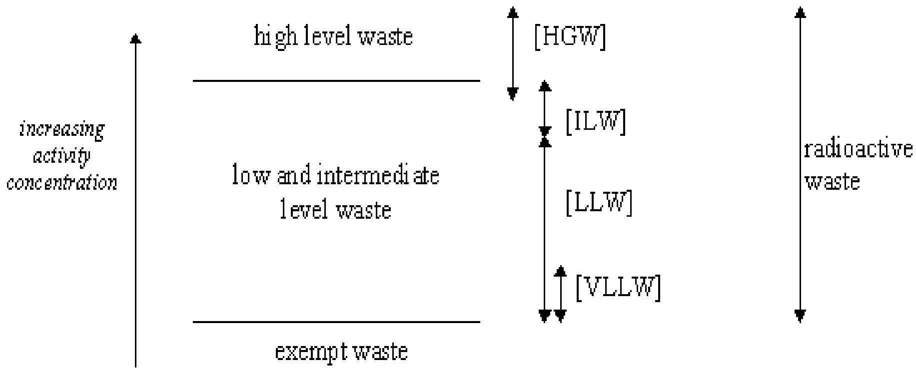


Figure 9: Waste classes

In Figure 10 ([81] pg.7) it is reported a schematic representation of the activity of all waste typologies and the relative disposal type. Obviously, the more it's the radioactivity and the half-life of the waste, the more it will be its confinement.

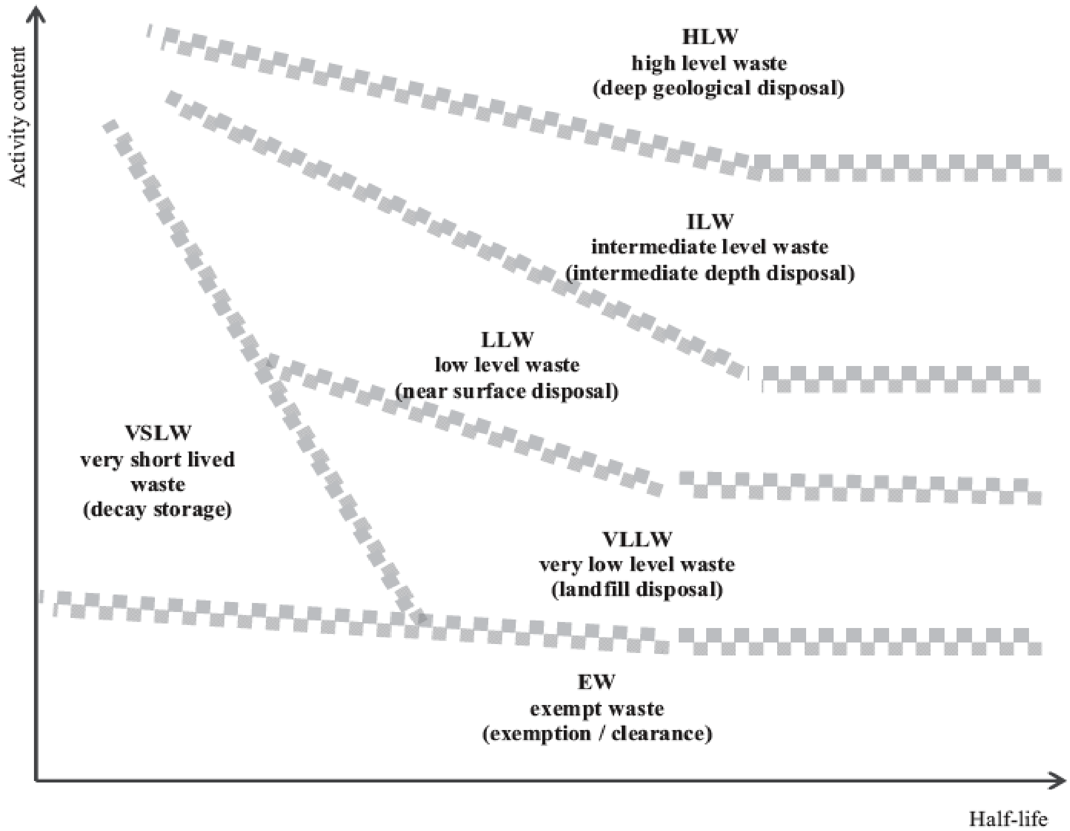


Figure 10: Waste classification scheme and their disposal
Source: [81] pg.7

It' s important to point out that subsist a difference between the different definition.

With reference to HLW, DOE's and NRC's definition are different each other and they're both in their turn different from IAEA's one. NRC definition is:

“High-level radioactive waste or HLW means:

- Irradiated reactor fuel;
- Liquid wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuel;
- solids into which such liquid wastes have been converted”

Source: [82] pg. 1043.

And DOE give the following definition:

“High-level waste is the highly radioactive waste material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and other highly radioactive material that is determined, consistent with existing law, to require permanent isolation" ([83] pg. 3).

So, it can be noted that HLW definition given by DOE, unlike NRC one, doesn't include SNF into HLW, and none of two settles exactly a radioactivity level to define a waste as HLW.

Moreover, DOE (USA) provides as well another specified category of waste, defined as follows ([83] pg. 3):

- **Transuranic Waste** (**TRU**): radioactive waste containing more than 100 nanocuries (3700 becquerels) of alpha-emitting transuranic isotopes per gram of waste, with half-lives greater than 20 years, except for:
  - a) HLW;
  - b) Waste that the Secretary of Energy has determined, with the concurrence of the Administrator of the Environmental Protection Agency, does not need the degree of isolation required by the 40 CFR Part 191 disposal regulations [84] or
  - c) Waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61 [85].

It must be pointed out that currently each country refers to these categories not in an harmonised way (an example of this is the tables of Section 2, where the amount of waste for each nation is subdivided not always in the same manner): a typical case is the inclusion of SNF and/or TRU categories in HLW category. In this order, one of the aim of IAEA is an international standardization of regulation and definition for its members.

3.2 From nuclear power plants

When we talk about the radioactive waste from NPP, we have to refer not only to the HLW and SNF from the nuclear core (one of the most radioactive parts, of course), but also to the other waste coming from other systems and structures of the plant (generally LLW/ILW).

3.2.1 Fuel

The most significant contribution in quantity and radioactivity terms come from NPPs, for which it's necessary to refer to the fuel cycle. Nuclear fuel cycle provides several steps where waste is produced in variables quantities and dangerousness, concerning to relative cycle's step. This cycle is subdivided as follows (Figure 11):

- Uranium mining;
- Milling;
- Processing;
- Conversion in UF_6;
- Enrichment;
- Fuel fabrication;
- Operation in nuclear reactor;
- Interim storage;
- Reprocessing;
- Vitrification;
- Disposal.

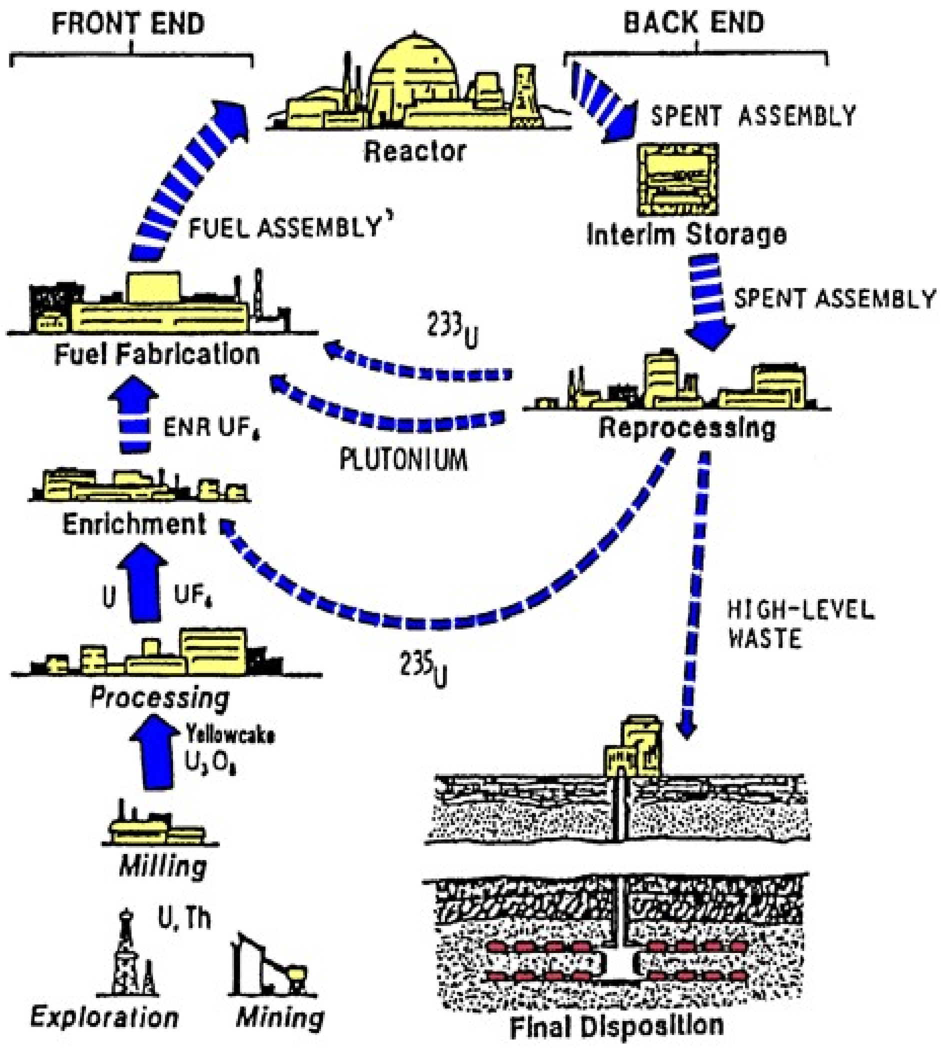


Figure 11: A fuel cycle representation

Typical waste proportions for a NPP are:

- LLW: 90% of volume, 1% of radioactivity;
- ILW: 7% of volume, 4% of radioactivity;
- HLW: 3% of volume, 95% of radioactivity.

Normally, a 1000 MWe NPP produces:

- 90 m^3 LLW;
- 7 m^3 ILW;
- 3 m^3 HLW.

SNF in LWRs contents about:

- 95,6% uranium (less than 1% of this is U-235);
- 2,9% stable fission products;
- 0,9% plutonium (about two thirds is fissile, PU-239 and Pu-241);
- 0,3% caesium and strontium (fission product);
- 0,1% iodine and technetium (fission products);
- 0,1% other long-lived fission product;
- 0,1% minor actinides (americium, curium, neptunium).

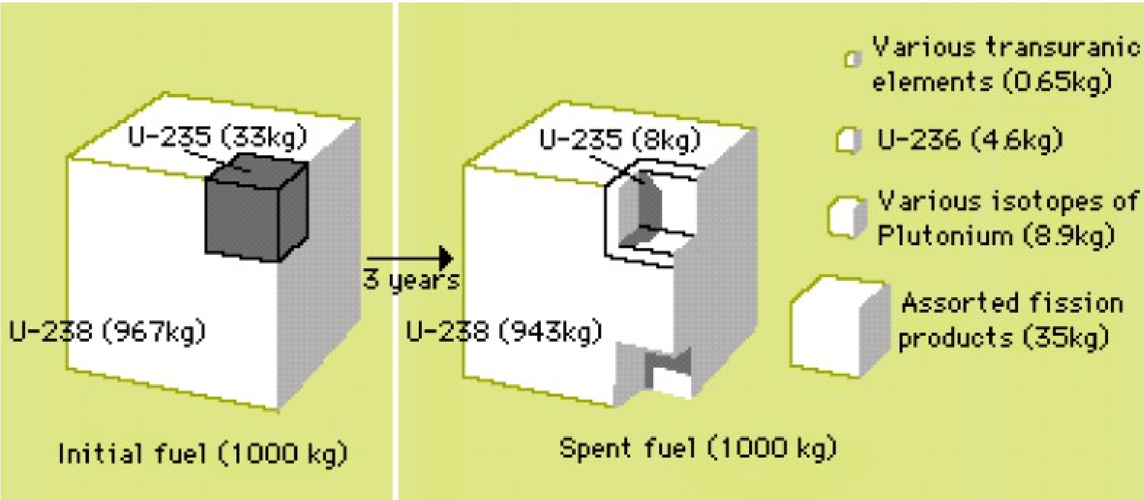


Figure 12: Typical fuel composition (1000 kg) for a thermal LWR, 3,3% enriched, at charge and at discharge

This SNF contents more than 95% of its original energy, but with the actual open fuel cycle, this potential energy is considered as a waste. An implementing of a closed fuel cycle supplementing actual thermal reactors with fast reactors can exploit this energy with consequential waste reduction because the second ones can use as fuel the heavy and fissionable isotopes that accumulate in thermal reactors; so in this kind of a really closed cycle, the waste for disposal is only fission products with a small part of actinides and this reduces the heat load in the repository, increasing its capacity by about a factor of 5 ([9] pg. 2).

Table 17: Radionuclides in PWR SNF

Nuclides	Half-life (years)	Activity (Gbq/MTHM) after: 100 y	10000 y	10^6 y
Transuranics				
Np-239		1200	480	
Am-241	433	190000	5,9	
Pu-242	376000	100	100	18
Pu-241	14,4	52000	5,9	
Pu-240	6570	14000	4800	
Pu-239	24100	11000	8100	
Np-237	2,14 x 10^6	19	56	41
Pa-233		19	56	41
U-238		12	12	12
Th-234		12	12	12
Pa-234		12	12	12
U-236	23,4 x 10^6	10	13	13
Fission Products				
Tritium	12,3	85		
C-14	5,730	0,005	0,002	
Se-79	65000	17	16	
Kr-85	10,7	590		
Sr-90	28,8	270000		
Y-90		270000		
Zr-93	1,5 x 10^6	74	74	48
Tc-99	214000	560	520	21
Pd-107	6,5 x 10^6	5,2	5,2	4,8
Sn-126	100000	34	31	0,033
I-129	16 x 10^6	1,3	1,3	1,3
Cs-135	3 x 10^6	14	14	11
Cs-137	30,2	440000		
Sm-151		6700		
Induced activity				
C-14	7730	12	3,6	
Co-60	5,3	0,3		
Ni-59	75000	140	130	0,02
Ni-63	100	11000		
Zr-93	1,5 x 10^6	3,7	3,7	2,3
Nb-93m		3,7	3,7	2,3

Source: [86] pg. 22

There are three main approaches to SNF use and they change with the relative fuel cycle: thermal reactors without reprocessing, thermal reactors with reprocessing and fast reactors (Table 18).

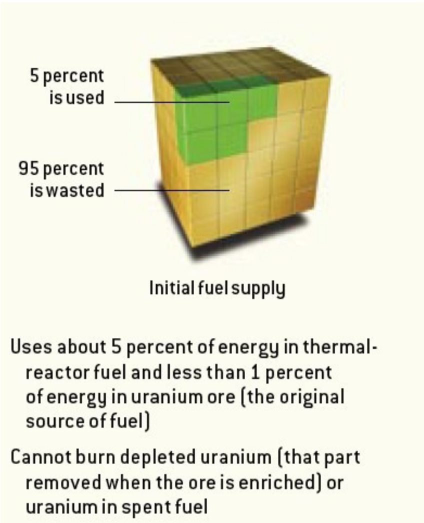
In the first case (*once through*), fuel is burned in thermal reactors and is not reprocessed and we have a SNF still rich in energy that is isolated in apposite canisters and then in underground repositories.

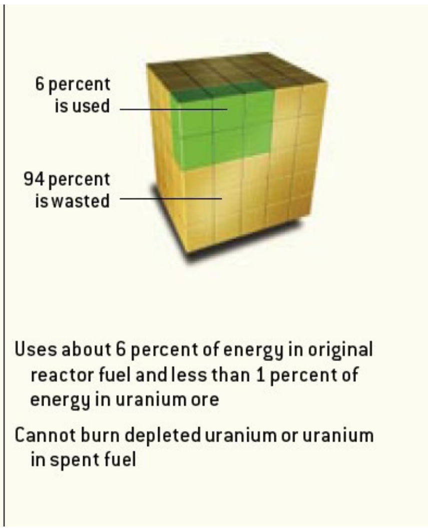
Ih the second possibility, fuel is burned in thermal reactors and after the plutonium is extracted using what is called PUREX processing.

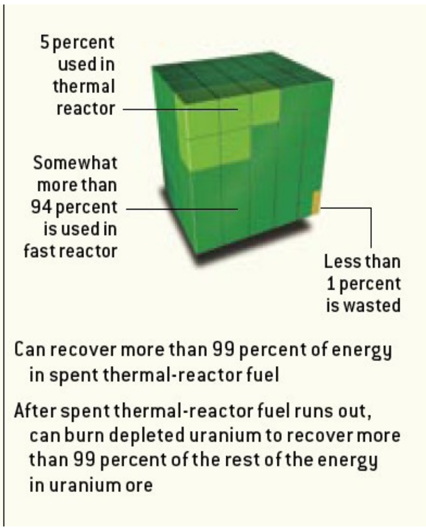
In the third situation, recycled fuel prepared by pyrometallurgical processing would be burned in advanced fast neutron reactors (prototype technology).

Table 18: Comparing three nuclear fuel cycles

ONCE-THROUGH ROUTE	PLUTONIUM RECYCLING	FULL RECYCLING







REQUIRED FACILITIES AND OPERATIONS (Red: requires rigorous physical safeguards; Orange: needs only moderate physical safeguards; Blue: potential risks for future generations)		
Uranium mines; Fuel enrichment to concentrate fissile uranium; Fuel fabrication; Power plants; Interim waste storage (until waste can be permanently disposed of); Permanent storage able to securely segregate waste for 10,000 years; (Needs no plutonium handling or waste processing operations)	Uranium mines; Fuel enrichment; Plutonium blending (mixing); Off-site fuel fabrication; Off-site PUREX reprocessing; Power plants; Interim waste storage; Off-site waste processing; Permanent storage able to securely segregate waste for 10,000 years	On-site fuel fabrication; On-site pyrometallurgical processing (prompt recycling of spent fuel); Power plants; On-site waste processing; Storage able to segregate waste for less than 500 years; (No mining needed for centuries; no uranium enrichment needed, ever)

Waste typologies

PLUTONIUM FATE		
Increasing inventories of plutonium in used fuel; Excess weapons-grade plutonium degraded only slowly by mixing into fresh fuel	Increasing inventories of plutonium in used fuel and available for economic trade; Excess weapons-grade plutonium degraded only slowly by mixing into fresh fuel	Inventories eventually shrink to only what is in use in reactors and in recycling; Existing excess weapons-grade plutonium can be degraded rapidly; Plutonium in the fuel is too impure for diversion to weapons
TYPE OF WASTE		
Energy-rich used fuel isolated in containers and underground storage facility; Waste is radioactive enough to be defined as "self-protected" for a few hundred years against most groups wanting to obtain plutonium 239 for building nuclear weapons	Energy-rich, highly stable glassy waste; Waste is radioactive enough to be defined as "self-protected" for a few hundred years against most groups wanting to obtain plutonium 239 for building nuclear weapons	Tailored waste forms that would only have to remain intact for 500 years, after which material would no longer be hazardous; Lacking plutonium, waste would not be useful for making weapons

Source: [10] pg. 7

From this study, it emerges a substantial difference in waste amount and typology using thermal reactors or fast reactors: a 1.000 MWe thermal reactor generates more than 100 tons of SNF a year, while a fast reactors with the same electrical capacity produce a little more than one ton of fission products, in addition to traces of TRU. Moreover, an AMLR fast reactor has a no significant quantity of long-lived TRU as waste so its radiation would decay to ore level (from which it came) in several centuries, rather than tens of thousands years ([10] pg. 6). With such a cycle, the need of highly radioactive materials transportation would exist only to ship it to disposal and to bring star-up fuel to a new reactor; in this way, commerce in plutonium would be effectively eliminated as well.

3.2.2 Not fuel

The other main source of waste from NPPs is the D&D phase. These activities have to decontaminate the plant's structures, with appropriate decontamination techniques on metal, concrete and other surfaces in order to facilitate access to working areas and the manipulation of components and equipment to be dismantled, reduce the radioactivity of plants and equipments to facilitate cutting, satisfy the standards on waste disposal or return this material to the public domain and to prepare the plant's structures for transport and future management. A basic IAEA principle about waste management says that "generation of radioactive waste shall be kept to the minimum practicable", which wants to lay emphasis on reuse or recycle of this waste within nuclear field or, for other less radioactive material, the removal from regulatory control ("clearance") for conventional reuse or recycle. As it was said above, some big components – like heat exchangers, steam generators, large tanks, etc... – have to be segmented in smaller pieces to insert them into containers for disposal. The problem of cutting and packaging of these kind of large components is that they can lock other works in the NPP because of their consuming time. Moreover, segmenting *in situ* suffers of the scarcity of space for the operations and of the high ambient dose in the containment the operators are subjected. Therefore, is not a rare choice to remove such components "in one piece" to cut and package them in a eventually available separate facilities out of the containment. Examples of this approach are the German MZFR project (The Multi-purpose Research Reactor Decommissioning Project) and Greifswald project. Regarding on (suspected) alpha contaminated areas, their decontamination to release from regulatory control involves a great engagement in terms of time consuming and labour intensity ([11] pg. 22, 23); the difficulties of these operation can be found in walls decontamination, where there is a problem about the good activity measurement at the very low levels required by authorities, the seepage of contamination into cracks and its reappearance on walls already declared "clean"; in this case, it can be envisaged to remove several centimetres of concrete before the wall can be declared "clean".

It's opportune, in this context, to specify what "clearance" and "exemption" mean: "clearance" is referred to the process by which the radioactive materials resulting from an authorized practice are withdrawn from any later control. Thus, the release implies the removal from the control, while "exemption" means that no regulatory control is applied to the practice in question right from the start ([4] pg. 9). The thresholds for exemption were published both in IAEA's "International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources" and in the Directive 96/29/Euratom and they have international consensus, but these values have limited applications in terms of quantities, e.g. 1 tonne of radioactive materials, and therefore their general application on usually superior amount is not suitable. With unconditioned removal from regulatory control, the materials have no restrictions for future use, whilst a conditioned removal implies several conditions to be respected in the future use; therefore in summary, three typical situations can be envisaged (e.g. metals):

- unconditioned release without restrictions: metals destined to a direct reuse, a recycling or also a definitive storage;

- conditioned release without restrictions: metals for non-conditioned reuse only after a fusion into a classic foundry (not direct reuse);
- conditioned release with restrictions: metals for conditioned reuse (typically, in the nuclear industry) only after a fusion into specialised foundry.

A series of cases of decommissioning can be here considered as example to understand the various typologies of waste generated from "not-combustible" part of a NPP. The first set of examples concerns the completed project and then the second one concerns parts of the full decommissioning.

A SKB study ([14] pg. 2) reports the following data about a decommissioning of the Forsmark BWR (unit 3) with 1.000 MWe:

- radioactive materials: 760 t of metal from RPV, 5.950 t from other contaminated circuits, 1.230 t of concrete, 1.050 t of sand, 400 operational waste;
- non-radioactive or decontaminated materials: 7.700 t of metals (including 3.000 t from vapour turbine), 229.500 t of concrete.

The external cooling circuits of G2 and G3 French GCR (250 MWe, shutdown in 1980) consisted of about 1.500-2.000 t of carbon steel in each reactor. Because of their too high cost for direct disposal, a melting facility was built near the plants and the results was 25 kg ingots or 4 t blocks, which were monitored and stored awaiting a VLLW repository or a recycling project in nuclear industry ([11] pg. 59, 60).

The KKN was a 100 MWe German HWR shut down in 1974 after only 18 equivalent full-power days. The core components dismantling generated 522 t packaged into 139 containers just agreed with repository. If the total activity was $8,6 \times 10^{12}$ Bq, about 20% of this material had less than 200 Bq/g and so it was sent to a melting facility for a reuse into nuclear industry. The following activity was the removal of activated concrete from structures as biological shield, the upper and lower support ring, the walls of coolant distribution room and the wedge areas ([11] pg. 60, 61).

Also the HDR German superheated reactor had a short operational life: 5 equivalent full power days and shutdown in 1971. About 550 t of metals were removed, most of which could be recycled without radiological restrictions. A particularity of this plant was the concrete contamination, due to condensation during blow-down tests and earthquake simulations ([11] pg. 61, 62).

The reactor of Gentilly-1, heavy water moderated and boiling water cooled, had 250 MWe and it was shutdown in 1979 after 15 years of operation. The service building, cleared and decontaminated, was converted in a training centre, as the former SNF pool in a calibration facility. LLW from decommissioning was stored in the turbine building, that has been relocated in the reactor building; removed asbestos insulation was shipped off site ([11] pg. 58).

Decommissioning of BR3 PWR Belgian reactor (40 MWth, 10,5 MWe net), shutdown in 1987 after 25 years of operation, started in 1990-1991 with a pre-D&D of the primary loop; after this, the dismantling of first (cutting remotely and when necessary under water) and second set of internals, as well as the RPV, produced pieces packaged in 400 l drums, then conditioned by grouting with cement and stored in a interim storage. After these operations and the decontamination of stainless steel and carbon steel, about 80% of treated mass could be cleared from regulatory control, whilst the remaining 20% has a low residual activity (less than 1 Bq/g) and could cleared after melting in a nuclear foundry. Concerning the concrete, the major problem of its contamination is not so the surface contamination as the spread of contamination by dispersion of fine dust eventually contaminated ([11] pg. 36, 37).

The following data regard now just some operations of a total decommissioning project on NPP with a medium-high power, to make a comparison with Italian situation.

One of the widest program in the world is the decommissioning of VVER Greifswald plant: there are 4 units of 440 MWe shutdown in 1990 after 18 years of operation, 1 unit with the same power but with just one year of operational life (and for his consequential lower dose to operators, used as test bench), 1 unit ready for operation and 2 units under construction at that time; so the main project is about the first 5 units. To 2006, a total of 21.000 t of material has been dismantled, about 5.400 t of which can be released without restrictions, 5.600 t is under control and 10.000 t is contaminated waste ([11] pg. 42, 43).

The waste estimations from Japanese Fugen HWR (165 MWe, shutdown in 2003, with MOX, some containing plutonium, as fuel) are 370.000 t, 4.000 of these classed as radioactive waste, with an important presence of tritium due to heavy water as moderator ([11] pg. 48).

The decommissioning of MAGNOX GCR Tokai 1 (166 MWe, shutdown in 1998) started in December 2001 with the aim to obtain “green field conditions” and reuse the site for a new NPP. 2.700 t of pond water was drained and 1.600 t of graphite core have to be dismantled ([11] pg. 48, 49).

The Vandellòs 500 MWe GCR was shutdown in 1990; from graphite fuel sleeves, 1.000 t graphite, with low activity and long life C-14, and 2 t of stainless steel wire with high activity and relatively short life Co-60 were stored after packaging graphite in baskets and loaded into metallic containers agreed to place in concrete, and loading wires into high integrity containers ([11] pg. 52, 53).

In Italy, from Garigliano BWR (160 MWe and shutdown in 1978) the following waste was treated:

- LLW: 796 packages (320 l) of super-compacted DAWs, previously stored in 2.429 drums (220 l), 86 packages (320 l) of non-compressible DAWs, after sorting and monitoring, 600 t of material released from the controlled area with limit of 1 Bq/g or cm^2 (β/γ) or 0,1 Bq/g or cm^2 (α);
- 280 m^3 of sludge, concentrates and resins, retrieved from storage tanks and cemented in: 399 shielded (to remove before final disposal) packages of conditioned sludge, 255 unshielded packages if conditioned evaporated bottoms, 767 shielded (to remove before final disposal) packages of conditioned resins;
- HLW: 4 t (fuel channels, control rods, in-core parts, etc.) retrieved from the storage trench and cemented in 6 concrete containers of 50 t and 15 m^3 each. ([11] pg. 45, 46).

Latina NPP had a 210 MWe GCR MAGNOX (but since 1971, his capacity was reduced to 160 MWe), shutdown in 1987. Two activities, the dismantling of two ducts of the primary circuit and the decontamination of two sections of the SNF pool, produced: 500 packages (380 l) of super-compacted treated DAW (LLW), previously stored in 1.512 drums (220 l) and other untreated radioactive waste, mainly sludge and MAGNOX debris ([11] pg. 36, 42, 43, 45-49, 52, 53, 58-62).

Finally, a NEA study of 2003 points out the different amounts of waste generated from different reactor technologies:

Table 19: Waste amounts according to reactor typology

REACTOR TYPE	RADIOACTIVE WASTE WEIGHT (t/MWe)
PWR	10
BWR	10
PHWR/CANDU	13
VVER	17
GCR	100

It can be noted the significant quantity of waste from a GCR: it is due to its greater dimensions and to the typical large amount of graphite of this reactor. In Italy there was only one NPP with this technology (Latina, 210-160 MWe) and other plants used BWR (Garigliano, 160 MWe, and Caorso, 860 MWe) and PWR (Trino, 260 MWe). In a scenario as the Italian one, a reuse/recycling of this type of decommissioning waste is suitable not only for IAEA's basic principle mentioned above, but also for practical situations such as economics and logistics: in Italy, where there is no actual repository, it is suitable to separate the material requiring treatment as radioactive waste from the great amount able to be normally reused and, also in the case where such a repository would be available, nevertheless the costs for conditioning and packaging into agreed containers usually can surpass the costs for segmenting, decontamination and clearance ([4] pg. 12).

3.3 From other fields

Although civilian NPPs are the most evident source of radioactive waste, it must be pointed out that other several field, such as medical and pharmaceutical research, conventional and military industry, can produce these typology of waste.

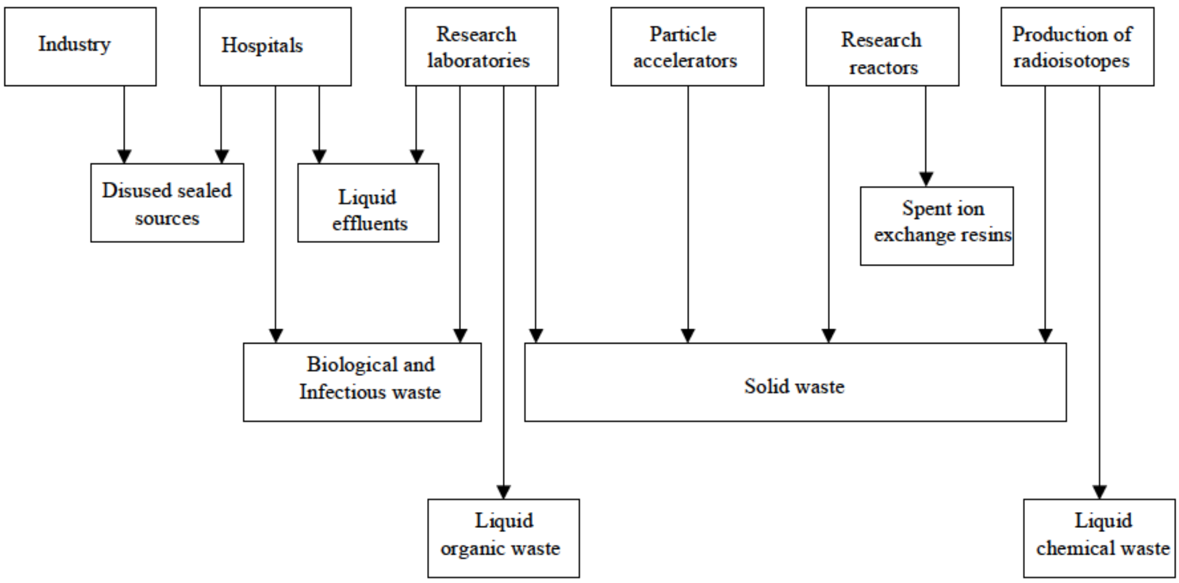


Figure 13: Principal categories of radioactive waste arising from other nuclear applications

Source: [2] pg. 13

3.3.1 Military

The arising of radioactive waste from military field has, on the one hand, the same origin of nuclear fuel cycle for NPPs and, on the other hand, has his particularity due to reactors for nuclear weapons production, their testing, submarines and craft with nuclear propulsion, manufacture of depleted uranium munitions and military research. Although the origin of nuclear exploitation was of military character, not all of these applications have an important influence on current Italian situation about radioactive waste.

The production of nuclear weapons releases carcinogenic and mutagenic materials such as plutonium, uranium, strontium, caesium and other dangerous chemical substances. Solid waste from submarine operations comes in a variety of forms, e.g. ion exchange resins or large bulky items such as old storage tanks or coolant pumps and small items such as contaminated tools, protective clothing and plastic sheeting; the replacement of devices from the core and from other plants forms a contribute of waste. Gaseous tritium light devices have been used for luminosity in a large number of instruments and dials.

3.3.2 Hospital

Nuclides used in medicine are normally short-lived or medium-lived and with low or medium activity. After their use, these are treated as waste, temporally confined *in-situ* and then collected by the authorised firm for the disposal. Pharmacological and biomedical research uses radioactive materials as tracers, normally medium-lived and long-lived nuclides with low or medium activity usually mixed with other substances. Among this waste, it can find also contaminated animal carrions and unusable sources (as Co-60); moreover, according to Italian law, the radioactive sources must be declared to authorities (SSN, VVFF, APAT) and kept in authorised stores or returned to producers. The necessary condition to dispose of this waste is the conformity with at least one of these two condition:

- Activity concentration lower than 1 Bq/g and half-live lower than 75 days:
- Conformity with non radiological relevance:
    - Effective dose forecasted for any person of the population lower than 10 μSv/y;
    - Effective collective dose for one year not major than 1 Sv/person or a valuation analysis about the optimization of the procedure.

It can be useful to refer to the following scheme:

- Liquid waste:
  - residues of administered solutions;
  - washing waters (typically from glass washing);
  - serum or marked biological liquid;
- Solid waste:
  - bottle with seal cap, syringes and test-tubes, also with small volumes of liquid waste;
  - solid waste from use of not-sealed radioactive sources (mono-use gloves, syringes, test-tubes, bottle, decontamination material and contaminated material);
  - ion-exchange resins;
  - used sealed radioactive sources (typically with medium/long-lived radionuclides).

As it's possible the presence of infective risks related to some pathogenic agents, the disinfection before management as “radioactive waste” is weighed up.

The waste from nuclear section of hospitals are an half-life below 75 days and the typical present radionuclides are: Tl-201, I-131, Ga-67, In-111, I-125, Sm-153, Y-90.

Regarding to waste from human body (after the assumption of radioactive medicinals or tracers), the dumping from the hospital wards in which nuclear therapy is used has to wait the descending below allowed level of radioactivity in decay tanks before draining in the normal sewer.

3.3.3 Conventional industry

“Non-nuclear” industries, such as food processing, chemical, steel also produce VLLW as a result of the concentration of natural radioactivity present in certain minerals used in their manufacturing processes. The waste is therefore disposed of with domestic refuse, although countries such as France are currently developing facilities to store VLLW in specifically designed VLLW disposal facilities ([12] pg. 1).

Also other industrial fields give a contribution in terms of radioactive waste: European fertiliser manufacturing gave rise to discharges of phophogypsum containing significant quantities of Ra-226, Pb-210 and Po-210 into the North Sea and North Atlantic; this has been overtaken as a source of radioactivity by offshore oil and gas production in Norwegian and United Kingdom waters releasing some 10 TBq/yr of Ra-226, Ra-228 and Pb-210. This means that they contribute 90% of the alpha-active discharges in those waters. In the oil and gas industry Ra-226 and Pb-210 are deposited as scale in pipes and equipment; building materials can contain elevated levels of radionuclides including Ra-226, Th-232 and K-40; in smelting iron ore, Pb-210 and Po-210 accumulate in dust from smelter and sinter plant operations; granite, widely used as a cladding on city buildings and also architecturally in homes, contains an average of 3 ppm (40 Bq/kg) uranium and 17 ppm (70 Bq/kg) thorium. Radiation measurements on granite surfaces can show levels similar to those from low-grade uranium mine tailings. Scrap steel from gas plants may be recycled if it has less than 500,000 Bq/kg (0.5 MBq/kg) radioactivity (the exemption level). This level however is one thousand times higher than the clearance level for recycled material (both steel and concrete) from the nuclear industry! Anything above 500 Bq/kg may not be cleared from regulatory control for recycling. The largest TENORM waste stream is coal ash, with 280 million tonnes arising globally each year, and carrying U-238 and all its non-gaseous decay products, as well as Th-232 and its progeny ([13] pg. 4, 5)

There is the presence of radioactive materials also in more common devices as used radioactive sources, some types of lightning rod, smoke detectors, contaminated metallic scrap.

3.4 Conclusions

As it was pointed out above, the problem of waste management has a double aspect: if the most radioactive material (i.e. HLW, SNF) arises with a relative small amount, other waste (i.e. LLW/ILW) has the trouble of its quantity.

For this purpose, clearance and recycle ([4] pg. 9) are key concepts concerning LLW/ILW production. The removal from regulatory control for reuse in conventional industry, i.e. clearance, or the recycle/reuse of the waste within the nuclear industry (when it's possible, of course) have as an important consequence the reduction of impact on the final disposal. The principle according to which "the generation of radioactive waste shall be kept to the minimum practicable" runs in this way. A typical example can be the choice of a reactor technology producing less waste than another: as seen in Table 19, a GCR will have more waste amount than other reactor types to be managed in D&D phase.

The fuel cycle steps that can have a considerable influence in Italy are those included in back-end cycle, so after fuel exploitation, the phases of:

- Interim storage
- Reprocessing
- Vitrification
- Disposal.

Because of the absence of active uranium mines on Italian land and fuel fabrication facilities (activities characterizing the front-end cycle), the front-end cycle has not direct waste production in Italy.

But within those back-end operations, just interim storage and disposal (vitrified waste disposal) have indeed an importance for Italy, because reprocessing and vitrification are currently operated abroad. This is not a negligible aspect for HLW production: one of the main activity where liquid HLW is generated is just SNF reprocessing. Therefore, if there is a certain cost to send abroad the SNF for reprocessing – excluding in this way the possibility to reuse the energy contained in SNF (see 3.2.1) – there is the advantage to dispose of only vitrified waste after its repatriation.

Another consideration coming from 3.2.2 is the different waste production (quantity and typology) between different technologies.

A first discrepancy exists with thermal reactors and fast reactors: the latter technology allows a waste production from fuel operation much less than the thermal one. This is due to the possibility to operate a full recycle of SNF coming from the nuclear core, as shown in Table 18.

This is a obvious advantage of fast reactors, but they are not currently commercially available in a wide scale.

Therefore, a second discrepancy about waste arising is that between current reactor types. A summary of this is in Table 19, where, as said above, GCR technology involve the greatest waste amount.

In a scenario as the Italian one, a reuse/recycling of this type of decommissioning waste is suitable not only for IAEA's basic principle mentioned above, but also for practical situations such as economics and logistics: in Italy, where there is no actual repository, it is suitable to separate the material requiring treatment as radioactive waste from the great amount able to be normally reused and, also in the case where such a repository would be available, nevertheless the costs for conditioning and packaging into agreed containers usually can surpass the costs for segmenting, decontamination and clearance ([4] pg. 12).

The several examples provided in 3.2.2 ([11] pg. 36, 42, 43, 45-49, 52, 53, 58-62; [14] pg. 2) can function as reference cases to predict waste typologies and quantities coming from Italian NPPs decommissioning.

From there, the consideration is that the large amount of waste is formed by metals and concrete. They are present in any case, for every reactor technology.

These two waste stream have an substantial difference: metallic waste can be recycled as "cleared" waste or reused into nuclear industry whilst concrete is currently very difficult to treat due to its contamination, so a current, possible and considerable reduction of pressure on the final disposal can be provided only by metal recycling.

Radioactive waste typology from other fields can vary according to their origin.

Military industry can produces almost the same kind of waste of NPPs but also its nuclear weapons production, their testing, submarines and craft with nuclear propulsion, manufacture of depleted uranium munitions and military research. These activities, as said in 3.3.1, have no a critical impact on Italian situation – e.g. we can consider the difference from the large consequences due to the wide nuclear energy exploitation in military field, such as submarine reactors, nuclear weapons production in France, United Kingdom, United States, where, although their Non-Proliferation Treaty signature, there is a considerable radioactive waste amount coming from military activity during the Cold War.

This evident difference doesn't exist for waste from hospital and conventional industry, where the main radioactive waste arising concerns LLW/ILW as shown in 3.3.2 and 3.3.3.

4 Treatments

In this section a general description of the treatments will be expounded. The techniques taken into account are those now existing and commercially exploited at international level as well as those at the research stage. In the following paragraphs, where necessary, a brief description of the decontamination techniques, considered rather as pre-treatment, precedes the part about the treatment; it is important to note that “waste treatment” refers to processes that change the chemical state of the waste material, that is distinct from “decontamination” which typically only alters the surface of the material. So, decontamination is considered a desirable precursor to both “waste treatment” and “disposal” options.

This section considers mainly two paragraphs, one dedicated to VLLW/LLW/ILW treatments – because of the similarity of methods for these categories – and one another for HLW treatments. Each of these paragraphs is subdivided in sub-paragraphs regarding to a specific waste stream for which specific technologies are thus described. Some treatments, i.e. compaction and cementation for VLLW/LLW/ILW, are analysed in a general context because of their wide range applicability.

Conditioning processes such as cementation and vitrification are used to convert waste into a stable solid form that is insoluble and will prevent dispersion to the surrounding environment. A systematic approach incorporates:

- Identifying a suitable matrix material – such as cement, bitumen, polymers or borosilicate glass – that will ensure stability of the radioactive materials for the period necessary. The type of waste being conditioned determines the choice of matrix material and packaging;
- Immobilising the waste through mixing with the matrix material;
- Packaging the immobilised waste in, for example, metallic drums, metallic or concrete boxes or containers, copper canisters;

The choice of process(es) used is dependent on the level of activity and the type (classification) of waste. Each country's nuclear waste management policy and its national regulations also influence the approach taken. At present, ocean dumping is predominantly banned by international law.

Although the implementation of well proven or innovative treatments, the need of final repository always exists. VLLW, as well as short-lived LLW/ILW (i.e. decommissioning waste) containing radionuclides that decay to insignificant radiation levels within a few decades or centuries, can be disposed of near the surface. HLW and long-lived wastes require a higher degree of isolation and should be predominantly disposed of in geological formations (i.e. emplacement in engineered structure at depths of hundreds of meters). In principle, the higher the activity and the longer the half-live of major radiocontaminants, the deeper the facility should be. In addition, some national approaches to disposal prefer the emplacement of all types of radioactive waste (short and long-lived, low and high level) in geological formations. Multi-barrier concept shown in Figure 14 considers a typical system for SNF (the repository strategies adopted internationally are shown in Figure 7). In developing any disposal system concept, reliance is placed on a multi-barrier system approach in which both the site characteristics and the engineered (technical) barriers, namely the waste form and the packaging, together contribute to the isolation of the radioactive waste from the environment for time periods that are sufficiently long enough for radionuclides to decay to acceptably low levels. This general approach has been technically elaborated and adopted for all types of disposal facilities; naturally, the barrier system compositions differ accordingly.

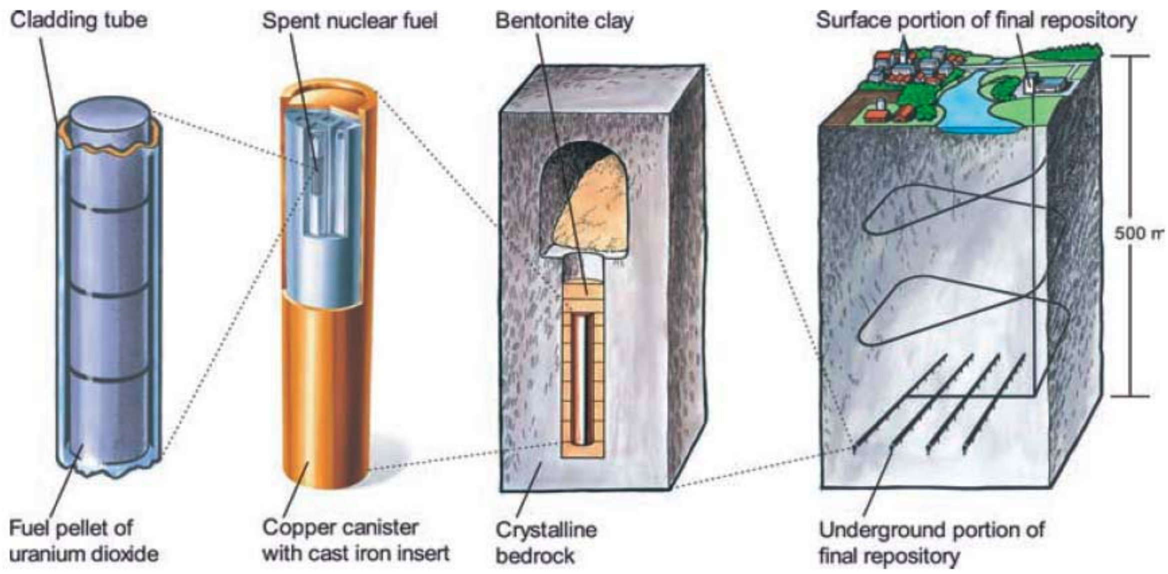


Figure 14: A typical multi-barrier system for SNF

Other disposal option are: deep boreholes, seabed and extraterrestrial disposals for HLW and SNF.

In several current deep boreholes concepts, material would be placed in thin-walled canisters in the bottom of a deep hole, with clay seals separating each canister and a long column of clay, topped by concrete, on top of the entire assembly of canisters. As a result of the great depth of the boreholes and very low permeability of the granite formations proposed for the concepts, deep boreholes may potentially isolate radioactive materials from the biosphere for much longer periods than even mined geologic repositories.

The idea of subseabed disposal is to put the material in metallic canisters that would be emplaced in the "abyssal clay formation" several kilometres beneath the ocean surface. The canisters would be emplaced perhaps 30m below the deep ocean mud surface, for which core samples demonstrate has been undisturbed in some areas for millions of years.

Extraterrestrial disposal involves placing the waste into distant earth orbit, a heliocentric orbit between Venus and Earth, or launching into the sun. To maximize payloads and reduce costs would require the SNF to be processed to remove short-lived (tens to perhaps a 100 years) radionuclides as well as any useful elements, such as uranium or plutonium. Since these options are in very preliminary stage or a not applied in any country, they are not the target of this work ([87] pg. 601-626).

4.1 Treatments for VLLW/LLW/ILW

For VLLW/LLW/ILW in general, a range of decontamination techniques have been used to minimise volumes requiring disposal. Decontamination of solid LLW/ILW is performed using different processes, such as flushing with pressurised water, chemical baths [88].

LLW/ILW-SL may be compacted to reduce its volume, or solidified if it is a liquid. Usually, it is placed in metal or concrete containers and then embedded in concrete. Thus, a package of LLW/ILW-SL is composed of 15 to 20% radioactive waste and 80 to 85% embedding matrix [89].

Compaction is a mature, well-developed and reliable volume reduction technology that is used for processing mainly solid man-made LLW. Some countries (Germany, UK and USA) also use the technology for the volume reduction of man-made ILW and TRU. Compactors can range from low-force compaction systems (~5 tonnes or more) through to presses with a compaction force over 1000 tonnes, referred to as super-compactors. Volume reduction factors are typically between 3 and 10, depending on the waste material being treated. Low-force compaction is typically applied to the compression of bags of rubbish, in order to facilitate packaging for transport either to a waste treatment facility, where further compaction might be carried out, or to a storage/disposal facility. In the case of super-compactors, in some applications, waste is sorted into combustible and non-combustible materials. Combustible waste is then incinerated whilst non-combustible waste is super-compacted. In certain cases, incinerator ashes are also super-compacted in order to achieve the maximum volume reduction. Low-force compaction utilises a hydraulic or pneumatic press to compress waste into a suitable container, such as a 200-litres drum. In the case of a super-compactor, a large hydraulic press crushes the drum itself or other receptacle containing various forms of solid LLW or ILW. The drum or container is held in a mould during the compaction stroke of the super-compactor, which minimises the drum or container outer dimensions. The compressed drum is then stripped from the mould and the process is repeated. Two or more crushed drums, also referred to as pellets, are then sealed inside an overpack container for interim storage and/or final disposal. A super-compaction system may be mobile or stationary in concept, supplied as a basic system manually controlled, with a minimum of auxiliary equipment, to an elaborated computer controlled system which selects drums to be processed, measures weight and radiation levels, compresses the drums, places the crushed drums in overpack containers, seals the overpacks, records the drums and overpacks content via a computerised storage system. Every year worldwide tens of thousands of drums are volume-reduced and stored, with waste generally being reduced in volume by up to a factor of 5 ([3] pg. 3)

Compaction and high-force compaction are already a regular part of LLW management and have realised a significant amount of volume saving prior to disposal. The current baseline treatment technology for most LLW generated from operations and decommissioning is high-force compaction (where applicable) followed by encapsulation (by grouting) prior to disposal. Compaction can be carried out by routing the waste in 200-litres drums and direct it to the super compaction suite. Both waste forms are ready for super compaction, which is then carried out. Typically the volume reduction achieved with super compaction is in the range of 4:1 to 10:1 depending on the waste stream characteristics, whilst with compaction is 5:1 Moreover, using blasting as a pre-treatment, followed by melting, can allow a wider envelope of material to be recycled ([15] pg. 51, 77, 83, 190, 192).

Thermal treatment of waste refers to the use of heat to stabilise and reduce the volume of waste. The most common example of this is incineration of VLLW/LLW, but other approaches exist such as pyrolysis, plasma arc processes, melting. These processes significantly reduce the volume of waste and remove some of the volatile and hazardous components of the waste ([16] pg. 24). Following the segregation of combustible waste from non-combustible constituents, the waste is incinerated in a specially engineered kiln up to around 1000°C. Any gases produced during incineration are treated and filtered prior to emission into the atmosphere and must conform to international standards and national emissions regulations. Following incineration, the resulting ash, which contains the radionuclides, may require further conditioning prior to disposal such as cementation or bituminisation. Compaction technology may also be used to further reduce the volume, if this is cost-effective. Volume reduction factors of up to around 100 are achieved, depending on the density of the waste.

Cementation through the use of specially formulated grouts provides the means to immobilise radioactive material that is on solids and in various forms of sludges and precipitates/gels (flocks) or activated materials. In general the solid wastes are placed into containers. The grout is then added into this container and allowed to set. The container with the now monolithic block of concrete/waste is then suitable for storage and disposal. Similarly in the case of sludges and flocks, the waste is placed in a container and the grouting mix, in powder form, is added. The two are mixed inside the container and left to set leaving a similar type of product as in the case of solids, which can be disposed of in a similar way. This process has been used for example in small oil drums and 500-litres containers for intermediate-level wastes and has been extended to ISO shipping containers for low-level waste materials. The technology is being used in the immobilisation of many toxic and hazardous wastes that arise outside the nuclear industry and has the potential to be used in many more cases ([3] pg. 3).

Although billions of dollars have been invested in glass technology for HLW, considerable quantities of waste exist that are very difficult to incorporate in glass and it is these waste streams in particular that Synroc technology refers to. Synroc can take various forms depending on its specific use, but generally speaking it is an advanced ceramic comprising geochemically stable natural titanate minerals which have immobilised uranium and thorium for billions of years. These can incorporate into their crystal structures nearly all of the elements present in HLW and so immobilise them. Those which are not suitable for transmutation can then be immobilised in Synroc, since the hot isostatic pressing (HIP) involved copes with volatile radionuclides (such as Tc and Cs) and eliminates off-gases in a one-step process. The waste suitable for Synroc is HLW (containing Am, Cm, Cs, Sr, Tc, Pu), rare earths, calcined waste as well as ILW ([17] pg. 1, 5; [18] pg. 8, 23, 30, 37).

The waste form is the key component of the immobilization process, as it determines both waste loading (concentration), which directly impacts cost (due to volume reduction), as well as the chemical durability, which determines environmental risk (especially in relation to highly mobile and long-lived I, Tc & Cs). Synroc is also thermally robust and can incorporate high concentrations of caesium and strontium, with high radiogenic heat output. Other advantages claimed relative to vitrification are greater processing flexibility with elimination of off-gas emissions. To achieve maximum cost savings and optimum performance the Synroc waste forms are tailored to suit the particular characteristics of nuclear waste to be immobilised rather than adopting a single one-size fits all approach. Moreover, because of practical difficulties in achieving high separation factors which are required for efficient transmutation, P&T concepts have increased interest in conditioning certain partitioned waste streams in durable matrices such as Synroc.

Where there is a lot of either sodium or silicon in the wastes, these can form a glass as part of a durable glass-ceramic composite wasteform. An Australian technology provides a Synroc-glass combinations where the radioactive materials are typically incorporated into extremely durable crystalline titanate phases such as zirconolite and pyrochlore (which will hold actinides, particularly plutonium), within a glass matrix ([18] pg. 4).

For ILW treatment, see also partitioning and transmutation in 4.2.3.

4.1.1 Metallic waste

Metallic waste accounts for an important part of LLW generated. Metal decontamination and metal melting have been demonstrated as an effective way to manage these wastes and can achieve recycling rates of up to 95% of incoming material. In practice, this process broadly involves the removal of surface contamination, often by conventional metal cleaning processes such as dry grit blasting, followed by a clearance process to release the clean material to the recycling market. In some cases an additional stage of melting is required to remove all contamination from the metal.

Regarding to "particular" metal such mercury, it cannot be disposed of as a metal because it's liquid and toxic, so it has to be treated prior to disposal. The most common way of immobilising mercury is by amalgamating it with zinc, but the final waste is not robust enough to prevent mercury from leaching into environment over longer periods of time. Also the reaction to make cinnabar form, that can be disposed of in a LLW repository as solid waste, requires verification.

Lead requires treatment to remove contamination before it can be re-used or recycled.

Generally, LLW metallic is received, characterised, size reduced and decontaminated prior to melting in an induction or electric-arc furnace. Once melted (see also *Molten metal*, *High temperature incineration*, *Incineration*, *Pyrolysis* and *Plasma arc* descriptions in 4.1.2.2, 4.1.2.7, 4.1.2.4, 4.1.2.5 and 4.1.2.6), the radioisotopes concentrate into the floating slag layer which can be collected and subjected to further size reduction via compaction or simply packaged for final disposal or storage. This radioactive waste is then usually returned to the customer for disposal as LLW. The homogenised metal is then cast into an ingot which can be more easily assayed, handled, stored and recycled or cast into components for the nuclear industry such as shielding blocks. Sampling and analysis of the bulk metallic mass is undertaken in the melted state which allows representative sampling to occur (i.e. a small sample represents the characteristics of the homogenised bulk). Even if the original radioactive contamination is too high to provide a recyclable ingot, the reduced volume and stable form of the ingot facilitates easy storage of the scrap metal. In many cases a reasonable decay time may render ingots suitable for recycling. After melting the metal ingots are released for recycling subject to the exemption criteria prevailing in the country of treatment (it is noted that a standardised approach to this exemption exists across most of Europe). Treatment processes such as melting can allow up to 95% of the original metal to be free-released into the steel industry for recycling. Radioactive residues and secondary wastes (estimated at around 5% of the original waste material) are returned for disposal.

Treatments

A description of treatments on metallic VLLW is reported in the following table, where for each method a reference to waste hierarchy level is reported (see also Figure 4):

Table 20: Metallic VLLW treatment methods summary

METHOD	DESCRIPTION	APPLICABILITY TO THE WASTE HIERARCHY
Segregation	The aim of segregation is to ensure that the lowest disposal category (ILW/LLW/VLLW/EW) is used for disposal where possible. This method does not necessarily minimise waste generation unless coupled with other methods, but it ensures the best use of available disposal routes in the absence of treatment by decontamination or other processing.	Minimisation (but only with regard to disposal to premium capacity facilities)
Size reduction	Size reduction is an important aspect of decommissioning and includes: disassembly of structural components; cutting techniques; demolition techniques; volume reduction (e.g. shredding, baling and compaction methods.)	Reduction
Decontamination	Commonly used in decommissioning, decontamination techniques can be carried out chemically or mechanically. Each of these sub-categories is further divided on the basis of materials use and physical or chemical principles employed. Decontamination usually results in the generation of a secondary waste, and a product that is either clean for recycling or is exempt waste. It may also result in a waste form of a lower category, e.g. ILW may result in LLW; LLW may result in VLLW or even EW.	Minimisation, reduction, recycling
Smelting	The primary aim of metal melting is volume reduction by releasing a significant proportion of the waste for recycling. Radioactive contamination is generally recovered in the floating slag layer of molten metal. The recycled metal may have a number of applications, particularly in the nuclear industry as shielding or disposal containers.	Minimisation, reduction, recycling
Encapsulation	Encapsulation is an internationally accepted method of conditioning waste forms for disposal by burial in	Disposal

METHOD	DESCRIPTION	APPLICABILITY TO THE WASTE HIERARCHY
	near-surface facilities. It is commonly used in the UK, Europe and the US. Encapsulation uses sealants such as cement, bitumens, polymers or phosphate-ceramic matrices. The sealants act to fill voids in the waste-form and to immobilise radioactive and other hazardous contaminants.	

Source: [5] pg. 19

The metal structures surrounding reactor fuel are cut into small sections in order to later separate the uranium and plutonium from non-reusable residues. ILW-LL is mostly composed of metal structures as cladding, hulls and end caps. It also comes from residues (waste from effluent treatment, equipment, etc.) originating from the operation and maintenance of nuclear facilities. Disposal of this type of waste is currently under study, but in order to reduce its volume, a significant fraction of solid ILW-LL is compacted to form pucks which are then transferred into concrete or metal packages..

4.1.2 Combustibles waste

For some combustible LLW materials, such as graphite and soft organics, a conventional incineration may not be appropriate, depending on their exact chemical nature. However, a not-negligible part of waste is adapt for conventional method of thermal destruction ([5] pg. 64).

4.1.2.1 Cold crucible vitrification

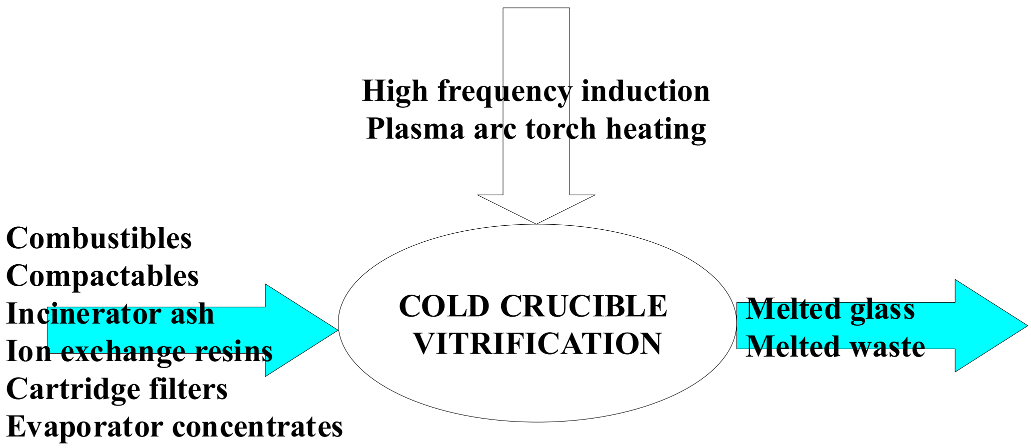
Developed thanks to the HLW experience, the cold crucible is typically a water cooled melter design in which glass and waste are melted by high frequency induction or plasma arc torch heating.

Advantages:

virtually unlimited melter life and upper reaction temperatures, thanks to the protection from corrosion of melter internals by cooling of the reactor walls, and direct transfer of heat into the melter; uniform composition of the end product assured by mechanical stirring of the melted mass; no requirements for continuous operation; high waste throughput; volume reduction efficiencies 50:1 to 100:1; low sensitivity to waste composition;

Disadvantages:

generally applicable to low dose rate materials and large input volume; full-time operation to maintain operation temperatures and a melted mass; (combustibles, non-combustible compactables, incinerator ashes, ion exchange resins and related media, cartridge filters, evaporator concentrates).



Source: [1] pg. 29

4.1.2.2 Molten metal

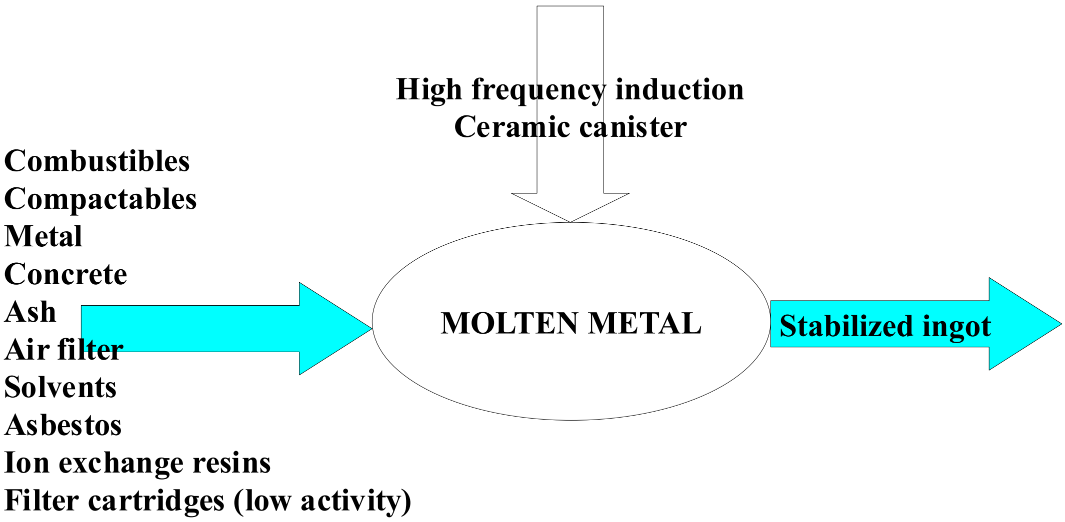
Dry active wastes (metal, concrete, etc.) are combined in a ceramic canister and melted by high frequency induction. The melting temperature is about 1500°C. The eventual waste form is a stabilized ingot. (Note this differs from metal melt in that it combines multiple waste forms with at least 10% metal composition, and not just metallic waste.).

Advantages:

volume reduction 3:1 to 5:1, without addition of cement, bitumen, etc.; stabilised waste form; contamination minimisation due to direct discharge into disposal canister; less expensive than plasma arc melting; virtual unlimited meltor life;

Disadvantages:

high installation cost, high energy requirement cost for melting; relatively low throughput; expensive ceramic canister; massive off gas treatment system; slow start-up.



Source: [1] pg. 41

4.1.2.3 PVA dissolution

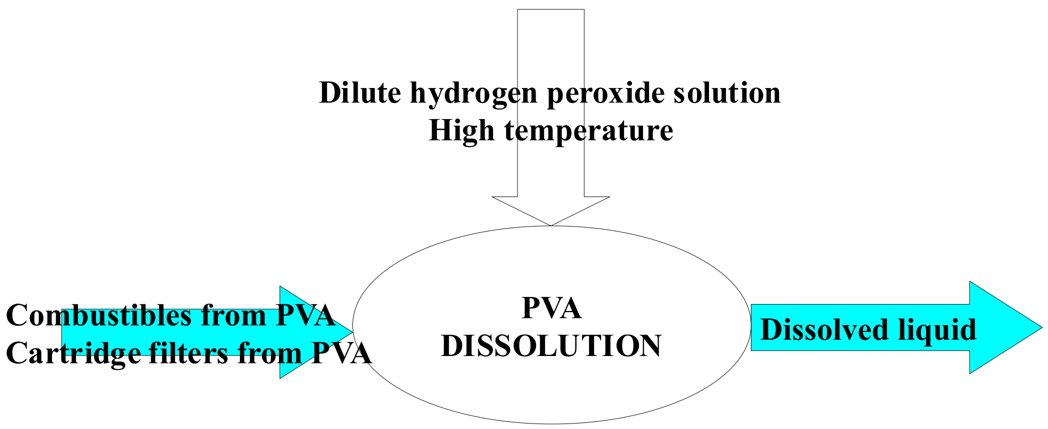
This process requires plant operators to first adopt the use of protective clothing manufactured from polyvinyl alcohol (PVA) plastic. The technology has been perfected to dissolve PVA materials at high temperature in a tank (reactor) containing the PVA waste and a dilute hydrogen peroxide solution. The end product is a completely dissolved liquid which can be discharged or directed to a bioreactor for further treatment of any organics. (Organics are derived from human perspiration, oily rags and mop heads, and other cleanup activities.) Secondary waste arises from tape, zippers, or other foreign materials attached to the PVA product.

Advantages:

high waste throughput; elimination of need for conventional laundry; no expensive; adaptability to frequency uses; low labour requirement; volume reduction efficiencies of 20:1 to 40:1 for cartridges filters and almost 100% for dry solid waste;

Disadvantages:

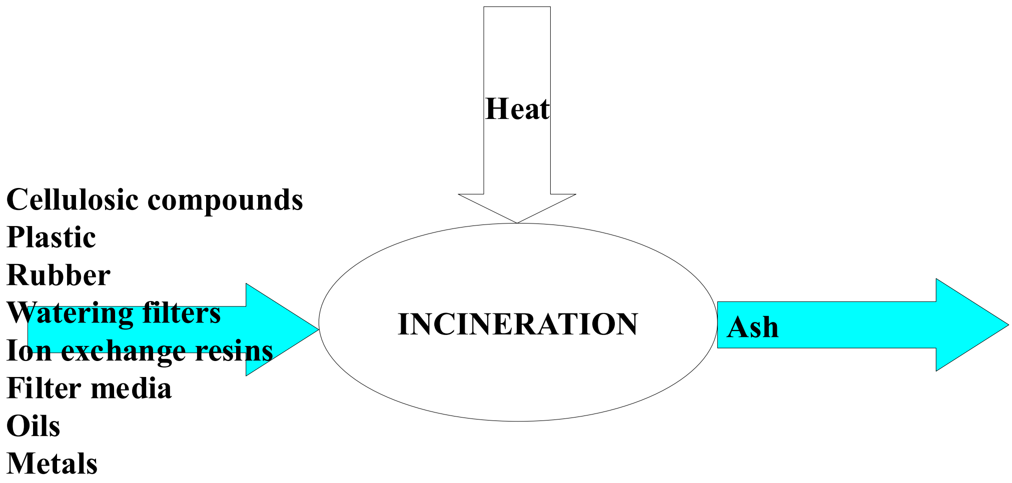
suitable for on single-use (non-recyclable) protective clothing and other materials.



Source: [1] pg. 45, 46

4.1.2.4 Incineration

A generic "incineration system" consists in its entirety of the "incinerator" itself (a combustion system comprising of one or more combustion chambers completed with auxiliary equipment, instrumentation and process controls), the waste feed preparation and loading (metering) system, the ash removal system, and the off-gas treatment system. The main aim of this treatment is the total oxidation of all combustibles material in the waste.



Below, different incineration techniques are shown.

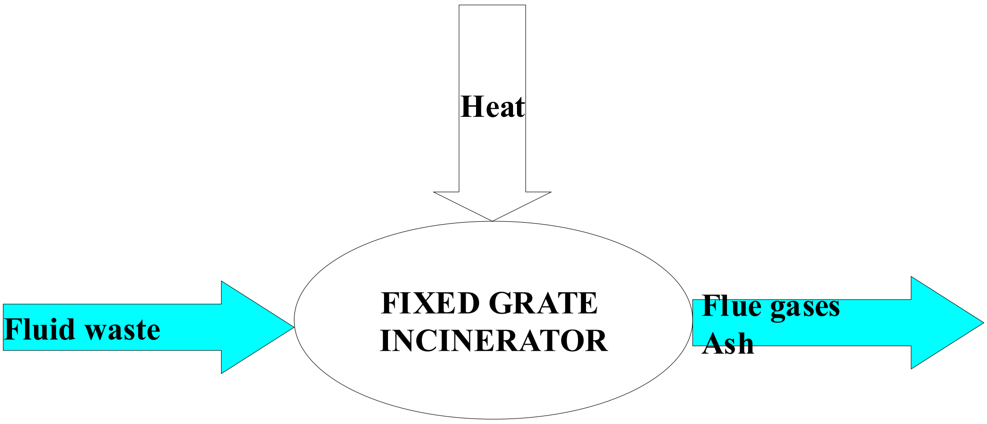
Multiple Chamber (Hearth or Fixed Grate) Incinerators

Advantages:

capital costs are normally relatively low compared to all other commercial or engineered incinerator types; maintenance requirements are relatively low as loading/ash handling, control systems, abatement plant and scale are likely to be less than all other commercial or engineered incinerator types;

Disadvantages:

the effective operation of the incinerator, even if controlled by modern instrumentation, is heavily dependant on the expertise and knowledge of the plant operators as continuous interventions are often required; throughput/capacity is normally limited; the range of waste materials is limited compared to other techniques particularly plastics and wastes containing heavy metals; ash quality for further processing and disposal is not always good. Ash management is likely to be more manually intensive than other types of incinerator, although automated system can be employed.



Source: [5] pg. 71

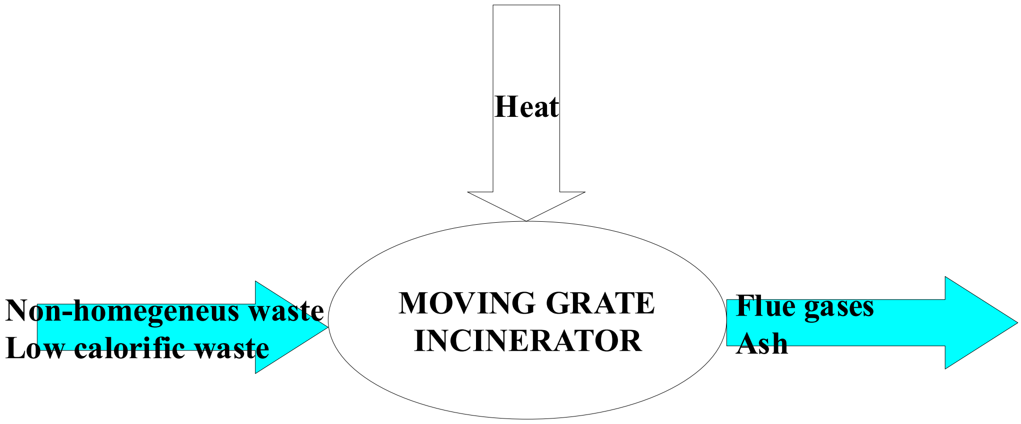
Multiple Chamber (Moving Grate) Incinerators

Advantages:

with advanced grate technology, optimal combustion chamber design and complete combustion control, this equipment is flexible enough to handle a wide range of calorific values and throughputs while generating a minimum of residues and achieving compliance with emission limits; experience indicates that grate combustion assures very high operational reliability;

Disadvantages:

typically large capacity systems requiring continuous operation and capital costs likely to be most significant of all conventional incineration technologies; maintenance requirements for grate systems tend to be more significant than other techniques but long operational cycles are normally achieved between shutdowns; the processing of highly flammable packaged wastes such as solvents is not normally possible as these might damage the incinerator components; materials which do not combust readily such as bitumen, tars and other thermoplastics that flow at high temperatures cannot be handled due to potential impacts from under grate fires and difficulties with ash management and maintenance.



Source: [5] pg. 72

Rotary kiln incinerators

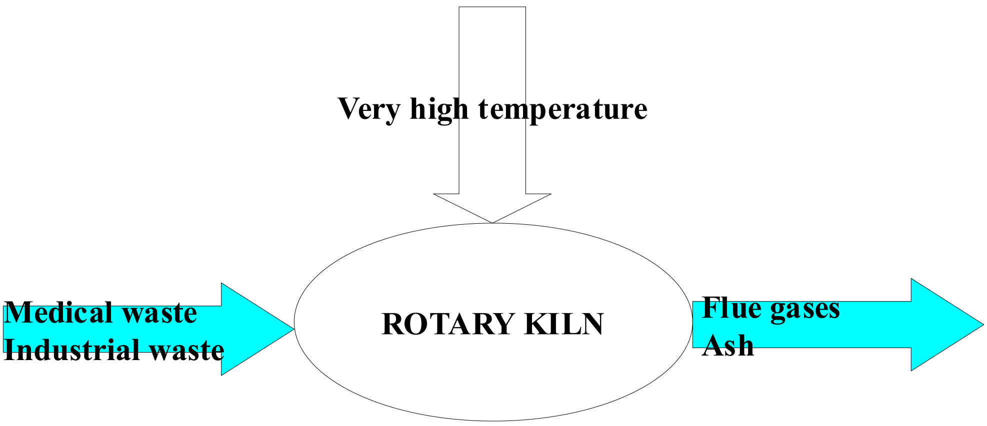
Rotary kiln incinerators are based on a large, horizontal (slightly inclined) tubular hearth which rotates at a low speed, providing agitation of the waste and efficient mixing with air. As the wastes come into contact with the air, they oxidize and gravity moves the remaining waste to the lower end of the kiln. The exhaust gas enters a secondary combustion chamber to provide for complete oxidation of residual organics

Advantages:

able to accept a wide range of waste types. More flexible than grate type incinerators; arguably the most effective method of making wastes with hazardous properties safe as high temperatures and residence times are achieved; dependent on the design selected the ash/slag management requirements can be tailored to minimise heavy metal discharges; experience in the UK for the incineration of liquid and solid radioactive waste.

Disadvantages:

relatively large capacity systems with high capital and operational cost; design requirements are complex; requires large volumes of waste throughput to justify operation; where waste is often low calorific value very significant quantities of fossil fuels are required to maintain temperatures; refractory maintenance can be significant depending on design, types of waste and operating characteristics.



Source: [5] pg. 73

Fluidised Bed Combustion (FBC) Incinerators

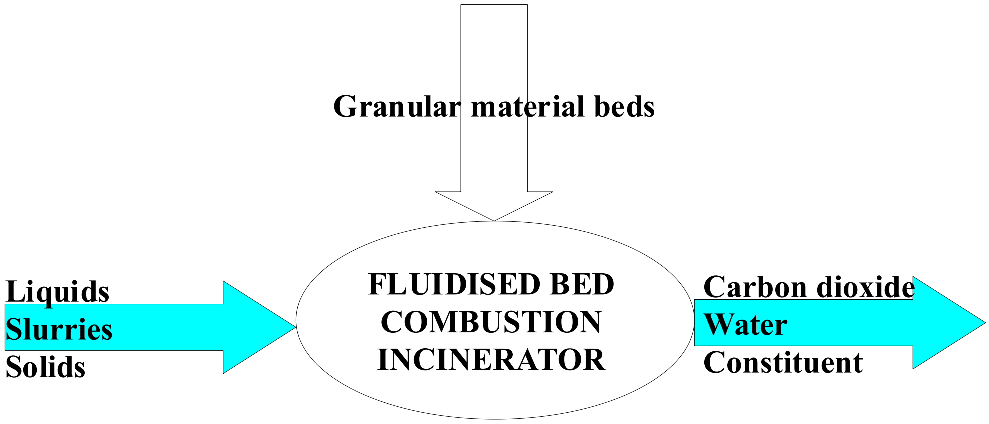
These plants generally operate as single chamber, excess air systems with beds of granular material to heat the waste, where waste is injected directly onto the bed. Air is heated by exhaust gases and goes through waste, causing agitation or fluidization.

Advantages:

the combustion process within the primary chamber is very efficient due to aggressive mixing and long residence times. Emissions are relatively low providing fuel provision is adequate; FBC incinerators are more amenable to short term shutdowns than grate or rotary kiln type incinerators reducing costs; the production of corrosion products from combustion can be reduced significantly; the simple refractory design in the combustion chamber, and minimisation of significant thermal gradients ensures that maintenance costs are lower than rotary kiln or moving/grate type incinerators;

Disadvantages:

heterogeneous wastes normally require pretreatment to improve homogeneity prior to combustion; like moving-grate and rotary kiln type incinerators, FBC requires an almost continuous throughput of fuel/waste to maintain combustion temperatures; plants costs are significant as FBC is only economical on a relatively large scale; bed de-fluidisation is a potential weakness in FBC although controls systems and waste characterisation should avoid occurrence; electrical power usage is high for bed fluidisation air pumps.



Source: [5] pg. 74

4.1.2.5 Pyrolysis

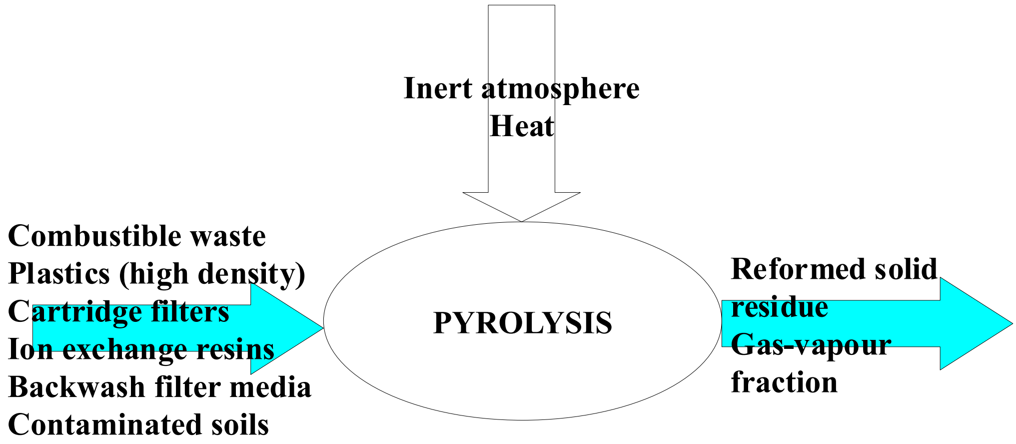
During pyrolysis, with a temperature range 500°C to 800°C, the wastes are degraded in an inert atmosphere and any long chain polymer materials are dissociated into a solid residue and a gas-vapour fraction. At the upper range of operating temperatures, the organics are destroyed, and the resulting synthesis gas exits the pyrolyser. The solid residues are transferred to a fluidized bed reformer, heated again, and subsequently transferred to a disposal or storage container.

Advantages:

gaseous emissions are normally lower than conventional incineration as the process is carried out in the absence of oxygen and at a lower temperature. The production of corrosive acids is not as significant as incineration and volatile species, such as caesium, are retained; flexible for a wide range of organic wastes, volume throughputs and high radioactive content; particularly suited to ion-exchange resins and sludge type wastes where high stability waste form is desirable; wastes with high alkali/heavy metal content can be tolerated; the capital and operational costs are considered to be comparable to a conventional incinerator although this is dependant on pre-treatment requirements; the production of corrosive compounds is less than incineration due to lower temperature of the process; waste with high water content can be processed using pyrolysis, which may be problematic for rotary kiln and FBC type incinerators; may be more acceptable process to external stakeholders than incineration;

Disadvantages:

application of the technology is more complex than other incineration technologies; the final waste product may not be as homogenous as the ash from incineration and may required further processing to allow its disposal; consistent with moving grate and rotary kiln incineration pyrolysis plants are normally operated continuously and as close to capacity as is practicable; waste pre-treatments are often necessary and can be complex significantly increasing temperatures; in practice, the use of pyrolysis is not applied to general LLW rather more specific higher radioactivity wastes for a specific application; plants constructed for radioactive waste applications are of relatively low throughput and development of a large capacity facility sufficient to meet a national demand would be significant. Any new plant for the UK arisings would be highly bespoke in all aspects.



Source: [19] pg. 30-37; [5] pg. 75; [1] pg. 46, 47; [20] pg. 44, 45

4.1.2.6 Plasma arc

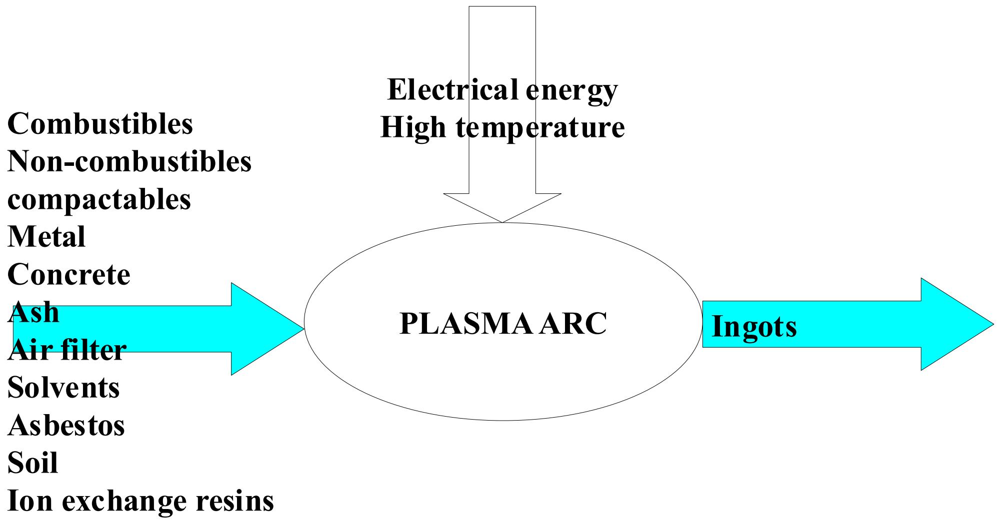
Wastes emplaced in the melting furnace are exposed to the plasma arc torch at temperatures above 5000°C. Melted waste is discharged into the disposal container and cooled into ingots. To prevent the melted waste from sticking inside of the furnace, the furnace is always rotating.

Advantages:

very high temperatures ensure that all organic compounds are destroyed.; wide range of waste materials can be processed or disposed; high stability waste residue is produced.

Disadvantages:

very high development and capital costs; hazardous operations due to high temperature operations; limited application and experience for radioactive wastes; throughput is likely to be low compared to moving grate, rotary kiln and fluidised-bed incinerators; management of the volatile radionuclides; specialised materials and cooling systems are required; high electrical energy consumption; unproven technology for a range of waste types.



Source: [1] pg. 44; [5] pg. 76

4.1.2.7 High temperature incineration

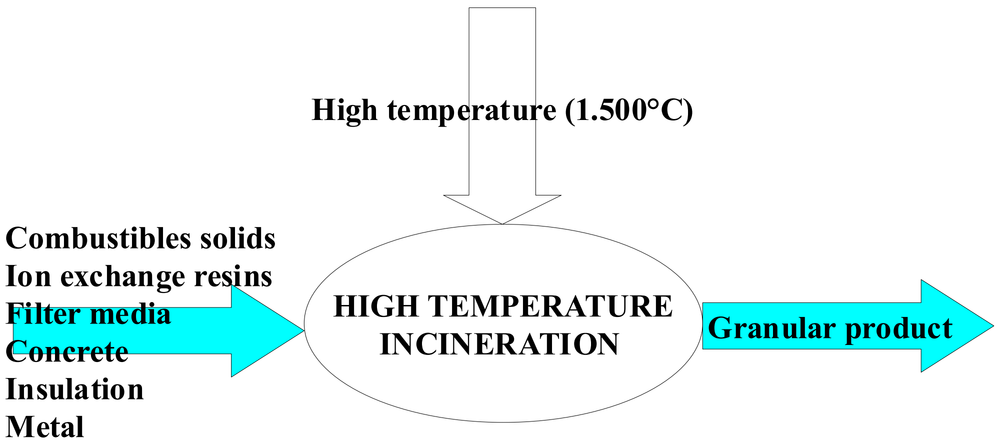
This improved incineration technology can treat also not-combustible waste along with other combustible waste, thanks to its temperature of 1.500°C (whereas a conventional incinerator runs at 700 to 1000°C). The waste is melted in a rotating furnace, then discharged at a controlled rate with water jet cooling to produce a granular product.

Advantages:

stabilized waste form;volume reduction efficiencies typically in the range of 3:1 to 5:1 for light metal, air filters and insulation. The volume reduction ratio rises as high as 100:1 for some other combustibles; a small percentage of metal, air filters, and insulation can be incinerated along with other combustible waste, since high temperature incineration has a powerful burner and runs at 1500°C (whereas a conventional incinerator runs at 700 to 1000°C);

Disadvantages:

very sensitive to waste composition; deviation may shut down the system; pre-sorting of waste required; high installation cost; massive off gas treatment system required; not generally suitable for high dose rate wastes.



Source: [1] pg. 32; [19] pg. 19

4.1.2.8 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*

Thermo-chemical conversion	4.1.8.1

4.1.3 Resins

Presumably, the deep geologic repository will provide a permanent disposal route for exchange resins, but a typical current thermal treatment for this type of waste following process: a pyrolysis and steam reforming process with a working temperature around 700°C – e.g. THOR (Thermal Organic Reduction, Sweden). This method provides a volume reduction and a adapt waste for disposal (no biological growth or hydrolysis off gas potential). Resins are also encapsulated in many countries. Concrete is the most commonly used stabiliser of ion exchange resins and there are several different formulations depending on country specific and disposal facility specific requirements. A polymer was also used to encapsulate resins in Italy, but the waste produced by this process does not fulfil any conditions for acceptance in any repository, since the polymerisation was not complete in all cases so the final product is not well-defined; this resulted in separation of the solid phase and some of the liquid which was partly the sulphuric acid. The final product ranged from slush to solid monoliths. With the encapsulation of resins, there is also an volume increasing of final waste. Currently, drying, wet oxidation, and melting are not in commercial use ([5] pg. 134; [19] pg. 4). An interesting IAEA's technical document ([17] pg. 24, 32, that should be integrated by new publications in the period 2010-2014) points out that one of the main problem related to spent ion exchange resins is the release of radionuclides (e.g. C-14) into the gaseous phase and the risk of spreading of these into the environment; an appropriate treatment would involve a preliminary step for removal of C-14 (if present) followed by a suitable oxidative destruction method such as the photo-Fenton reaction or molten salt oxidation. For long-term storage, there are non-destructive methods of processing spent ion exchange resins, characterized either by increase of total volume of radioactive waste (cementation) or by slight decrease of this volume (bituminization, polymerization) – without problems of decontamination of large amount of radioactively contaminated gases and spreading of decontamination of C-14 occurring with carbon oxides emissions during the resins incineration – and the destructive methods, including incineration techniques, wet oxidation, pyrolisis, acid destruction, usually accompanied by a volume reduction of solid waste part.

The same document shows the state of art for treatments on spent resins and sludges (the unabsorbed and unfiltered sediment and other solids remaining after removal of the liquid phase in aqueous solutions); in summary, the situation, up to 2007, is the following: separation, drying, storage, elution, electrochemical deposition, photo-degradation. Also for sludges, it can possible to apply the encapsulation. ([5] pg. 133, 134).

4.1.3.1 Drum drying

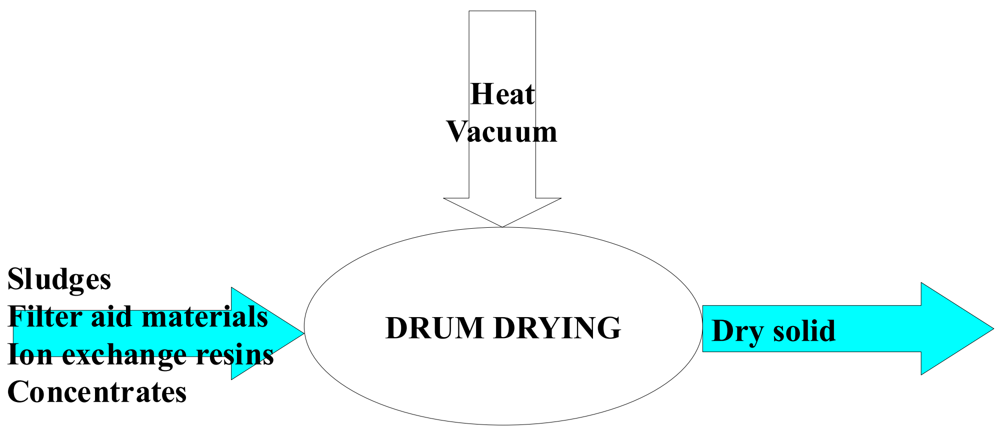
Waste is loaded into a standard 200-litres storage drum, and the drum is then heated within a cabinet to drive off the contained water. Heating may be by circulation of warm air or electrical heating jackets fitted around the drum. Vacuum can be applied to increase the rate of drying. The removed water is extracted by an air recirculation system, where it is condensed and monitored prior to further treatment or disposal.

Advantages:

simple and low-cost technology with a dry and volume-reduced (2:1 to 6:1) end product adapt for storage or disposal;

Disadvantages:

slow throughput; potential fire risks from solvent and other organics.



Source: [1] pg. 30,31

4.1.3.2 Geopolymerization

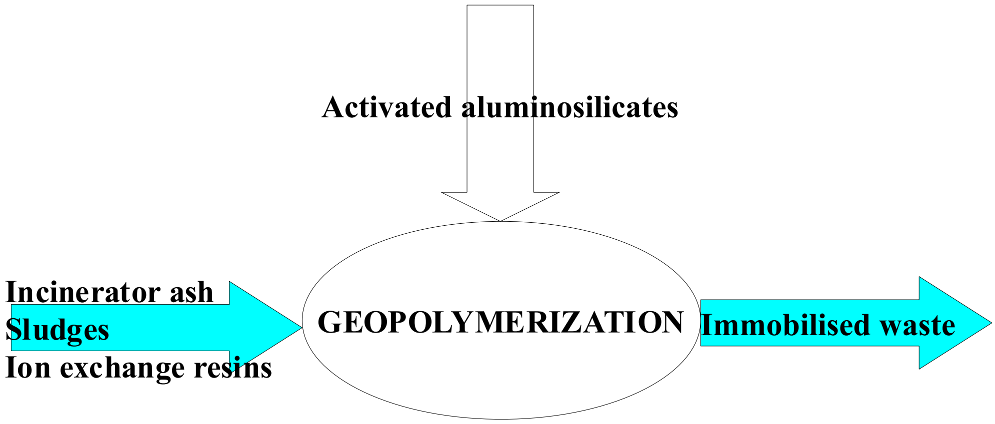
It achieves the waste immobilization objectives through reactions of the activated aluminosilicates (kaolinitic raw materials) dissolved in an alkaline aqueous solution.

Advantages:

room temperatures operation; easy off-gas technology; no secondary waste; higher immobilization capacity for soluble salt (compared with Portland cement);

Disadvantages:

technology at research level for almost waste streams;



Source: [1] pg. 31, 32

4.1.3.3 Hot isostatic pressing

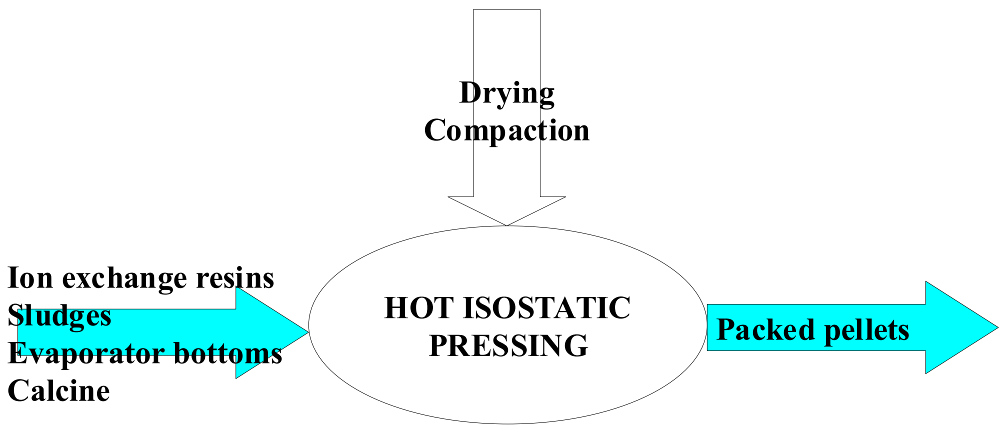
Spent resins are first dewatered or dried to a residual water content (water of hydration) of between 12% and 50% in a drying vessel. Following the drying step, the waste is loaded into special metal cartridges which are capped (lid attached) and then immediately transferred into a high force compactor. The resulting pellets are then measured for dose rate, height and weight, and then packed for storage and/or disposal. The resulting products must be packed into watertight containers to avoid resin swelling from contact with water.

Advantages:

multiple waste streams treatment; possibility to produce a solid monolithic waste form; volume reduction typically of 6:1;

Disadvantages:

potential problems with disposability of product due to possibility of resin rehydration; potential off-gas treatment requirements; potential adverse chemical reaction between waste types;



Source: [1] pg. 33

4.1.3.4 Pelletization

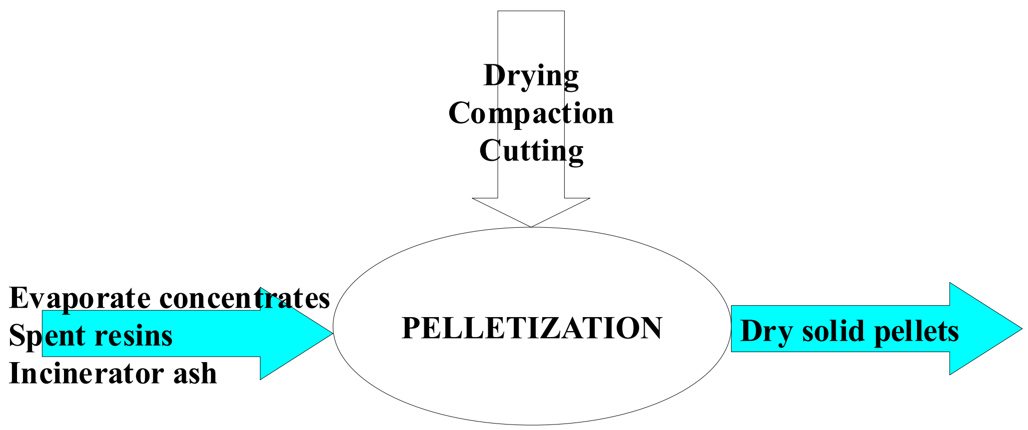
For this process the raw waste is dried into a powder form, compacted in a mould into a solid form, and cut into small pieces; the treatment of ion exchange resins requires a chemical binder, whereas other waste types may not.

Advantages:

high waste throughput; volume reduction efficiencies of 4:1 to 8:1; conversion from a wet form into a dry form, suitable for storage; no requirement for continuous operation;

Disadvantages:

difficult post-treatment solidification with cement because of the absorbency of moisture; possibility of explosion due to powdered form; some carcinogenic binder used;



Source: [1] pg. 43

4.1.3.5 Wet oxidation process

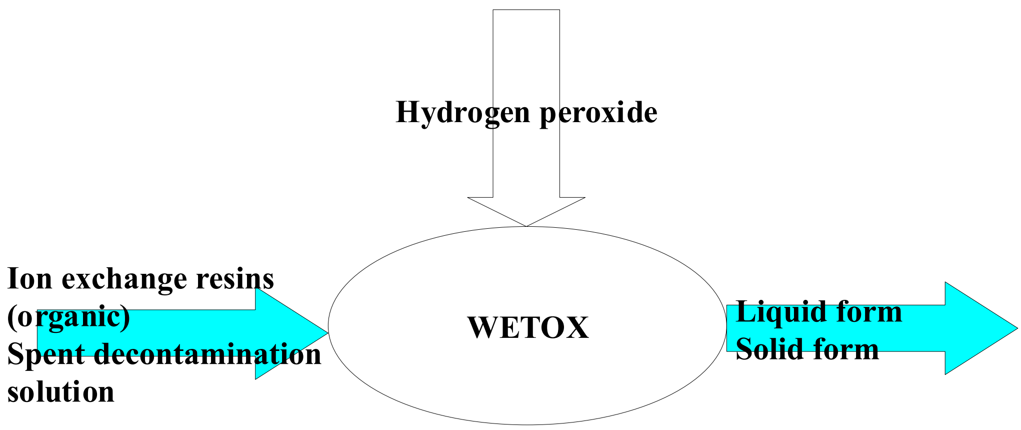
In this process the organic waste is reacted with hydrogen peroxide in the presence of a catalyst at modest temperatures and atmospheric pressure with excess water and distilled or evaporated to leave a concentrated inorganic waste which contains the radioactivity; the concentrated residue may then be sent for continued storage in liquid form or solidified for storage and potentially disposal.

Advantages:

potential benefits for long term stability and disposability due to organics destruction; volume reductio of 5:1 to 100:1; reduced salinity of solution;

Disadvantages:

gaseous emissions; concentration of activity and hence increase in potential doses to operators; potential to raise the categorisation of the waste (e.g. from LLW to ILW);



Source: [1] pg. 51; [20] pg. 55-57

4.1.3.6 Molten salt oxidation

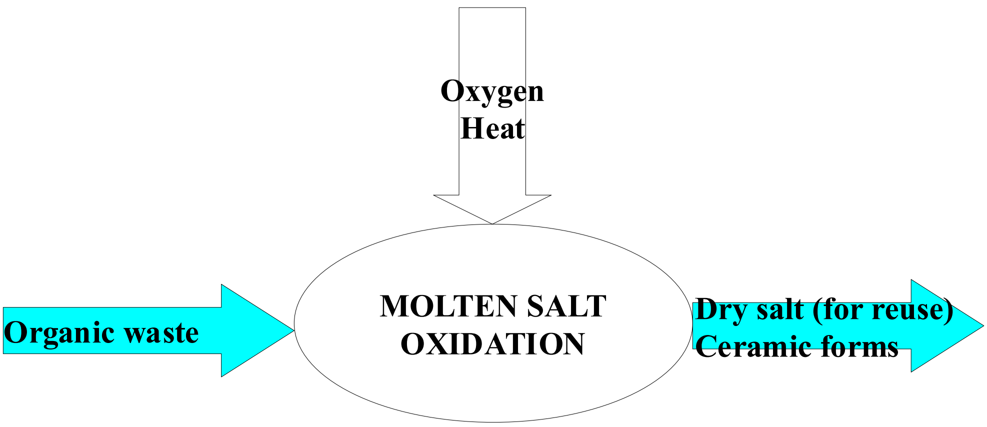
In this alternative to traditional incineration, the combustible organic species are oxidized in a bath of alkaline molten salts at temperatures between 500 and 950°C. The organic components react with oxygen to produce carbon dioxide and water, and the inorganic component residues formed (including actinide species) are contained within the molten salt. Any acid gases produced in the oxidation, such as hydrochloric acid, are scrubbed by the alkaline salt. Recycling of the salt removes the residues from the bath for immobilization.

Advantages:

complete organic material destruction; lower temperature than vitrification, plasma or conventional incineration; negligible dioxin and furan production; radioactive species capturing in salt bath;

Disadvantages:

high capital cost; specialised techniques requiring for salt product conditioning.



Source: [19] pg. 30; [20] pg. 52, 53

4.1.3.7 Acid digestion

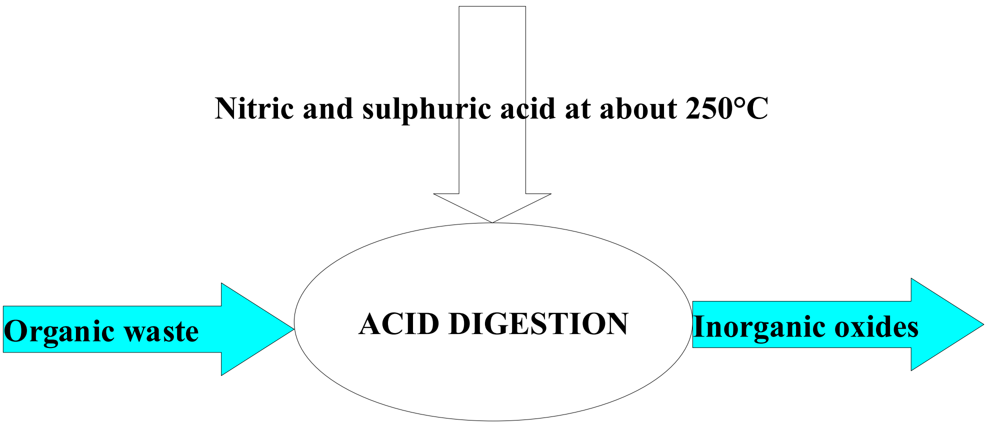
This technique uses hot, strong mineral acids (nitric and sulphuric acids at about 250°C) to oxidize the organic components of the waste, producing a range of gases and an aqueous sludge consisting of inorganic oxides.

Advantages:

low pressure; low temperature; wide range of organic waste;

Disadvantages:

high cost of corrosion resistant equipment materials (due to corrosive nature of the process); off-gas treatment system; neutralization system before immobilisation.



Source: [19] pg. 15-18; [20] pg. 55

4.1.3.8 Supercritical water oxidation

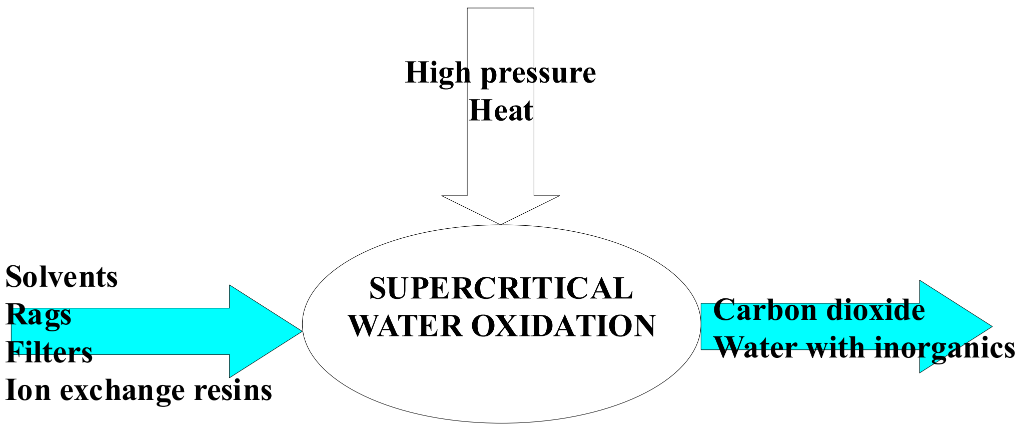
This technique, as an advanced form of wet oxidation, uses the properties of water at above its critical temperature and pressure, combined with air, to oxidize organic material, producing carbon dioxide and water with inorganic components, resulting in insoluble precipitates.

Advantages:

no NO_x or SO_x generation; efficient separation of dissolved heavy metals and fission products; applicable in mobile treatment plant;

Disadvantages:

high pressure; high temperature; limited to 2-25% of organics presence; temperature and corrosion control; immobilisation of produced sludge.



Source: [20] pg. 59, 60

4.1.3.9 Thermochemical/Advanced thermochemical treatment process

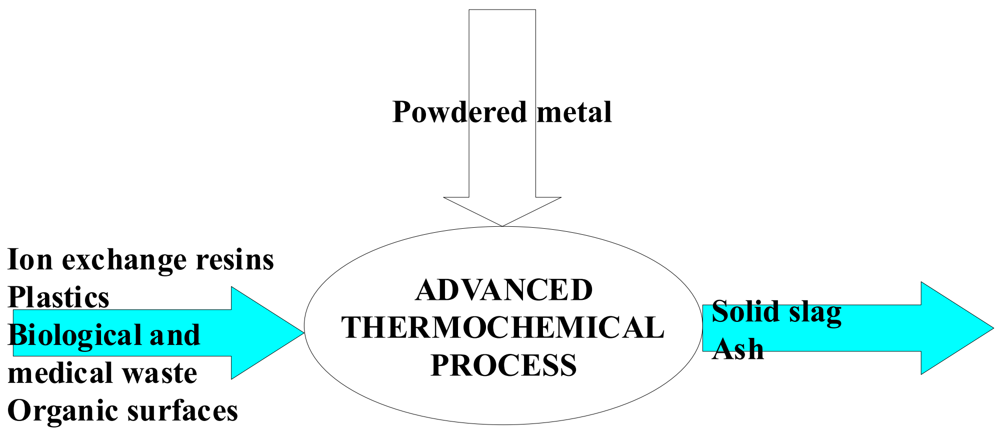
This process uses a powdered metallic 'fuel' such as aluminium or magnesium, which interacts with the waste both chemically and physically through reaction with the water present in the waste, with a consequential destruction of organic material.

Advantages:

simple technology; applicable to mixed solid waste;

Disadvantages:

not-easy handling of end product.



Source: [19] pg. 37-41; [20] pg. 61, 62

4.1.3.10 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Biological treatment	4.1.4.11
Cold crucible vitrification	4.1.2.1
Incineration techniques	4.1.2.4
Microwave treatment	4.1.11.1
Molten metal	4.1.2.2
Plasma arc	4.1.2.6
Pyrolysis	4.1.2.5
Thermochemical conversion	4.1.8.1

4.1.4 Liquid waste

Liquid LLW/ILW are segregated on the basis of their aqueous or organic condition. They are subsequently treated using physical or chemical methods in order to reduce their contamination and volume. Among the physical methods used are filtration, centrifuging and evaporation. The most habitually used chemical methods are precipitation and ion exchange. Most wastes have to go through several processes before decontamination achieves the levels sought. Finally, they have to be solidified, since this is the safest way to transport and store them. To achieve this they are uniformly mixed with concrete, mortar or cement [90].

Organic ion exchange resins are used in specialized applications to remove contaminants from water (e.g. in water reactor circuits and prior to discharge of effluents into the environment). Therefore they accumulate a radionuclide burden. They are expensive materials that are used with care and regenerated if possible. They are discarded as waste only when this is necessary or economically justified ([20] pg. 5).

Photodegradation of the organic complexing agents and/or surfactants followed by selective sorption can be considered as the most promising approach to these problems. Future work in the area of aqueous concentrates should include:

- the development of more effective processes for the removal of ruthenium and cobalt;
- the proper management of spent sorbents and secondary waste streams;
- the scale-up of promising processes and testing with actual waste;
- recovery and recycle of chemicals (e.g. boric acid) wherever possible.

Other treatments on liquid waste are: coagulation, flocculation, sorption, ambient-temperature evaporation, vitrification, hydro-thermal oxidation ([17] pg. 7, 17).

More detailed techniques are the followings.

4.1.4.1 Electrochemical Ion Exchange (EIX)

An evolution of conventional ion exchange is the Electrochemical Ion Exchange (EIX) process. It is the combination of ion exchange, electro dialysis, and elusion processes, in which an electric potential in place of chemical reagents is used to elute ion exchange media. The main application areas for EIX relate to the removal/recovery of metals from aqueous streams. These include: the decontamination of streams produced by PWRs and the separation of radioactivity from tank waste storage facilities, the selective removal and recovery of precious metals from metal refining operations and base metals from electroplating rinse waters, the treatment of hospital waste (active) streams and the removal of silver from photographic wash waters. With a combined electro-remediation (primary treatment) to provide a total, integrated package of treatment technologies, this method has been employed for soil decontamination and site clean-up [91] pg. 1; [92] pg. 4.

4.1.4.2 Ion exchange membranes

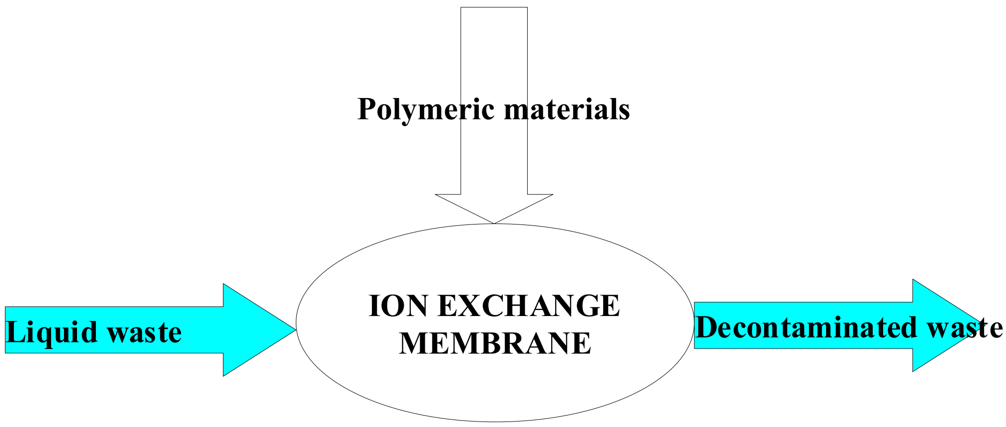
Used in a number of treatment systems, the ion exchange membranes are thin sheets of polymeric materials.

Advantages:

high ion exchange efficiency; possibility of incineration and compaction;

Disadvantages:

high cost; limited mechanical stability; not very long useful life;



Source: [1] pg. 34, 35

4.1.4.3 Ion-specific filtration

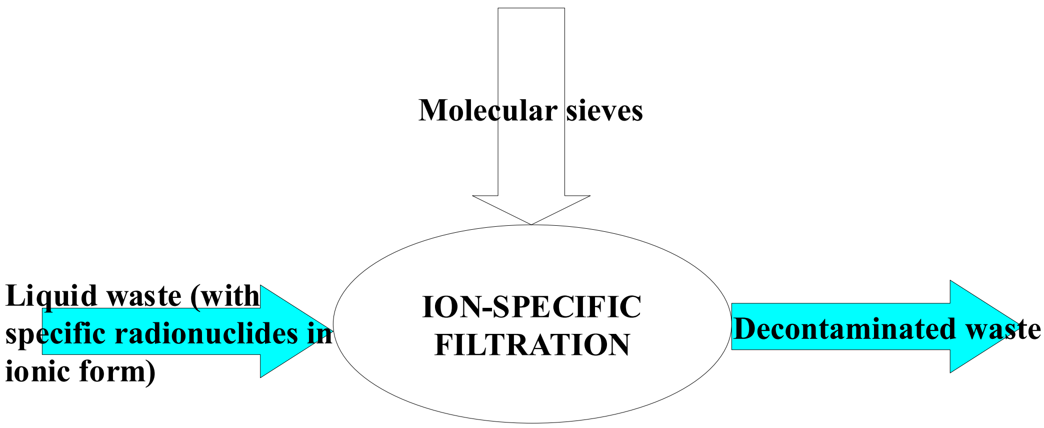
Water is circulated through the submersible unit, containing a cartridges, and the activity of the selected radionuclide is concentrated on the ion exchange cartridge.

Advantages:

specific radionuclide capacity up to 10^6 times that of traditional ion exchange materials; high volume reduction; inorganic adapt for disposal; suitable for a simpler encapsulation, rather than in-drum mixing;

Disadvantages:

volume reduction benefit limited by the pratcical difficulties in handling the material after use; not suitable for very high specific activity materials;



Source: [1] pg. 35, 36

4.1.4.4 Membrane filtration

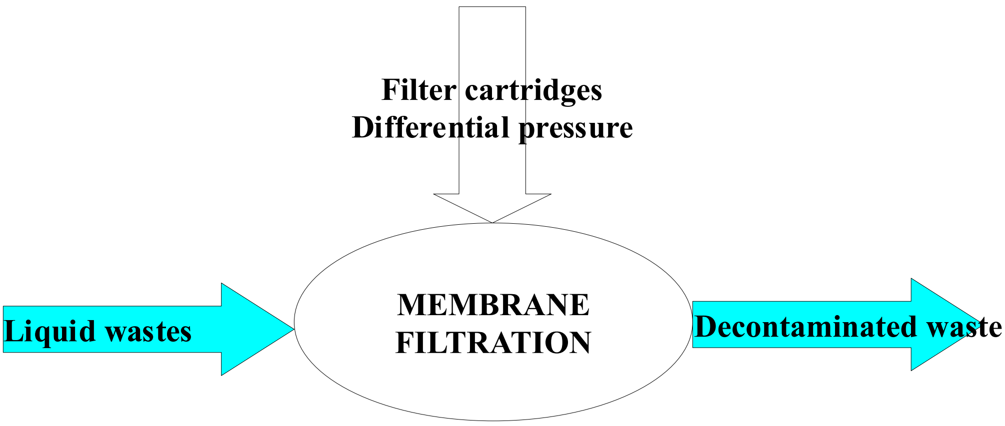
Ultrafiltration and cross flow filtration are used to remove suspended fine particles from liquid streams, while hollow fiber filtration is used in condensate systems, as well as in liquid waste treatment systems. Filter cartridges consist of hundreds of fine, hollow fibers, or they contain numerous micro-pores on the surface.

Advantages:

high removal efficiency (almost 100%); life 3 to 10 years; waste minimization by combustion;

Disadvantages:

no use as ion trap; filter capacity limitation if it is installed in an addition yo an existing system;



Source: [1] pg. 39, 40

4.1.4.5 Reverse osmosis

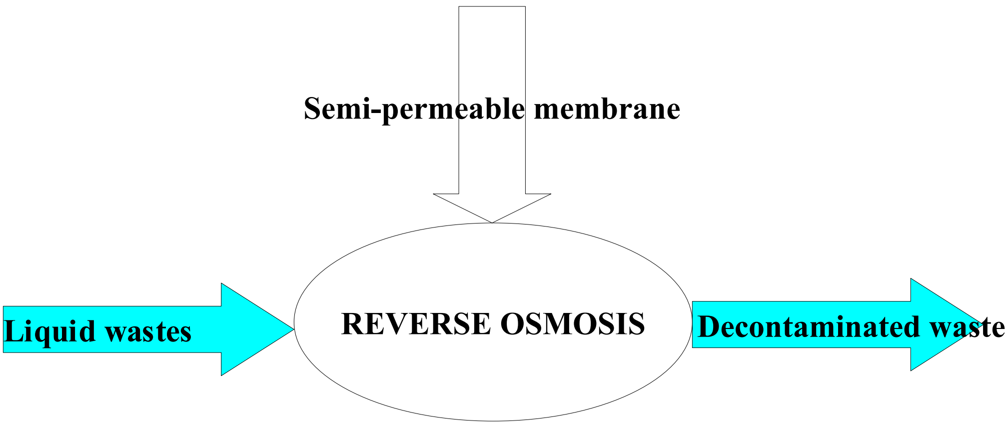
This technology involves movement of a solvent out of solution under pressure through a semi-permeable membrane into pure solvent or a less concentrated solution at lower pressure; this process can be used to increase the radionuclide concentration in solution; this is often used as the final polishing stage in low level liquid waste treatment.

Advantages:

ionic species free permeate, suitable for releasing into the environment; large scale operation; concentrates dissolved salts; high waste throughput; high decontamination factor of 100:1 to 1000:1;

Disadvantages:

high pressure system; limitation due to osmotic pressure; not backwashable; high fouling susceptibility;



Source: [1] pg. 47, 48

4.1.4.6 Super absorbent polymers

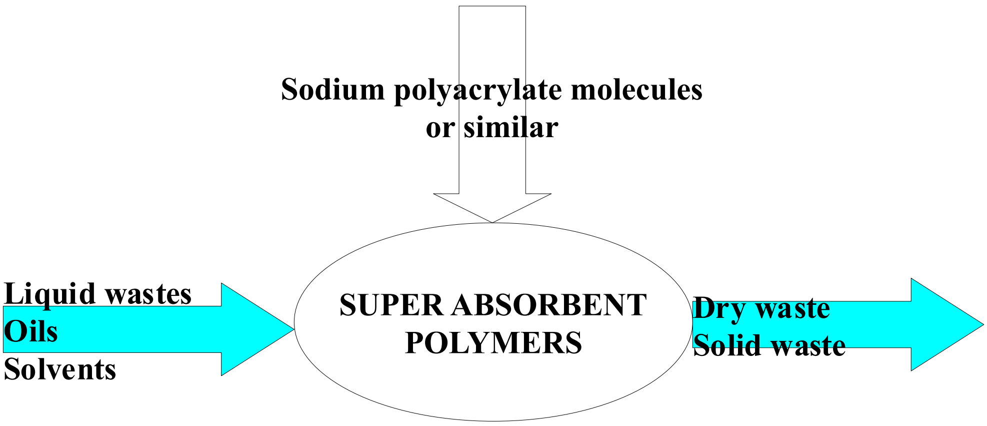
This is a class of compounds which can absorb liquid in dry wastes or convert a liquid to a solid; when mixed with liquids, they have the ability to absorb several hundred times their weight in liquid; the original liquid is locked in the molecular structure along with any dissolved or suspended solids;.

Advantages:

simplifying of transportation and further treatments; high absorption capacity (several hundred times their weight in liquid); possibility of following incineration; formulations available for aqueous and organic liquids; little volume increasing; simple equipment; stable product;

Disadvantages:

absorption efficiency limited by high concentration of some ions (e.g. Na); not suitable for disposal or storage due to low compressive strength; need to test with real waste stream for a optimum formulation; possible damage to polymer with high radiation fields;



Source: [1] pg. 48, 49

4.1.4.7 Alkaline hydrolysis

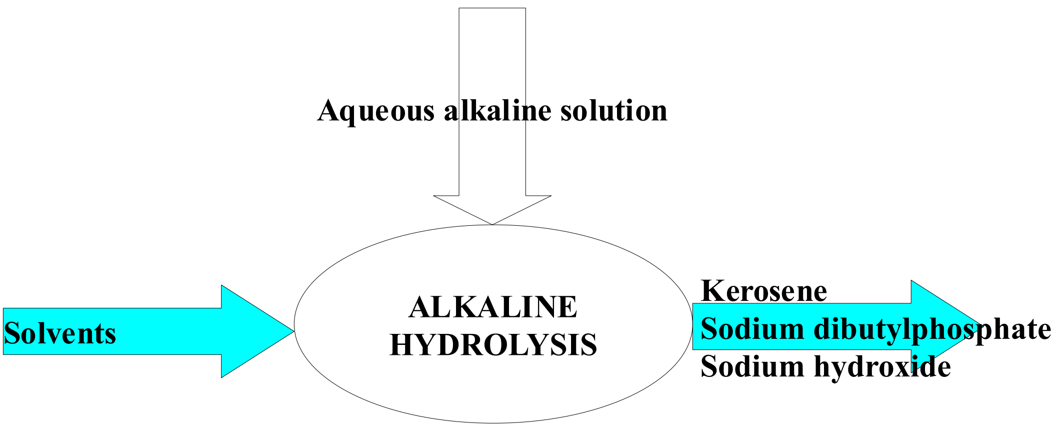
It is a wet, chemical extraction process in which a liquid organic waste is put into contact with an aqueous alkaline solution. Hydrolysis reactions alter the nature of the organic species and result in transfer of the radioactivity to the aqueous phase. Subsequent separation of the phases results in a clean organic liquid.

Advantages:

low operating temperature, size flexibility;

Disadvantages:

limited application for organic waste, complex waste products that require further treatments before storage or disposal.



Source: [20] pg. 46, 47

4.1.4.8 Direct chemical oxidation

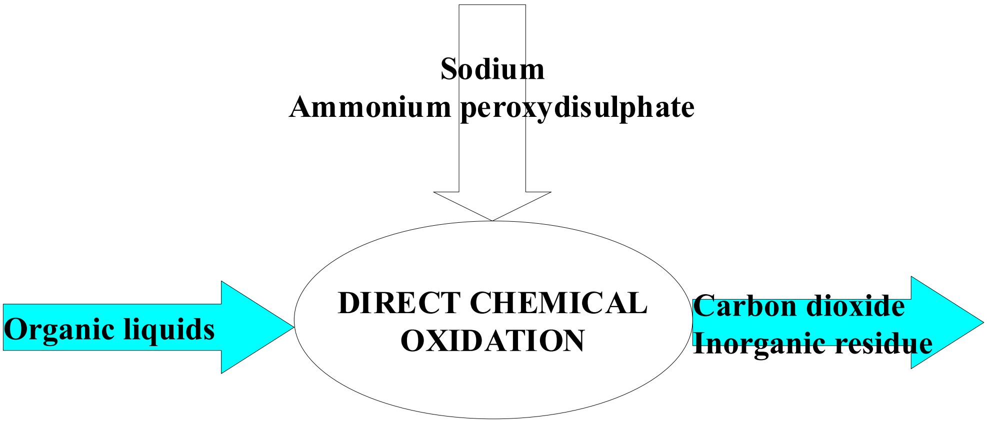
It was designed to retain the benefits of an aqueous system (i.e. capturing dust while products remain within a liquid medium) but increase the efficiency of oxidation in an aqueous process by specifically utilizing sodium or ammonium peroxydisulphate. The operating temperature is normally 80-95°C and the final bisulphate ion is recycled to produce new oxidant by conventional electrolysis. The organic material is converted to carbon dioxide and the inorganic residue products can be collected for immobilization in cement.

Advantages:

low temperature; low pressure;

Disadvantages:

only suitable for liquid organic waste



Source: [20] pg. 54, 55

4.1.4.9 Advanced oxidation processes

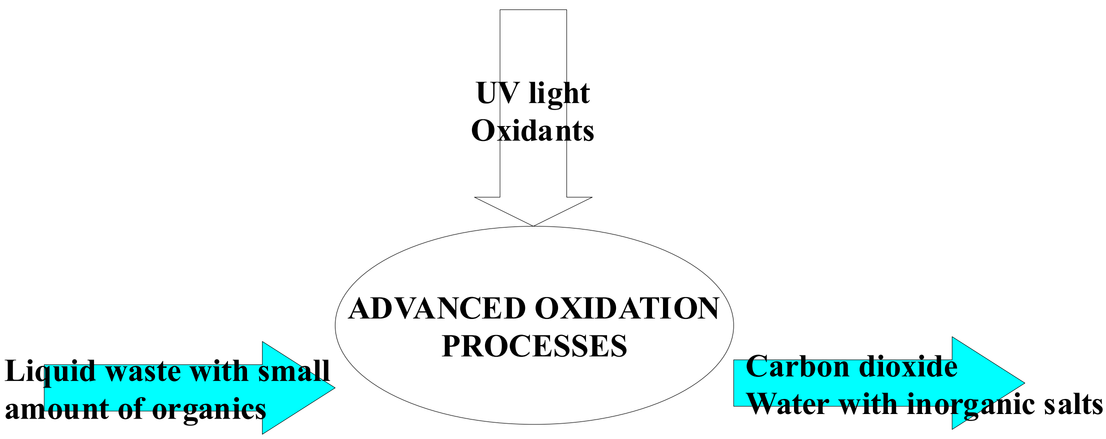
These methods include the use of ultraviolet light and oxidants (hydrogen peroxide or ozone), sometimes combined with catalysts, to destroy organic materials, producing carbon dioxide and water (with inorganic salts if catalysts are present).The waste stream must be of low turbidity to enable penetration by UV light. A possible application for nuclear waste streams may be removal of the organic component of an aqueous radioactive waste so that the aqueous stream can then be treated by a conventional method such as biological treatment or flocculation.

Advantages:

usable in a mobile treatment plant; simple equipment; low temperature; low pressure;

Disadvantages:

need of dilute aqueous systems; limited applicability to radioactive waste.



Source: [20] pg. 57, 58

4.1.4.10 Calcination

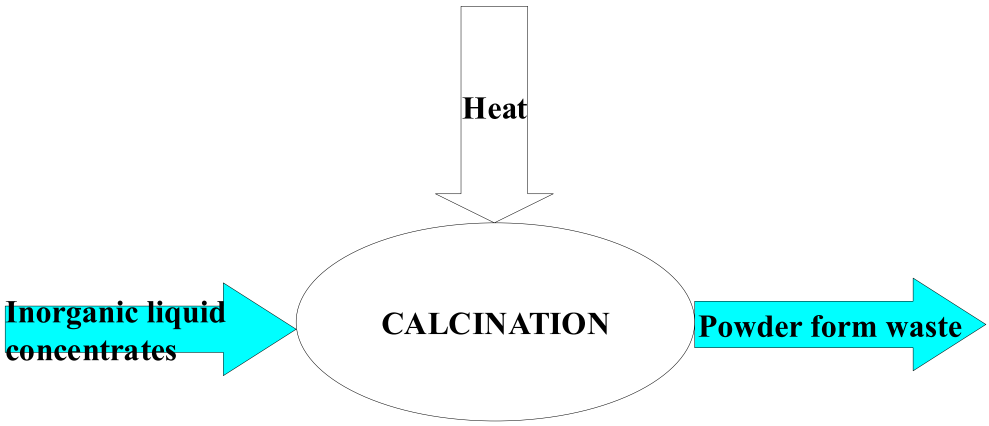
Two-stage vitrification processes utilize preliminary calcination of the waste. The process is based on the elimination of volatile fraction from the waste by different techniques: pot calcination, spray calcinantion, fluidised-bed calcination, rotary kiln calciner.

Advantages:

high volume reduction; water elimination; soluble salt decomposition; oxide form product;

Disadvantages:

additional conditioning/packaging due to powder waste form;



Source: [19] pg. 12-14

4.1.4.11 Biological treatment

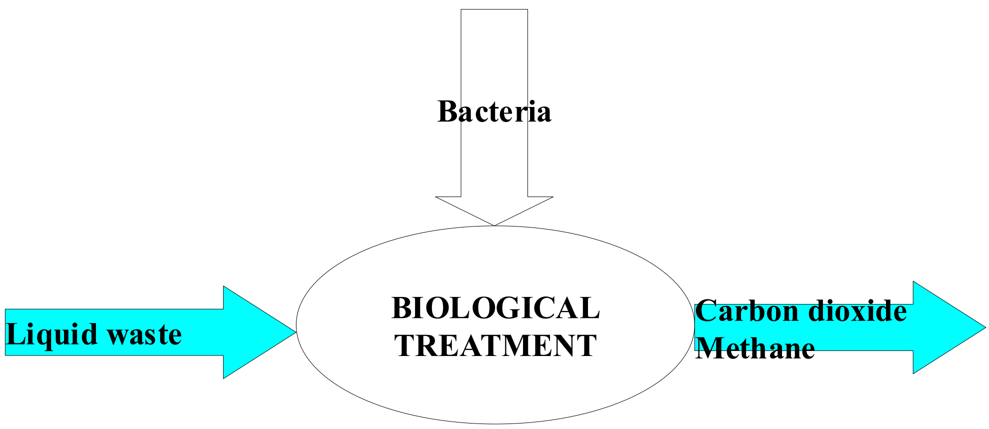
The biological treatment technique uses the ability of bacteria to metabolize and digest the organic components of waste. Under aerobic conditions, the gaseous product is carbon dioxide, but anaerobic conditions will produce a 50:50 mixture of carbon dioxide and methane. The technology is not utilized at present, although a pilot facility has been constructed for Electricité de France and another pilot plant for biological treatment of ion exchange resins has been constructed at Loviisa in Finland.

Advantages:

good efficiency for low concentration organic with aqueous streams and for specific substrate;

Disadvantages:

suitable only for low volume and low concentration; not suitable for mixed waste; need for further treatments of biomass and large volume of liquid waste; active gaseous product if C-14 is present into the waste.



Source: [20] pg. 60, 61

4.1.4.12 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Molten metal	4.1.2.2
Plasma arc (for solvents)	4.1.2.6
Supercritical water oxidation	4.1.3.8
Thermochemical conversion	4.1.8.1
Vitrification	4.2.1
Wet oxidation	4.1.3.5

4.1.5 Contaminated land

If an *in-situ* treatment strategy is applied, a containment of contamination within the site boundary will take place and a plan of action as Monitored Natural Attenuation (as in the UK) waits for a point of acceptable risk to human health reached by the natural decay of contaminant materials; so this approach is adapt for radioactive content with short-lived isotopes. A more rapid method is to "excavate and dispose", that has a major pressure on LLW repository in short term.

4.1.5.1 Phytoremediation, Phytostabilization

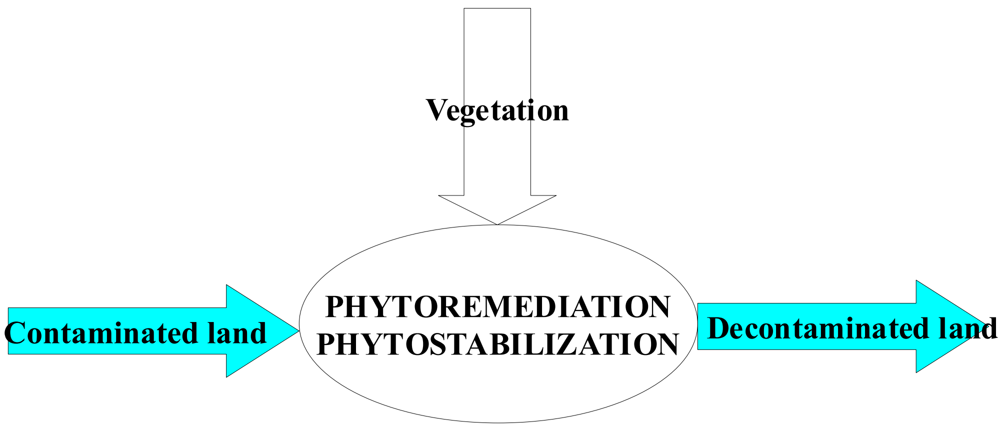
Phytoremediation absorbs radioactive species from contaminated land (e.g. soils, sand, clay); the vegetation can then be cropped to remove the activity, and treated by further means, for example incineration; phytostabilisation makes use of vegetation to stabilise areas of contaminated ground and reduce the risk of activity spread by erosion, thus reducing waterborne and dustborne exposure pathways.

Advantages:

low cost; easy application;

Disadvantages:

potential slow process; further treatments for cropped vegetation; applicable to low levels of contamination or large ares of land;



Source: [1] pg. 44

4.1.5.2 Other treatments

TREATMENT	*REFERENCE PARAGRAGH*
EIX	4.1.4.1
Plasma arc	4.1.2.6
Pyrolysis	4.1.2.5
Thermochemical/advanced thermochemical process	4.1.3.9

4.1.6 Concrete

Most of concrete waste is not compactable or otherwise treatable by primary techniques such as incineration and several options, such as re-use on-site in new build, re-use off-site – i.e. in landscaping, as capping material at LLW repository or use in sea defences – and disposal on-site or off-site.

Because the potential for decontamination of concrete after demolition is limited, a potential approach to better characterisation of waste streams containing concrete, involving enhanced monitoring and decontamination, should be applied, prior to highly selective segregation of wastes. However, it is generally accepted that the engineering uses of this recycled concrete can be limited, either because of inferior structural properties of old or crushed concrete, or because of chemical characteristics which adversely affect cementation processes in new build. The only other treatment for concrete prior to disposal is crushing as a volume reduction process

4.1.6.1 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
High temperature incineration	4.1.2.7
Molten metal	4.1.2.2
Plasma arc	4.1.2.6

4.1.7 Uranium-contaminated waste

Uranium-contaminated metals that cannot be decontaminated from uranium during melting – i.e. aluminium (very difficult) or copper, brass, nickel/nickel alloys (not proven or evaluated) – must, if they are to be recycled, be cleaned to exemption level by means other than melting, or before melting if melting is part of the treatment. Instead, metals that can be decontaminated from uranium during melting – i.e. steel, carbon steel, stainless steel, lead – can be “saved” for exemption or clearance if pre-treatment was not enough or unsuccessful.

Other uranium-contaminated LLWs are depleted uranium and uranium bearing. The disposal of large amounts of depleted uranium from enrichment operations has not been resolved in most countries in the world. At the moment, the vast amounts are stored awaiting decisions from authorities.

For uranium bearing waste, there are the wastes that are only contaminated by uranium and wastes that are also contaminated with other radionuclides. For the latter type, any of the available thermal treatment methods are suitable for volume reduction or to create a disposable waste form. The uranium content in the final residues after thermal treatment of organic uranium bearing and leaching should be so low that the waste can be disposed of unconditionally or as ordinary VLLW. The leaching of uranium from the residues, though performed by several methods (Sweden), doesn't reach the appropriate cleanness level to consider the waste as clean.

The current options for the treatment of uranium contaminated metals are:

- Waste minimisation/recycling;
- Immobilisation

Source: [5] pg. 101.

4.1.8 Asbestos

In the nuclear industry, decommissioning may give rise to asbestos waste that is contaminated with radioactivity. Some of this waste is LLW, some is VLLW and some is EW. If usually radioactive asbestos are directly disposed of as VLLW/LLW or priorly size-reduced by a super-compaction (whilst the EW can be disposed of in conventional repository), there are also different option for its treatments, such as chemical decontamination, thermo-chemical treatment, vitrification, molten metal, plasma arc.

An assessed option (United Kingdom and Japan) is to carry out an in-container vitrification, comprising the containment of the waste in a metal container with electrical heating to 1.500°C; the product is a vitrified mass (with approximately 80% volume reduction) which may potentially be re-used in construction. Although, the process is energy intensive, this may be off-set against saved space in a premium disposal facility and significantly reduced hazard characteristics of the waste.

Always in UK, and elsewhere also, a chemical treatment to convert the fibrous asbestos materials into non-fibrous products by the action of foam-borne acids is used, but there are no results of volume reduction and it may be not an appropriate treatment before the super-compaction.

Another related technique is admixing the waste to a fluxing agent and raising a temperature of 1.250°C to create a silica-like waste-form; again the product has the potential for re-use in construction, but the technique has not yet been successfully demonstrated in commercial terms, and landfill has remained the favoured option.

4.1.8.1 Thermochemical conversion

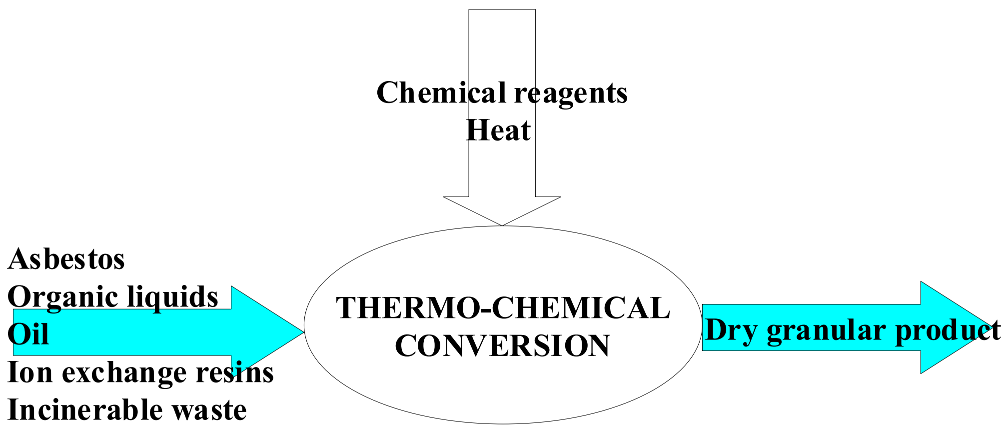
The process converts asbestos fibres into non-asbestos minerals; the waste must first be shredded and then mixed with the chemical reagents in a furnace at temperatures typically in excess of 2000°C; the product is removed from the furnace by mechanical means, dropped into a water bath, removed and dried to produce a dry granular product suitable for infilling of other waste or mixed with cement; other wastes suitable for incineration can be treated in the rotary hearth furnace after first mixing with the asbestos materials.

Advantages:

high waste throughput (typically 37 metric tons/day); elimination of chemical toxicity;

Disadvantages:

compliance with requirements for incineration and to handle asbestos; need for off gas treatment and authorisation to discharge aerials;



Source: [1] pg. 50

4.1.8.2 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Molten metal	4.1.2.2
Plasma arc	4.1.2.6
Vitrification	4.2.1

4.1.9 Oils

Oils are normally incinerated, returning also some energy with this procedure; the secondary waste from this process is either VLLW or EW and it can be disposed of into a conventional landfill. So, in general, oils and solvents can often be treated to obtain a secondary solid waste form that can be disposed of at the LLWR, or in another appropriate repository such as deep geological or landfill.

4.1.9.1 Oil filtration

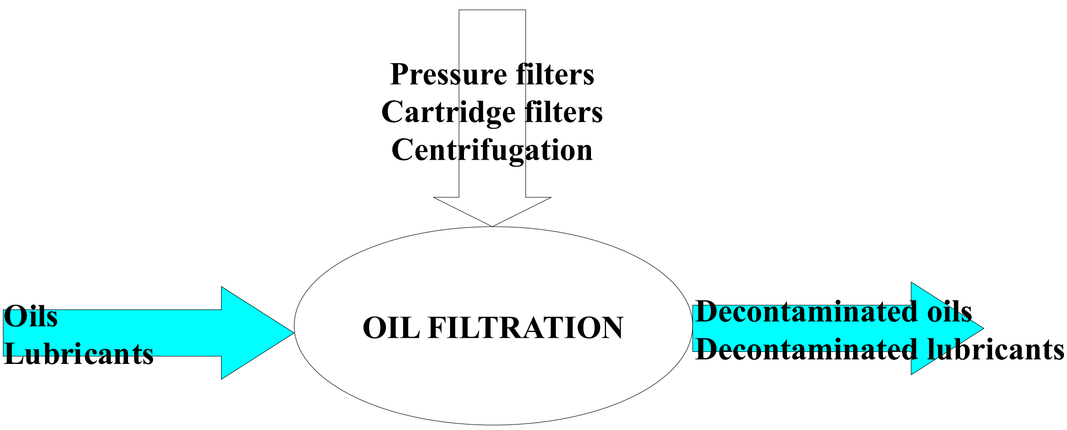
Particle-bound radioactive species can be removed from contaminated oils by using different separation processes (e.g. pressure filters, cartridge filters, centrifugation).

Advantages:

volume reduction depending on the initial contamination; oils and lubrificants can be reused after filtration;

Disadvantages:

effective removability only for particle-bound radioactivity; need to treat the secondary waste; economical competitive only with large volume of oil.



Source: [1] pg. 42

4.1.9.2 Oil solidification

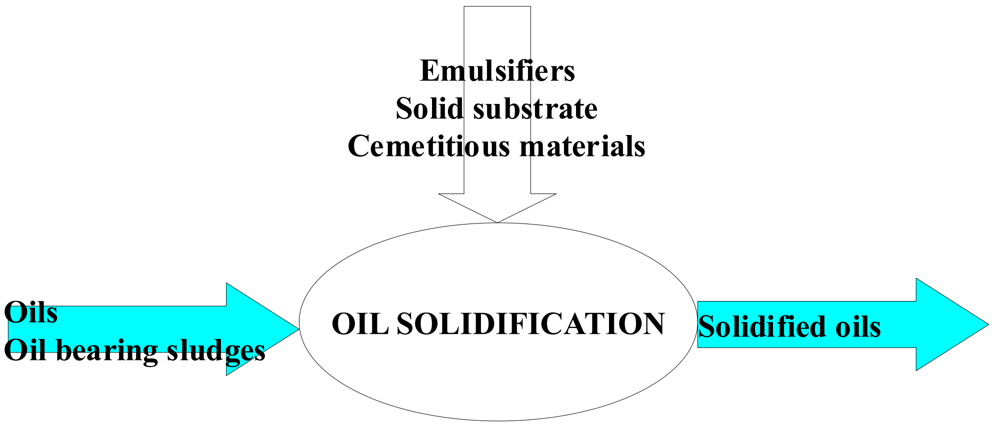
Solidification of oil is possible in several different matrices; some make use of absorbing the oil onto a solid substrate prior to solidification; others use emulsifiers to create a suspension of oil in water prior to solidification in cementitious materials.

Advantages:

conversion of a liquid waste into a solid waste, better form for safety storage;

Disadvantages:

a typical factor of 2 of volume increasing; possible release of oil from the end product if it is under pressure.



Source: [1] pg. 42, 43

4.1.9.3 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Incineration	4.1.2.4
Super absorbent polymers	4.1.4.6
Thermochemical conversion	4.1.8.1

4.1.10 Evaporator concentrates

4.1.10.1 Crystallization

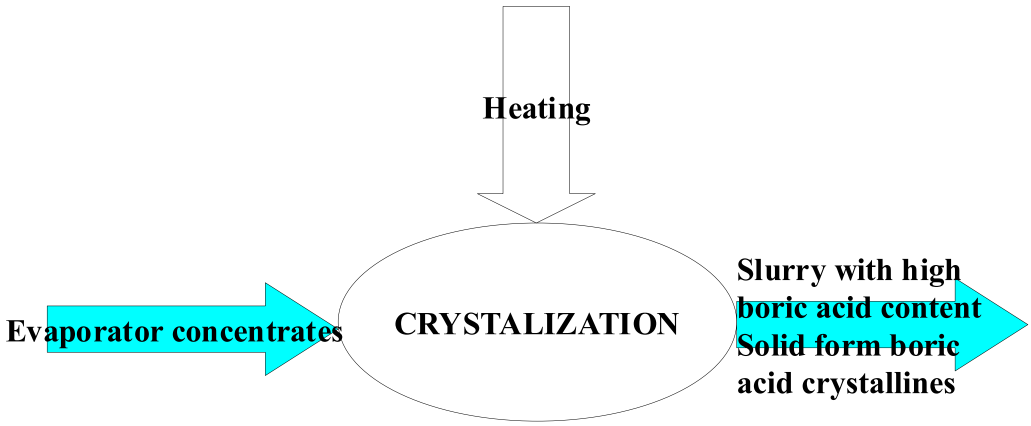
It is a deep drying process for high salinity solutions. For example, it is commonly used to perform the initial volume reduction of liquid waste containing boric acid prior to the final immobilization. With this technology, the boric acid is crystallized by heating and producing either a slurry stream with high boric acid content (e.g. 60%) or solid form boric acid crystallines ready to solidify.

Advantages:

typical volume reduction range of 4:1 (even though dependent on the starting concentration); suitable also for boric acid recycling combined with additional treatments;

Disadvantage:

required pipes heating (i.e. high operation cost) to avoid blockages.



Source: [1] pg. 30

4.1.10.2 Liquid concentrates volume reduction system

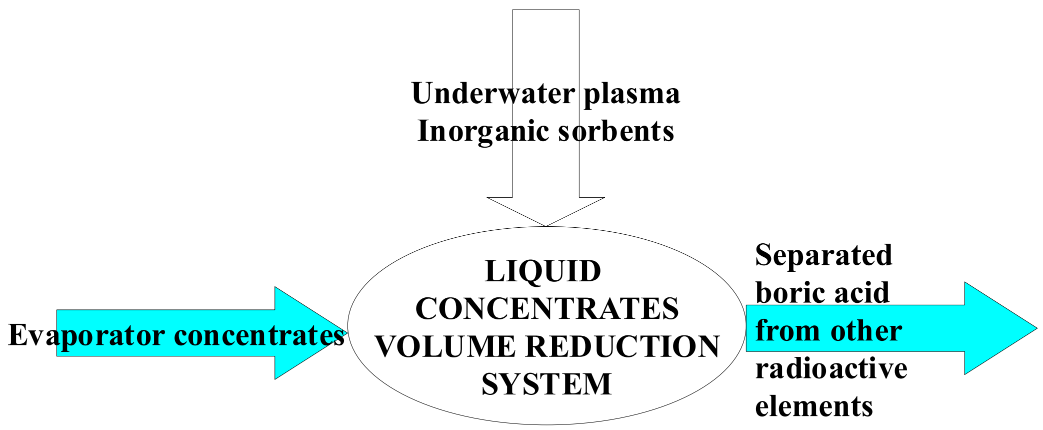
In this process, liquid radioactive concentrates with a boric acid content in the range of 200–250 g/kg are treated using a multi-step technology to separate boric acid from other radioactive constituents in order to minimize the final volume of LLW to be solidified.

Advantages:

high volume reduction 40:1 to 100:1; low and conditionable secondary waste generation; possible reuse of boric acid; clearance release of treated liquid phase, via monitored routes;

Disadvantages:

high concentration of boric acid in the concentrates; high energy consumption; low capacity (250-500 l/h), semi-continuous operation; high maintenance requirements.



Source: [1] pg. 36, 37

4.1.10.3 Hydrothermal treatment

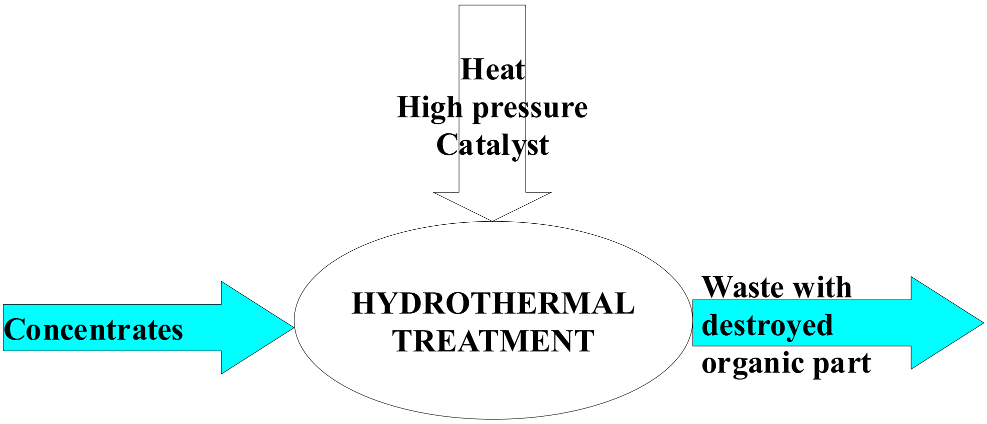
In this process, the organic portion in the waste is destroyed at 180-250°C, 50-150 bar pressure in the presence of a catalyst. The reaction was found to be completed in a few minutes (<10 minutes). Cobalt could be separated efficiently using a filter column.

Advantages:

completed process in few minutes;

Disadvantages:

high pressure process.



Source: [17] pg. 22

4.1.10.4 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Cold crucible vitrification	4.1.2.1
Drum drying	4.1.3.1
Pelletization	4.1.3.4

4.1.11 Sludge

4.1.11.1 Microwave treatment

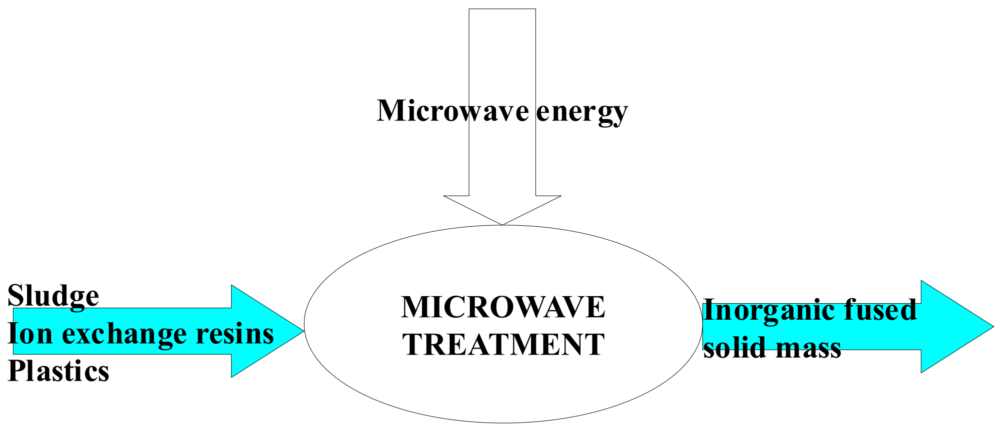
Microwave energy are used to heat the waste and destroy organic components. It is applied to the waste, which can be either in batch form (in a container) or on a continuous transport system (e.g. a conveyor belt). Large waste may be shredded first, in order to provide more even energy distribution.

Advantages:

simple technique; usable with mobile equipment; potential high throughput;

Disadvantages:

not-easy handling of end product; off gas system required.



Source: [20] pg. 62

4.1.11.2 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Drum drying	4.1.3.1
Geopolymerization	4.1.3.2
Hot isostatic pressing	4.1.3.3
Oil solidification (for bearing sludge)	4.1.9.2

4.1.12 Plastic waste:

4.1.12.1 Melt densification of plastic waste

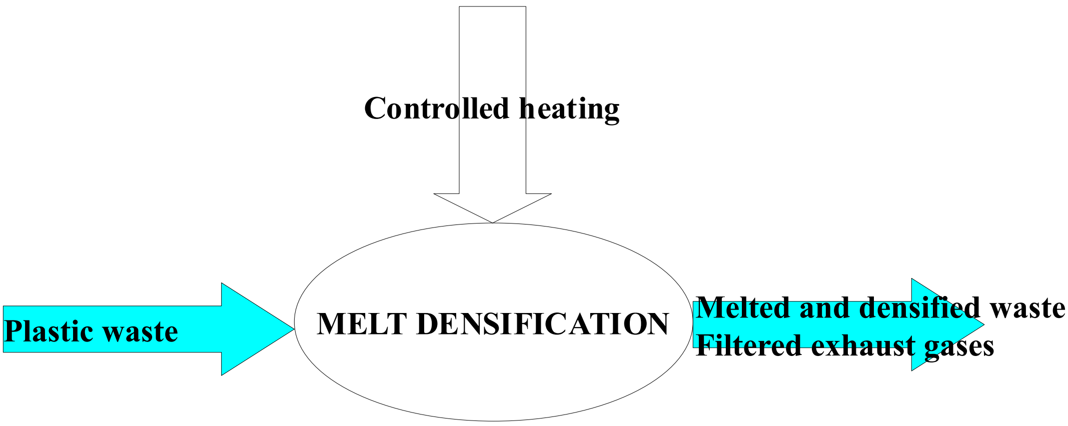
Polyethylene with up to 15% of PVC & rubber waste packed in polyethylene bags are fed into an insulated oven in a standard 200-litres metal drum. Temperature controllers maintain the temperature within the operating values of 170-180 °C for 3-4 hours for complete melting and densification. The exhaust gases are passed through a scrubber and a HEPA filter for removing organic vapours and any possible particulate activity.

Advantages:

simple process; no airborne activity; low temperature operation; volume reduction in the range of 20:1;

Disadvantages:

low throughput; possible hydrochloric acid production when PVC is present;



Source: [1] pg. 38, 39

4.1.12.2 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Incineration	4.1.2.4
Microwave treatment	4.1.11.1

Pyrolysis	4.1.2.5
Thermochemical/advanced thermochemical process	4.1.3.9

4.1.13 Evaporator bottom

4.1.13.1 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Drum drying	4.1.3.1
Hot isostatic pressing	4.1.3.3

4.1.14 Filters

4.1.14.1 Liquid cartridge filter shearing and shredding

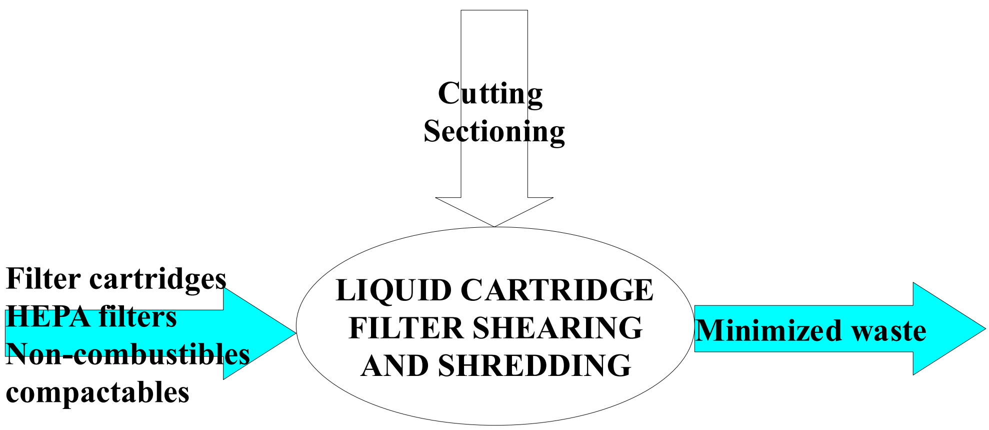
Shredding is applied for volume reduction, whilst shearing involves cutting or sectioning of the cartridge filters to minimize the void spaces internal to the filters.

Advantages:

low cost; low resources requirement; improved contamination control; volume reduction of 3:1 to 4:1;

Disadvantages:

potential airborne contamination (shredding more than shearing).



Source: [1] pg. 37, 38

4.1.14.2 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Cold crucible vitrification	4.1.2.1
Drum drying	4.1.3.1
High temperature incineration	4.1.2.7
Incineration	4.1.2.4
Molten metal	4.1.2.2
Plasma arc	4.1.2.6
PVA dissolution	4.1.2.3
Pyrolysis	4.1.2.5
Supercritical water oxidation	4.1.3.8

4.1.15 Graphite

4.1.15.1 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Incineration	4.1.2.4
Pyrolysis	4.1.2.5
Thermochemical/advanced thermochemical process	4.1.3.9

4.1.16 Ashes

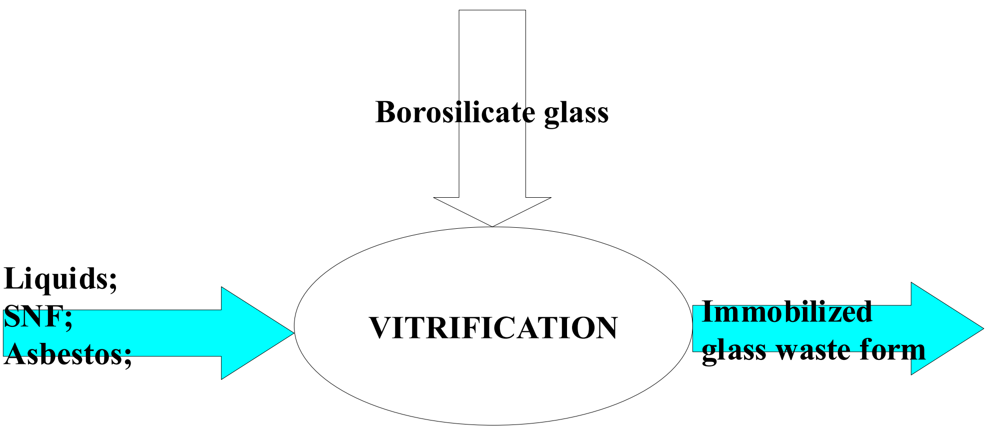
4.1.16.1 Other treatments

TREATMENT	*REFERENCE PARAGRAPH*
Cold crucible vitrification	4.1.2.1
Geopolymerization	4.1.3.2
Molten metal	4.1.2.2
Pelletization	4.1.3.4
Plasma arc	4.1.2.6

4.2 Treatments for HLW

4.2.1 Vitrification

The immobilisation of HLW requires the formation of an insoluble, solid waste form that will remain stable for many thousands of years. In general borosilicate glass[1] has been chosen as the medium for dealing with HLW due to its relatively low-melting temperature and potential for high chemical durability. The stability of ancient glass for thousands of years highlights the suitability of borosilicate glass as a matrix material. This type of process, referred to as vitrification, has also been extended for lower level waste where the type of waste or the economics have been appropriate (see 4.1.2.1). Most HLW other than SNF itself, arise in a liquid form from the reprocessing of SNF. To allow incorporation into the glass matrix this waste is initially calcined (dried) which turns it into a solid form. This product is then incorporated into molten glass in a stainless container and allowed to cool, giving a solid matrix. The containers are then welded closed and are ready for storage and final disposal. This process is currently being used in France, Japan, the Former Soviet Union, UK and USA and is seen as the preferred process for management of separated HLW arising from reprocessing. Several other alternative ceramic processes have also been developed which also achieve the desired quality of product. In-situ vitrification has also been investigated as a means of '"Fixing" activity in contaminated ground as well as creating a barrier to prevent further spread of contamination ([3] pg. 4). The confinement capacity of this special glass matrix is particularly high and durable. A package of HLW contains around 400 kg of glass for 11 kg of waste. To facilitate future handling, transport, storage and disposal operations, each primary package is due to be placed in a steel disposal container [93].



1 Borosilicate glass: any silicate glass having at least 5% of boron oxide (B_2O_3)

Vitrification is an internationally accepted treatment for HLW; glass is an amorphous material, able to incorporate a wide spectrum of elements over wide ranges of composition, resistant to radiation damage with long-term durability and with a relatively simple process, amenable to nuclearization at large scale. If the waste is organic, a fluidised bed steam reforming process can be desirable. During this process waste is converted into organic-free and minerals which are water soluble; this soluble nature allows them to be dissolved and pumped to the vitrification facility or returned for future vitrification.

4.2.2 Calcination

The description of this process is in 4.1.4.10.

Moreover, in a DOE's document ([94] pg. 2, 3), different alternatives are considered:

- Calcine separation alternatives:
  - The full separations option would separate the radioisotopes in the calcine into HLW and LLW fractions. The HLW fraction would be vitrified (see 4.2.1), placed in stainless steel canisters, and stored onsite until shipped to a storage or disposition facility. DOE would dispose of the LLW fraction on site, or at an offsite DOE or commercial LLW disposal facility;
  - The TRU separations option would consist of separating the HLW into two fractions. The resulting fractions would be managed as TRU waste and LLW. The TRU fraction that meets applicable requirements, would be solidified, packaged, and shipped to the waste isolation pilot plant for disposal. DOE would dispose of the LLW fraction on site or at an offsite DOE or commercial LLW disposal facility.
- Non-separation alternatives:
  - The hot isostatic pressing (see 4.1.3.3) waste option under which HLW calcine would be treated in a high pressure, high temperature process that would convert the calcine into a glass-ceramic waste form. The final product would be packaged for storage, transport, and disposition;
  - The direct cement waste option under which HLW calcine would be retrieved, mixed

with cement (see part about cementation in 4.1), poured in stainless-steel canisters, and cured at elevated temperature and pressure. The canisters would be placed in storage for transport and subsequent disposition;

- The early vitrification option would involve vitrifying the HLW calcine into a glass-like solid (see 4.2.1). The vitrified HLW would be placed in interim storage pending disposition;
- The steam reforming option (see the last part in 4.2.1) includes packaging of HLW calcine without additional treatment for shipment and disposition.

Any of the waste treatment alternatives that place the calcine in a waste form suitable for disposition outside of the State of Idaho would be environmentally preferable compared to the No Action and Continued Current Operations Alternatives.

4.2.3 Partitioning and transmutation

Partitioning and transmutation (P&T) is a technology to separate and transform long-term radiological hazard elements, such as transuranic actinides (plutonium, americium, curium, neptunium) and mobile fission products (caesium, iodine, technetium) into shorter-lived or stable ones. Through this process the radiological hazard of some long-lived radionuclides could be reduced, mainly in respect to the interim storage period and/or the operational phase of a (deep geological) repository. This technology is still under development and it may take some decades before this technique could be implemented on an industrial scale. Because it requires an increased reprocessing approach and new (fast) reactor systems, P&T is something to be incorporated into future fuel cycles and could therefore become an alternative option mainly in new waste management strategies.

P&T will not replace the need for final disposal in the future, but the amount of long-lived nuclides in the final waste will be reduced of a factor of 100 or more. Another important aspect is the possible reduction from 200.000 years to 2.000 years of the time needed for the radio toxicity to be reduced to the level of natural uranium. Even if TRU elements – neptunium, plutonium, americium and curium – are the main target of transmutation, certain fission products, e.g. Tc-99 and I-129, are involved as well. Being the process – a transmutation of TRU elements by a fission produced by neutrons – similar to the process in a nuclear reactor with a release of a great amount of energy, to be cooled, the heat can be used for electricity production as in a NPP. In order to avoid creation of new TRU elements in the transmutation process, the remaining uranium must be separated from the nuclides that targeted for transmutation reactions. In reprocessing plants (for example those used in France at La Hague) uranium and plutonium are separated from one another and from the other nuclides in the spent fuel by a chemical process.

According to a INL study ([95] pg. 14-17), an advanced separation allows development of waste management strategies by considering several strategic options to take advantage of natural chemical and radiation characteristics:

- After decay the Cs/Sr waste form could possibly be disposed as LLW; long-live Cs-135 content and cross-contamination with other isotopes would also be considerations in this disposal concept;

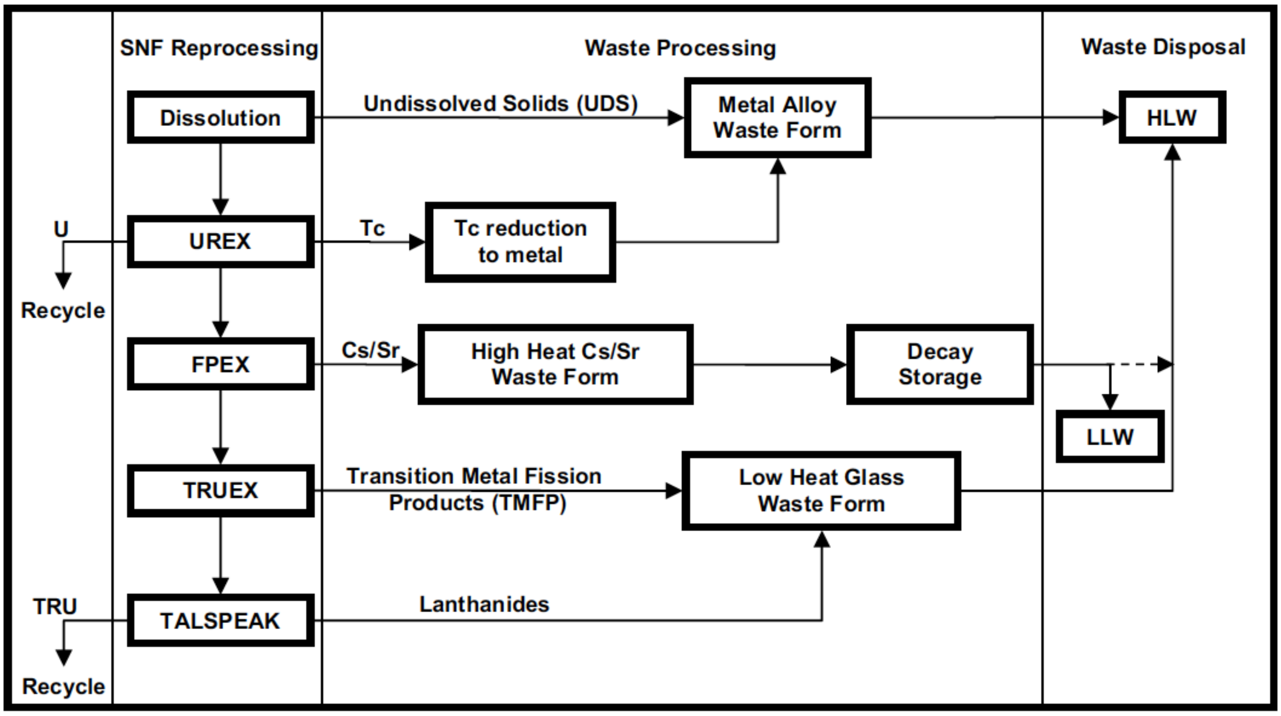


Figure 15: Option with 4 separation steps, 3 different waste forms produced, potential LLW disposal for Cs/Sr

– Readily oxidized elements including those in both the Cs/Sr and Ln streams could be combined in one waste form with high waste loading limited by only thermal stability; these elements are very soluble in glass and waste loading would no longer be limited by noble metal solubility as is the case with HLW derived from traditional PUREX processing;

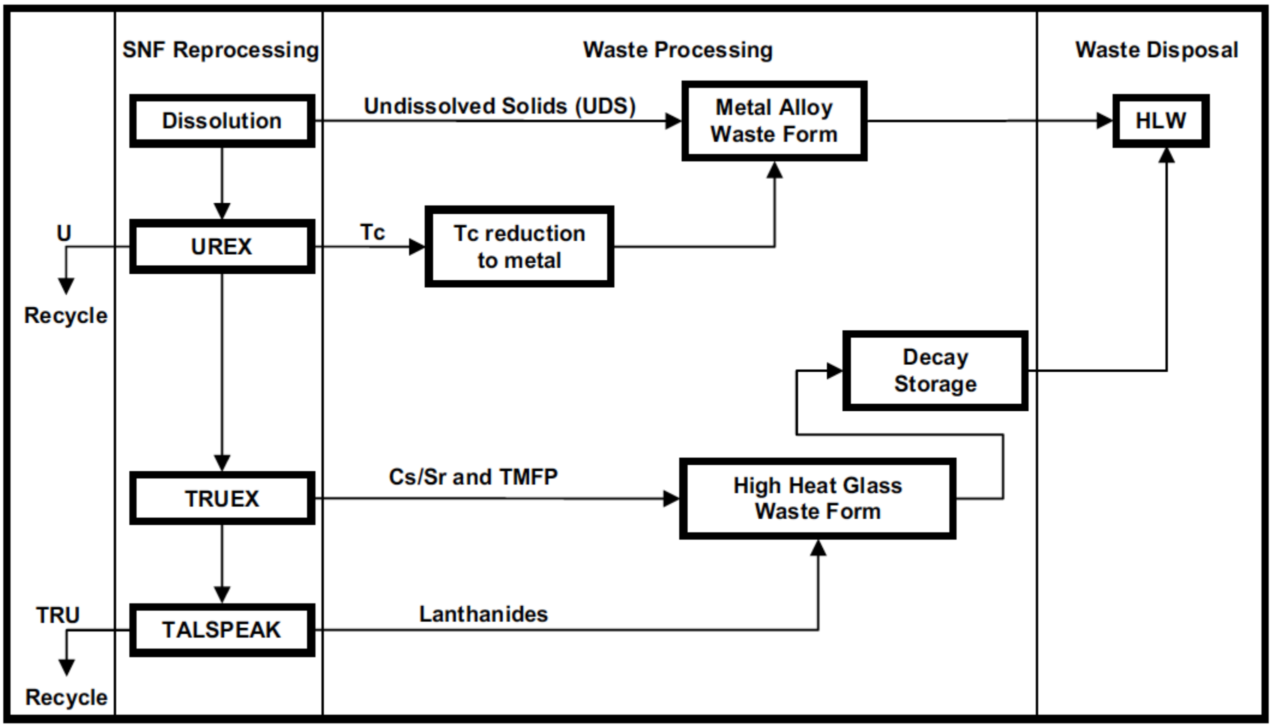


Figure 16: Option with 3 separation steps, 2 waste forms produced, no LLW disposal possibility

– The transition metals could be chemically or electrochemically reduced from the nitrate solution TRUEX waste to elemental form. These metals could be combined with the UDS which are comprised of the same elements, and melted with additives, potentially waste fuel cladding and hardware to make a high-density alloy that is nearly 100% waste.

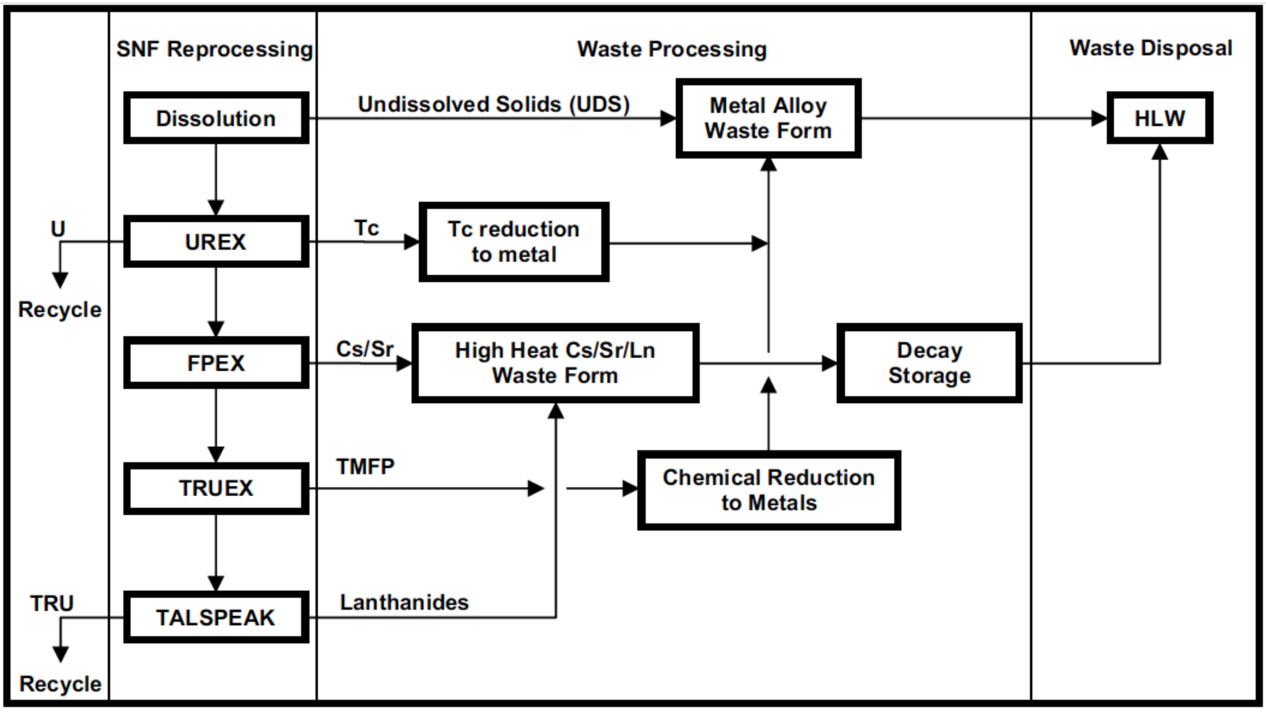


Figure 17: Option with 4 separation steps, 2 waste forms produced, optimised HLW disposal due to the high-density, high waste-loading alloy waste form

The potential benefits of these options must be weighed against the additional costs of the additional processes as well as the FPEX process itself (see next section).

4.2.3.1 PUREX (Partitioning)

Currently, an aqueous technique used in industrial reprocessing is the PUREX process which uses phosphoric organic compounds. This process separates pure uranium and pure plutonium by an oxide fuel separation. A disadvantage with this process is that it produces a considerable amount of LLW consisting of long-lived radionuclides. If completely incinerable reagents are used, instead of phosphor-based reagents, a strongly reduced amount of waste will be produced. One of the main problem of PUREX process is the production of pure plutonium, not very accepted in a non-proliferation scenario.

4.2.3.2 UREX (Partitioning)

To overtake the latter disadvantage of PUREX process, a well proven process to separate uranium from the rest of SNF is the UREX process (Figure 18), a PUREX variant that, instead of separate pure uranium and pure plutonium, separates many actinides and fission products for tailored recycling or disposal.

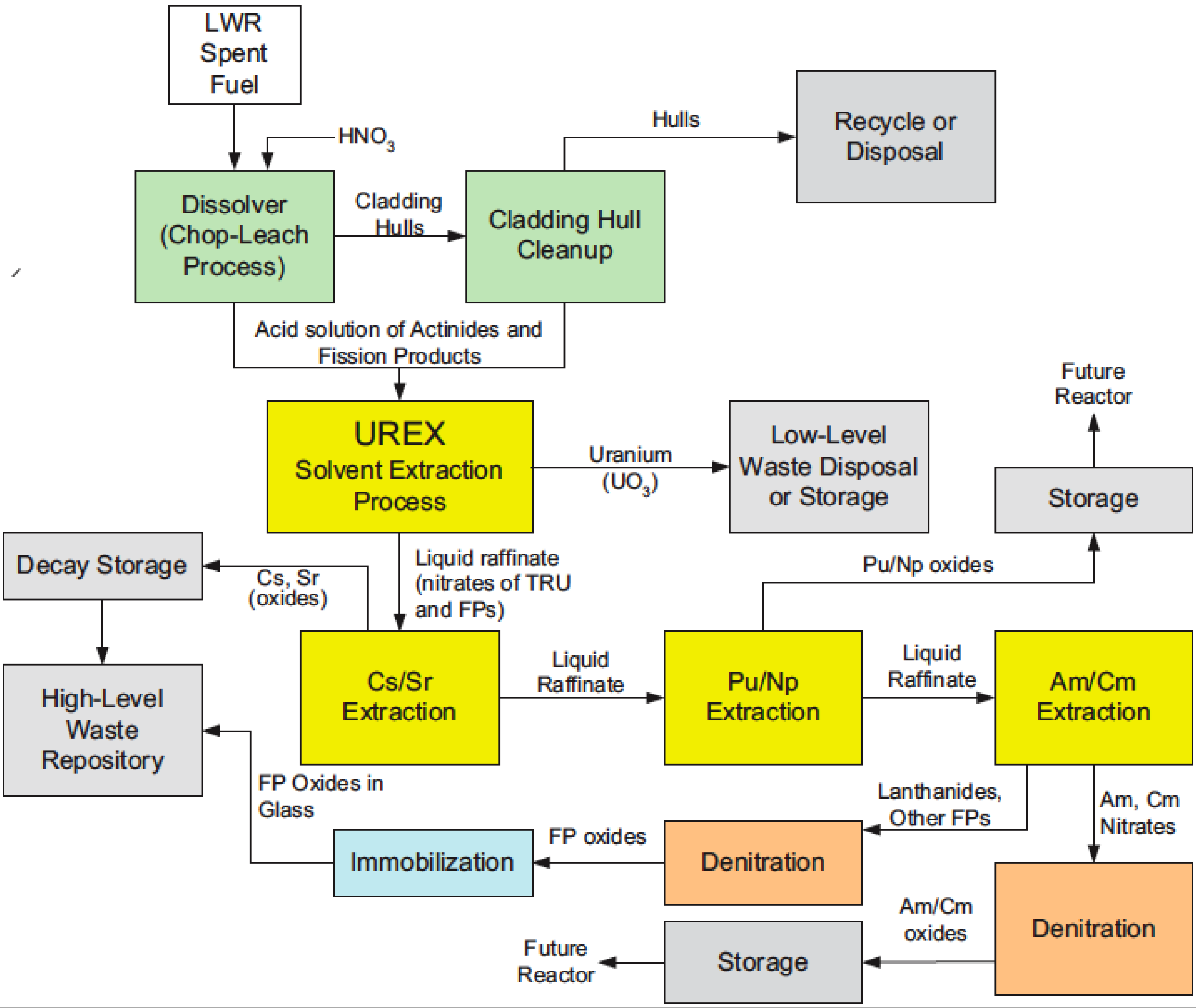


Figure 18: Example of UREX process flow

Source: [87] pg. 390

Not used in a wide scale yet are pyrochemical and pyrometallurgical processes ([87] pg. 411; [23] pg. 5).

4.2.3.3 Pyrochemical process (Partitioning)

Since a problem with PUREX aqueous techniques is the cost and the organic molecules limited resistance to damage by ionizing radiation as well, a non-aqueous partitioning process, i.e. pyrochemical, has been developed, in which metals, oxides and salts are used as carriers with the favourable property that higher concentrations can be handled, decreasing the size of the plant. Being this technique not well proven, certain problems are still left to be solved, for example to keep process losses low, to design processes with inherent criticality and radiation control, to develop materials and to control corrosion.

4.2.3.4 Pyrometallurical process (Partitioning)

Another more innovative technology to avoid the production of pure plutonium is the pyrometallurgical process, based on electroplating-using electricity to collect, on a conducting metal electrode, metal extracted as ions from a chemical bath.

So, the use of these techniques allows to extract from SNF a mix of TRU elements instead of pure plutonium, as in the PUREX route, so it cannot be achieved directly a weapon-grade plutonium.

4.2.3.5 Accelerator-driven sub-critical reactor system (Transmutation)

Transmutation can be accomplished with a fast reactor with a self-sustaining chain-reaction or an accelerator-driven sub-critical reactor system (ADS). Since many of the transuranic elements are only fissionable in fast neutron spectrum, a thermal neutron flux (like in a LWR) would only lead to capture reactions with transmutations from one long-lived nuclide to another as a consequence. Moreover, the fast spectrum permits multi-recycling of plutonium without any support of U-235 and leads to a smaller production of americium. Since the fast reactors with a self-sustaining chain-reaction are so difficult to control, for americium transmutation the development of ADS started to gain interest in the 1990ies. The main advantage with ADS is that a sub-critical reactor can be used. Since the neutron flux is controlled by the accelerator the reactor can be designed so that a self-sustaining chain-reaction cannot occur. This means americium can be transmuted in considerable amounts at a time without having to worry about the stability of the reactor. An ADS consists of many parts. The first stage is a proton accelerator, which gives a current of protons with about 1 GeV of particle energy. Then the proton current hits a spallation source where a neutron flux is created. The spallation source is situated inside the core of the sub-critical reactor. The core consists of the fuel containing the long-lived radio nuclides to be transmuted by the neutrons. The system also needs control equipment to control and monitor the process and a cooling system to take care of the energy released. Totally, the process releases 50 times more energy than the energy input in the proton beam. 10% of this energy is needed to run the accelerator. Currently there exist only two useful concepts of accelerators-cyclotrons and linear accelerators (linacs). Linacs have many advantages compared to cyclotrons but also a major disadvantage, namely the length. A linac has to be several hundreds of meters long in order to produce the desired proton energy.

Transmutation using a fast neutron spectrum is more effective than using LWR. Transmutation of the transuranic elements can be done in fast reactors or ADS. Plutonium however can be transmuted in existing LWRs whereby the need for ADS and fast reactors decreases ([23] pg. 6-9).

4.2.3.6 Deep Burn Modular Helium Reactor (Transmutation)

Another technology for transmutation is the DB-MHR (Deep Burn Modular Helium Reactor) which is a gas-cooled graphite-moderated high temperature reactor for transmutation of plutonium and other transuranic nuclides. The development of the Deep-Burn MHR transmutation concept is motivated by the need for a useful and practical nuclear waste management tool that could allow a more efficient, safe and secure use of a geological nuclear waste repository. In the Deep-Burn concept, destruction of the transuranic component of LWR waste is carried out in one burn-up cycle, accomplishing the virtually complete destruction of weapons-usable materials (Pu-239), and up to 90% of all transuranic waste, including the near totality of Np-237 (the most mobile actinide in the repository environment) and its precursor, Am-241. Waste destruction would be performed rapidly, without multiple reprocessing of plutonium – thus eliminating the risks of repeated handling of weapons-usable material and limiting the generation of secondary waste – in a critical MHR-technology based reactors, followed by further destruction in sub-critical, accelerator-driven systems of similar design. An essential feature of the Deep-Burn Transmuter is the use of ceramic-coated fuel particles that provide very strong containment and are highly resistant to irradiation, thereby allowing very extensive destruction levels ("Deep Burn") in the one pass, using gas-cooled modular helium reactor (MHR) technology developed for high efficiency energy production. The fixed moderator (graphite) and neutronically transparent coolant (helium) provide a unique neutron energy spectrum to cause Deep-Burn, and inherent safety features, specific to the destruction of nuclear waste, that are not found in any other design. The final waste-form is the irradiated waste/fuel, and can be placed directly in the repository after the desired transmutation levels have been obtained. The final waste discharged by the Deep-Burn Transmutation system consists of spent transmutation fuel, in the form of ceramic-coated particles encased in graphite blocks. The ceramic-coated particles are a very durable final residual waste form that remains impervious to moisture well beyond the life of metal containers currently considered for spent fuel disposal, so it makes up an excellent engineered barrier for containing radionuclides in a geologic repository environment. The driver fuel is the TRU waste plutonium (including fissile isotopes) plus neptunium, which comes directly from the UREX partitioning process. The transmutation fuel contains the americium and curium isotopes from the UREX partitioning process, plus the minor actinides remaining after the driver fuel irradiation (Figure 19). Both driver fuel and transmutation fuel are irradiated for 3 years in critical DB-reactor; after this, the transmutation fuel is irradiated for 4 years in sub-critical DB-reactor for its final destruction.

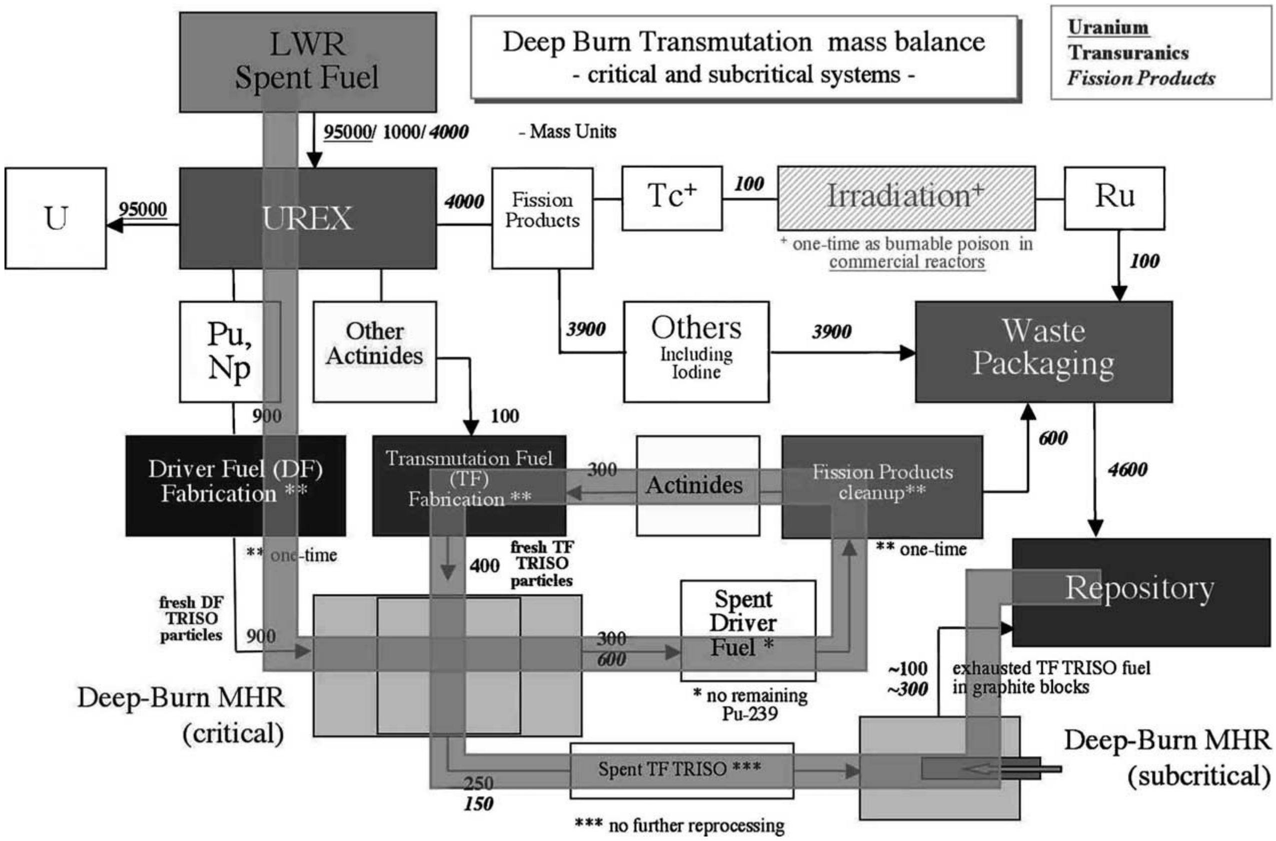


Figure 19: DB-MHR flow sheet

Source: [96] pg. 15

4.2.4 Other treatments

TREATMENT	REFERENCE PARAGRAPH
Pyrolysis	4.1.2.5
Calcination	4.1.4.10

4.3 Conclusions

LLW/ILW (with VLLW subcategory) have more available treatments than HLW. This aspect can be advantageous if we think about greater waste amount of LLW/ILW compared with that of HLW. This can involve more manageability of research and development phases for HLW treatments, because of its smaller arising; this signifies that some techniques currently not used for HLW have the possibility – due to a "not current critical" waste amount – to reach a full-scale utilisation. A similar reasoning can be valid for LLW/ILW, with the appropriate difference: several existing process are used for the great amount of this waste and, at the same time, others improve their implementation from research phase to full-scale use, with the consequence of a waste management optimisation. In any case, it need to point out again, a final disposal recourse is unavoidable, both for LLW/ILW and HLW treatments.

Because of the great heterogeneity of LLW/ILW, a wide set of treatments exists. Certainly, some of these are at research phase, development phase or pilot scale, whilst others are fully exploited. This difference for implementation process is more evident when a waste stream has several possible treatments; some can be well-proven, some can be innovated and others will become available in the next years or the future. Some processes are suitable for different waste type; a typical example is pyrolysis (see 4.1.2.5), that is adapt – and in the majority on the cases, currently used – for a very wide range of waste feeds (LLW/ILW such as metals, combustibles, resins, contaminated land, plastics, filters, graphite, and HLW), while other techniques or technologies are more specific (e.g. oil solidification, microwave treatment, melt densification of plastic waste, etc... for LLW/ILW or partitioning and transmutation for HLW) due to the particularity of some waste streams. Other examples of treatments with potential wide applicability are incineration, molten metal, thermochemical conversion, cold crucible vitrification, thermochemical/advanced thermochemical processes, etc... As will be shown in the next section, this applicability is sometimes only theoretical, because the implementation for some waste types can be not at the same development of that for another type. Generally, one process can be suitable for at least 3-4 waste types, some used both for LLW/ILW and HLW, others more specific and therefore suitable just for a defined radioactivity category.

An important difference for the treatments described above is the characteristic of their end-product. As it will be shown in the road maps of Section 6.1, the end product can take different ways, depending on its suitability for conditioning before final or interim disposal. The analysis provided above regards all technologies existing, concerning pre-treatment as well as treatment, immobilisation and conditioning phases; their “interconnection” will be shown in Section 6.1.

If some processes preview further treatments to adapt the end-product for pre-disposal conditioning, others have as output a waste already appropriate for it. Beyond the immobilisation techniques, such as cementation, bituminisation, vitrification, cold crucible vitrification, that just by definition produce an output directly for conditioning and then for disposal, other treatments usually have the immobilisation step in their flow chart before conditioning; however there are some of them that have directly a conditioning step before disposal.

Decontamination techniques – that sometimes are considered as a suitable pre-treatment just to separate “decontaminable” part from the rest of the waste (e.g. ion exchange membranes, ion-specific filtration, membrane filtration, reverse osmosis for liquids, oil filtration specific for oils and lubricants or phytoremediation for contaminated land) – can be seen as volume reduction process, because they reduce the amount of waste to be sent to further treatments or to disposal. An obvious consequence of these operations is the production of secondary waste (waste part other than the end-product), usually EW or VLLW and easily conditionable. Secondary waste arises also from PVA dissolution, oil filtration and liquid concentrates volume reduction system (but for both they are EW or VLLW), whilst geopolymerization, DB-MHR haven't of it ([1] pg. 36, 37, 42, 45, 46).

Volume reduction systems by pressure, such as hot isostatic pressing or compaction, generally acts on already treated waste, just to optimise the disposal space without further treatments, whilst volume reduction by destructive techniques, such as incineration, can involve consequential processes – e.g. ashes after incineration have several options between potential treatments before their disposal – and generally they have high capital cost, but their have however a large employment.

HLW has more specific treatments suitable for this higher radioactivity level, except for pyrolysis that, as said above, is one of the treatment with widest-range applicability, and calcination followed by vitrification, that can be used also for liquid LLW/ILW but originally developed for HLW.

We can underline that these latter operations aim only to immobolise the waste, while pyrolysis makes a volume reduction and partitioning and transmutation, with their different potential approaches, regard an innovative implementation of fuel cycle that preview a different waste arising. The importance of these applications is really evident for next reactors generation, because they virtually reuse what now is considered as a waste to extract further energy. Certainly, the other important raison to implement them is the possibility to reduce the radiotoxicity time of the waste.

5 Selection of treatments

In this section a first selection of treatments described in section 4 is provided. Here, non-currently attractive methods will be rejected on basis of economical, technical and social aspects. This selection aims to point out all currently applicable treatments at international level prior to the disposal. Therefore, all the methods at research, pilot, demonstration phase or non suitable with the criteria of above, are beyond from the scope of this section, although they have a good potential development for future use. Widely used immobilization methods, suitable for LLW/ILW as well as HLW, such as cementation, compaction, Synroc (more recent), are not here reported and they are described in 4.1, whilst more specific immobilization techniques, such as vitrification, are reported because of their suitability for particular waste feeds.

The same separation between LLW/ILW and HLW is followed, as in the previous section, also because to make clear the "filter operation" here provided.

This will be reassumed into tables (for each waste stream) where simply it will be chosen "yes" or "not" as option and the relative explication or note, on the basis of official documents reported as reference in the last column.

5.1 VLLW/LLW/ILW

Even if a treatment can be applied to different waste streams (as shown in the previous section), it's might be not the suitable method for all of these.

It is thought that complete dissolution, chemical separation and corrosion facilities do not currently exist on a significant scale whereas overseas melting LLW treatment facilities exist in countries such as Sweden, Germany and the United States.

Depending on the requirements for disposal, including price, there are other options for treatment which are not currently in commercial use. These processes include drying, wet oxidation, and melting ([5] pg. 134).

5.1.1 Liquid waste

Table 21: Selection of treatments for liquid waste

	YES	NO	WHY NOT/NOTES	Ref.
Advanced oxidation processes		X	Pilot scale	[97] pg. 58
Alkaline hydrolysis	X		SNF solvents; limited application with organics	[97] pg. 46, 47
Biological treatment		X	Pilot scale	[97] pg. 60-61
Calcination	X			[19] pg. 10, 14
Direct chemical oxidation		X	Development phase	[97] pg. 54
EIX	X		Recently developed	[21] pg. 38
Incineration	X		Adapt to large scale Low public acceptance High cost	[5] pg. 74 [97] pg. 34, 41, 42, 43 [2] pg. 28
Ion exchange membranes	X		High cost	[21] pg. 22, 23
Ion-specific filtration	X		Innovative technology	[1] pg. 12, 35
Membrane filtration		X	Innovative technology; Not widely used	[19] pg. 11-12
Molten metal		X	Wide use only in Japan	[1] pg. 41
Plasma arc		X	Limited full-scale experience with LLW; High cost	[97] pg. 50 [1] pg. 45 [5] pg. 76 [98] pg. 25
Reverse osmosis	X			[17] pg. 7 [2] pg. 27
Super absorbent polymers	X			[1] pg. 48
Supercritical water oxidation		X	Pilot scale	[97] pg. 59, 68
Thermochemical conversion		X	Development phase	[97] pg. 59 [1] pg. 17, 50
Vitrification	X		Post-calcination Suitable for HLW	[97] pg. 48 [19] pg. 10
WETOX		X	Pilot scale	[19] pg. 3-4

This table refers to liquid waste in general, where several different techniques are applicable. It can be noted that almost an half of technologies is currently under development, generally to improve its applicability scale, while the available methods are both well proven or innovative ones.

Since the large number of treatments reported in Table 21, a favourable consequence is the considerable set of these currently available.

5.1.2 Resins

Table 22: Selection of treatments for resins

	YES	NO	WHY NOT/NOTES	Ref.
Acid digestion		X	Expensive materials	[97] pg. 23, 55 [19] pg. 17, 18 [21] pg. 58
Thermochemical/ Advanced thermochemical process		X	No broad implementation	[21] pg. 64, 65 [19] pg. 39
Biological treatment		X	Pilot scale	[97] pg. 60, 61, 69 [21] pg. 58
Cold crucible vitrification		X	Development phase	[1] pg. 4, 8, 12 [19] pg. 61, 68 [21] pg. 65
Drum drying	X			[1] pg. 30, 31 [35] pg. 522
Geopolymerization		X	Research phase	[1] pg. 31
Hot isostatic pressing	X			[21] pg. 58 [1] pg. 17, 33
Incineration	X		High cost; Low public acceptance	[97] pg. 22, 34, 43, 66 [2] pg. 28 [17] pg. 24, 26 [19] pg. 10, 24, 25
Microwave treatment		X	Demonstration phase	[97] pg. 23, 62, 69 [21] pg. 65 [2] pg. 29
Molten metal		X	Wide use only in Japan	[1] pg. 41
Molten salt oxidation		X	Development phase; High cost	[97] pg. 22, 53, 67 [19] pg. 10, 30 [17] pg. 26
Pelletization	X			[1] pg. 43 [21] pg. 66
Plasma arc		X	Limited full-scale experience with LLW; High cost	[97] pg. 50 [1] pg. 45 [5] pg. 76 [98] pg. 25
Pyrolysis	X		High cost; Often applied to ILW; Good public acceptance; limited application with	[19] pg. 10, 34-37 [97] pg. 22, 44, 45 [17] pg. 24 [5] pg. 75

	YES	NO	WHY NOT/NOTES	Ref.
			inorganic materials	[2] pg. 28 [1] pg. 46, 47
Supercritical water oxidation		X	Pilot scale	[97] pg. 59, 68
Thermochemical conversion		X	Development phase	[97] pg. 59 [1] pg. 17, 50
WETOX		X	Not in commercial use; High maintenance	[1] pg. 17 [19] pg. 3, 4 [97] pg. 23, 68 [21] pg. 62, 63

For this type of waste, there an important part of methods with high cost; however, some of these treatments, such as pyrolysis or conventional incineration, are used due to their operational experience or an higher public acceptance.

5.1.3 Combustible waste

Table 23: Selection of treatments for combustible waste

	YES	NO	WHY NOT/NOTES	Ref.
Cold crucible vitrification		X	Development phase	[21] pg. 65 [19] pg. 61
High temperature incineration		X	Used in Japan; High cost; Very sensitive to waste feed	[1] pg. 32 [19] pg. 10, 19
Incineration	X		High cost; Low public acceptance	[99] pg. 39 [5] pg. 74
Molten metal		X	Wide use only in Japan	[1] pg. 41
Plasma arc		X	Limited full-scale experience with LLW; High cost	[1] pg. 45 [97] pg. 50 [98] pg. 25 [5] pg. 76
PVA dissolution	X			[1] pg. 45, 46
Pyrolysis		X	High cost; Not suitable for combustible LLW	[1] pg. 47 [5] pg. 75
Thermochemical conversion		X	Development phase	[97] pg. 59 [1] pg. 17, 50

Here, there is a larger part of technologies currently non-suitable, although they are a good perspectives in the future; but at the moment, only two of these are widely used.

5.1.4 Filters

Table 24: Selection of treatments for filters

	YES	NO	WHY NOT/NOTES	Ref.
Cold crucible vitrification		X	Development phase	[21] pg. 65 [19] pg. 61
Drum drying		X	Not suitable for filters	[1] pg. 12, 30, 31 [35] pg. 522
High temperature incineration		X	Used in Japan; High cost; Very sensitive to waste feed	[1] pg. 32 [19] pg. 10, 19
Incineration	X		High cost; Low public acceptance	[1] pg. 12 [19] pg. 10, 24, 25
Liquid cartridge filter shearing and shredding	X			[1] pg. 12, 37, 38
Molten metal		X	Wide use only in Japan	[1] pg. 41
Plasma arc		X	Limited full-scale experience with LLW	[19] pg. 10 [97] pg. 50 [98] pg. 25 [5] pg. 76
PVA dissolution	X			[1] pg. 45, 46
Pyrolysis	X		Suitable for powder or granular form; Good public acceptance	[1] pg. 12 [19] pg. 10, 34-37
Supercritical water oxidation		X	Pilot scale	[97] pg. 59, 68

A suitable technique – drum drying – for other waste feed, is not appropriate for filters, whilst other experienced technologies are applied and more innovative ones have the same implementaion problem of other cases.

5.1.5 Evaporator concentrates

Table 25: Selection of treatments for evaporator concentrates

	YES	NO	WHY NOT/NOTES	Ref.
Cold crucible vitrification	X		High cost	[1] pg. 8, 12, 29
Crystallization	X		High cost	[1] pg. 30
Drum drying	X			[1] pg. 30
Hydrothermal treatment		X	Pilot scale	[17] pg. 8, 22
Liquid concentrates volume reduction system		X	New technology developed in Hungary	[1] pg. 36
Pelletization	X			[1] pg. 43

A technology as cold crucible vitrification, generally in a development stage, is here more used, even if it has high cost, along with other processes, with high or normal cost.

5.1.6 Ashes

Table 26: Selection of treatments for ashes

	YES	NO	WHY NOT/NOTES	Ref.
Cold crucible vitrification		X	Development phase	[100] pg. 12 [21] pg. 65
Geopolymerization		X	Research phase	[1] pg. 31
Molten metal		X	Wide use only in Japan	[1] pg. 41
Pelletization	X			[1] pg. 43 [21] pg. 66
Plasma arc		X	Limited full-scale experience with LLW	[97] pg. 50 [98] pg. 25

It can be noted that just one of these treatments – pellettization – is currently suitable for ashes, while the others are in different steps of development.

5.1.7 Plastic waste

Table 27: Selection of treatments for plastic waste

	YES	NO	WHY NOT/NOTES	Ref.
Thermochemical/ Advanced thermochemical process		X	No broad implementation	[19] pg. 3, 4, 10, 39 [97] pg. 61, 69
Incineration	X		High cost; Low public acceptance	[1] pg. 4, 12, 13, 28, 33 [19] pg. 3, 4, 10 [97] pg. 41 [2] pg.28
Melt densification		X	Development phase	[19] pg. 3, 4
Microwave treatment		X	Demonstration phase	[97] pg. 23, 62, 69
Pyrolysis	X		High cost; Suitable for powder or granular form; Good public acceptance	[1] pg. 4, 28 [19] pg. 3, 4, 10, 31, 33, 34 [97] pg. 45

Also in this case, two are the predominant technologies applied to this waste, conventional incineration and pyrolysis, with their problem of high cost operational/implementation.

5.1.8 Sludge

Table 28: Selection of treatments for sludge

	YES	NO	WHY NOT/NOTES	Ref.
Drum drying	X			[1] pg. 30, 31 [35] pg. 522
Geopolymerization		X	Research phase	[1] pg. 31
Hot isostatic pressing	X			[21] pg. 58 [1] pg. 17, 28, 33
Microwave treatment		X	Demonstration phase	[97] pg. 23, 62, 69 [2] pg. 29
Oil solidification	X			[1] pg. 14, 28, 42, 43

Here, only two processes are in demonstration or research phase and the others suitable for sludge are commonly used.

5.1.9 Oils

Table 29: Selection of treatments for oils

	YES	NO	WHY NOT/NOTES	Ref.
Incineration	X		High cost; Low public acceptance	[1] pg. 13, 28
Oil filtration	X			[1] pg. 14, 28, 42 [97] pg. 13
Oil solidification	X			[1] pg. 14, 28, 42, 43
Super absorbent polymers	X			[1] pg. 14, 28, 48 [97] pg. 28
Thermochemical conversion		X	Development phase	[97] pg. 59 [1] pg. 17, 50

For this waste, only thermochemical conversion is at a development stage, while the rest of suitable methods are today used.

5.1.10 Contaminated land

Table 30: Selection of treatments for contaminated land

	YES	NO	WHY NOT/NOTES	Ref.
Thermochemical/ Advanced thermochemical process	X		In development phase, but used for organic surfaces	[97] pg. 61
EIX		X	Recently developed but for coolant and liquid effluent	[21] pg. 38 [91] pg. 1 [92] pg. 4
Phytoremediation, phytostabilization		X	Research phase	[101] pg. 19 [1] pg. 14, 28, 44
Plasma arc		X	Limited full-scale experience with LLW; High cost	[97] pg. 50 [1] pg. 45 [5] pg. 76 [98] pg. 25
Pyrolysis	X			[19] pg. 33, 35

There are specific treatments under development just for contaminated land, as well as others that are used in this case, i.e. thermochemical processes.

5.1.11 Metals

Table 31: Selection of treatments for metal waste

	YES	NO	WHY NOT/NOTES	Ref.
High temperature incineration		X	Used in Japan; High cost; Very sensitive to waste feed	[1] pg. 32 [19] pg. 10, 19
Incineration	X		High cost; Low public acceptance	[97] pg. 22, 34, 43, 66 [2] pg. 28 [17] pg. 24, 26 [19] pg. 10, 24, 25
Molten metal		X	Wide use only in Japan	[1] pg. 41
Plasma arc		X	Limited full-scale experience with LLW; High cost	[97] pg. 50 [1] pg. 45 [5] pg. 76 [98] pg. 25
Pyrolysis	X		High cost; More suitable for ILW;	[5] pg. 75

Even though metals are one of most abundant waste feed, there are only two processes widely implemented, while the others are not so developed mainly because of their cost.

5.1.12 Asbestos

Table 32: Selection of treatments for asbestos

	YES	NO	WHY NOT/NOTES	Ref.
Molten metal		X	Wide use only in Japan	[1] pg. 41
Plasma arc		X	Limited full-scale experience with LLW; High cost	[97] pg. 48, 50 [1] pg. 45 [5] pg. 76 [98] pg. 25
Thermochemical conversion		X	Development phase	[97] pg. 59 [1] pg. 17, 50
Vitrification		X	Suitable for HLW	[97] pg. 47, 48

It's clear that asbestos is one of most problematic waste, because of his radioactivity added to his normal toxicity. Along with treatments seen for other type of waste, there is also a typical method for HLW, vitrification (immobilization method), in research for asbestos.

5.1.13 Concrete

Table 33: Selection of treatments for concrete

	YES	NO	WHY NOT/NOTES	Ref.
High temperature incineration		X	Used in Japan; High cost; Very sensitive to waste feed	[1] pg. 32 [19] pg. 10, 19
Molten metal		X	Wide use only in Japan	[1] pg. 41
Plasma arc		X	Limited full-scale experience with LLW; High cost	[1] pg. 45 [97] pg. 50 [98] pg. 25 [5] pg. 76
Thermochemical/ Advanced thermochemical process		X	No broad implementation	[19] pg. 39 [21] pg. 64, 65

Another problematic waste stream, always present with large amount, but with no broad implemented technologies, but at different steps of development.

5.1.14 Graphite

Table 34: Selection of treatments for graphite

	YES	NO	WHY NOT/NOTES	Ref.
Incineration		X	Research phase	[5] pg. 32, 64 [102], pg. 1, 4
Pyrolysis		X	Limited experience	[19] pg. 35 [22] pg. 8
Thermochemical/ Advanced thermochemical treatment		X	No broad implementation	[19] pg. 39

A historical problematic LLW/ILW is graphite ([12] pg. 39). Also conventional technologies are here not suitable because of its particular nature (e.g. incineration is not appropriate for volatility of graphite particles).

5.1.15 Evaporator bottom

Table 35: Selection of treatments for evaporator bottom

	YES	NO	WHY NOT/NOTES	Ref.
Hot isostatic pressing	X			[21] pg. 58 [1] pg. 17
Drum drying	X			[1] pg. 30, 31 [35] pg. 522

For evaporator bottom, there are only two suitable treatments, but currently well proven and used.

5.2 HLW

Table 36: Selection of treatments for HLW

	YES	NO	WHY NOT/NOTES	Ref.
Calcination	X			[19] pg. 14
Hot isostatic pressing	X			[21] pg. 58 [1] pg. 17
P&T		X	Development phase	[23] pg. 3
Pyrolysis	X		High cost	[19] pg. 33, 37
Vitrification	X			[1] pg. 29 [97] pg. 47

For the most radioactive waste, techniques implemented also for LLW/ILW, as well as typical HLW processes are used, with a large and important part of research about partitioning and transmutation.

5.3 Conclusions

The subdivision according to the several waste streams allows to note the possibility to use a same technology for divers waste typologies. Again, a typical example is pyrolysis, that is suitable for wastes sensibly different each other: resins, filters, plastics, land and metals for LLW/ILW and HLW. This can be seen as an advantage in terms of implementation: a singular capital cost, even if it's high, will provide a process adapt for a set of wastes for which different techniques implementations, with relative costs for each, can be avoided ([19] pg. 30-37; [5] pg. 75; [1] pg. 46, 47; [20] pg. 44, 45). Other examples of wide range treatments are incineration, drum drying or hot isostatic pressing, with the same consideration of above ([5] pg. 71-74; [1] pg. 30,31, 33). Moreover, sometimes their use as only available solution, maybe waiting for new development of more innovative approaches, justifies their high cost or can take to the decision to go on with their exploitation in spite of their low public acceptance. Most likely, in view of the new research fields and relative developments, a process both highly expensive and with low public perception – e.g. incineration – won't be considered for the construction of new waste treatment facilities, but just to continue its operational life.

But more peculiar treatments are developed and therefore currently employed. Just for example, it's the case of liquid waste, with its largest set of specific treatments, such as alkaline hydrolysis, electrochemical ion exchange (in development phase also for contaminated land), ion exchange membranes, ion-specific filtration, reverse osmosis, super-absorbent polymers (currently suitable for oils also). Other waste feeds that have treatments with particular specificity are resins (pelletization), combustibles (PVA dissolution), filters (liquid cartridge filter shearing and shredding and PVA dissolution), sludge (oil solidification), oils (oil solidification, oil filtration, super-absorbent polymers, contaminated land (thermochemical/advanced thermochemical process, that has reached an exploitation scale just for organic surfaces, whilst is in development phase for other waste types).

For these treatments, a mobile technology implementation can be hoped for – also thanks to their mobile implementation availability for many of these ([1] pg. 15) – to serve several sites with radioactive waste, avoiding its transportation and to optimise their employment on a campaign basis. The advantage of this approach is its flexibility according to power plants situations and the possibility to adopt new technologies as they will be developed.

On the other hand also a central facility can be economically advantageous, if it can receive waste from sites of a regional area. The main characteristics of plants such as e.g. cold crucible vitrification, incineration, hot isostatic pressing, PVA dissolution, pyrolysis, are generally their high capital cost and high level of technical expertise required, therefore these aspects lead to prefer a centralised waste processing plant. But to compensate their considerable implementation investment, these facilities would to receive radioactive waste not only from local national nuclear sites, but also from sites in a designed regional zone (both national or international). For this purpose, a strong international cooperation (e.g. about studies, research...) and regulation harmonisation (about radioactive waste categories, transport) is needed, particularly in Europe, where several countries in a relative small space use or have used nuclear energy, with consequent radioactive waste arising.

A problematic waste management aspect remains: the way to treat asbestos, concrete and graphite. In these cases, also well-proven applications, such as pyrolysis or thermochemical treatments, are not developed for these waste typologies, because of their particularity ([19] pg. 35, 39; [21] pg. 64, 65; [22] pg. 8). Asbestos is usually dangerous (even when not radioactive), concrete has often a deep contamination and graphite has big problems with volatility of its particles (e.g C-14, so not even incineration is appropriate as its treatment). For these waste types, a experienced approach is not currently proven, so the R&D field plays a fundamental role to this purpose.

HLW has several treatments options, some created just for this kind of radioactivity levels, such as calcination, vitrification, and then developed also for LLW/ILW, or pyrolysis and hot isostatic pressing, usually applied both for HLW and LLW/ILW ([19] pg. 33, 37; [21] pg. 58; [1] pg. 17). Partitioning and transmutation are the most innovative and potentially the best HLW management implementation, but their optimised employment requires an advanced fuel cycle that is not currently developed ([23] pg. 3). They are the only treatments that can reduce the radiotoxicity of HLW and, therefore, its confinement time.

It will be recalled again that all these treatments won't avoid the recourse to final disposal, but some of these reduce the impact on it while others make waste stream suitable for it or for further process before repository.

6 Feasibility for Italy

In this section, a further "filtration" of the treatments described in previous section will be provided, on the basis of Italian scenario. For this purpose, Italian radioactive waste inventory will be showed and, after this, related treatments will be chosen.

It can be useful to point out that in Italy there is a different "local" classification for radioactive waste, related to international classification as follows:

- **Category I**: Waste whose activity decays in a few months to below a level at which there is any concern about safety. Such waste may be disposed of as ordinary waste under general waste regulations. It is generally described as VLLW and is mainly generated by hospitals and research establishments;
- **Category II**: Waste whose activity decays to the level of a few hundred Bq/g within a few centuries. The activity of several specified radionuclides must not exceed prescribed values. Such waste is suitable for near surface disposal. It is usually described as short-lived, LLW;
- **Category III**: Long-lived waste not included in categories I and II, high-level waste from reprocessing of spent fuel, and alpha-bearing waste from nuclear fuel cycle and R&D activities. Such waste will require deep geological disposal. This waste is described generally as long-lived and/or ILW/HLW.

Source: [103], pg. 2, 3; [104] pg. 18; [105] pg. 15, 35.

The radioactive waste inventory in Italy is the following:

- Category II (LLW/ILW): about 25.000-28.000 m^3 currently existing and 40.000 m^3 to be produced by NPPs decommissioning;
- Category III (HLW): 7.500 m^3, included the reprocessed waste from oversea.

Source: [106] pg. 6; [107]; [108] pg. 143, 144; [104] pg. 10, 21.

According to the quantities and typologies of Italian waste inventory, the suitable treatments for it – according to Section 5 – are reported in the following table (the existing waste feeds are listed according to [104] pg. 10-14, 523-625):

Table 37: Treatments according to waste feed existing in Italy

WASTE STREAM	TREATMENTS
Asbestos	Treatments under development
Ash	Pelletization
Concrete	Treatments under development
Contaminated land	Thermochemical/Advanced thermochemical process; Pyrolysis
Evaporator concentrates	Cold crucible vitrification; Crystallization; Drum drying; Pelletization
Filters	Incineration; Liquid cartridge filter shearing and shredding; PVA dissolution; Pyrolysis
Graphite	Treatments under development
Liquid HLW	Calcination; Pyrolysis; Vitrification
Liquid waste	Alkaline hydrolysis; Calcination; EIX; Incineration; Ion exchange membranes; Ion-specific filtration; Reverse osmosis; Super absorbent polymers
Metallic waste	Incineration; Pyrolysis
Oils	Incineration; Oil filtration; Oil solidification; Super absorbent polymers

WASTE STREAM	**TREATMENTS**
Plastic waste	Incineration; Pyrolysis
Radioactive sources	Conditioning (grouting, cementation) or decay for those ones with half-life <100 d. [2], pg. 34, 35, 40, 41 See Section 4
Resins	Drum drying; Hot isostatic pressing; Incineration; Pelletization; Pyrolysis
Sludge	Drum drying; Hot isostatic pressing; Oil solidification
Uranium waste	For U-contaminated metals: Immobilisation; Minimisation/recycling See 4.1.7

A different discussion is needed for Italian SNF. Up to 2005, the following quantities of SNF were sent to oversea for reprocessing:

- 936,2 MTHM (uranium and plutonium dioxide) before 1978 ;
- 678 MTHM (uranium and plutonium dioxide, 573 tons of MAGNOX fuel from Latina NPP and 105 tons of uranium oxide from Trino and Garigliano NPPs).

The return of waste from the foreign reprocessing in compulsory only for the waste sent to oversea after 1978. The SNF reprocessed abroad will return as vitrified residues of Category III and cemented residues of Category II in the following amounts[2]:

- 16,6 m^3 of Category III vitrified waste (0,074 m^3 for each ton of SNF) from Sellafield in UK and 4,6 m^3 from Superphénix plant in France ;

2 These estimates are valued according to the fuel from Trino and Garigliano, because the fuel from Latina is not representative of the total Italian fuel.

- 196 m^3 of Category III cemented waste (0.871 m^3 for each ton of SNF) from Sellafield in UK and 54 m^3 from Superphénix plant in France;
- 1405,7 m^3 of Category II cemented waste (6,248 m^3 for each ton of SNF) from Sellafield in UK and 387,3 m^3 from Superphénix in France .

The SNF stored in Italy and not sent abroad is 225 t; so, the estimate for the overall conditioned waste from reprocessing is the following:

- 1.153 m^3 of Category III;
- 6.838 m^3 of Category II.

SNF from ITREC (Elk River) plant is not included in the previous prevision because it will be stored in dry casks waiting for the transfer to national repository or it will be sent in USA after eventual agreements.

[104] pg. 18-20; [105] pg. 12

6.1 Conclusions and road maps

To sum up, we think it's important to point out an interesting IAEA's approach to treatment technologies implementation.

There are two options for a scenario with a small number of plants (that typically will not produce sufficient volumes of waste to justify the large expenditures required for some high efficiency technologies). The most common is the use of regional, centralized, off site processing facilities which accept waste from many nuclear plants. These may be used for any individual country, or they may support a consortium of countries.

The second solution is the use of mobile systems which can be transported among multiple nuclear sites for processing campaigns. Typically such a system might be at an individual site for one to three months, but in some situations the mobile system may remain at an individual site for several years (e.g. the use of a supercompactor to recover some of the storage capacity of a ten-year accumulation of drummed and stored waste) ([1], pg. 16).

Depending on the national situation, centralized waste management can be done by a major waste generator, by a service organization, or by a specialized waste management organization. In countries where the national regulatory system is not very well developed, the waste management organization should be a State organization or a public company. In special cases the service of a foreign organization, inside or outside the country, specialized in waste management can be considered. It may also be possible to use the services of companies which are normally working with the equipment containing sealed radioactive sources and which have capacities for managing disused sources ([2], pg. 37).

To show a possible implementation of radioactive waste management in Italy, a flow chart for each waste stream will be here developed, with the suitable treatments for it, the end products of these and the relative immobilisation options before the storage/disposal. Of course, some methods provide for further treatments if the end product of first ones is not suitable for storage or disposal.

When possible, implementation options are discussed (locally, plant site, regional, etc...).

As can be pointed out, a storage or disposal as final step of the process cannot be avoided, as any industrial activity.

As said before, immobilisation techniques are wide-range methods available for all waste stream, in some cases with a direct immobilisation, in others after further processes on the end product of a previous treatment. Furthermore, volume reduction methods, such as compaction and super-compaction, due their very large application before and after specific treatments, are not reported in the diagrams, but it's evident their importance for the optimization of storage/disposal.

The same types of processes are used for waste feed, such as contaminated asbestos, concrete, graphite, that have not other currently available treatments (and that therefore are not here reported).

Where not specified, the references are the same of Section 5.

6.1.1 Liquid waste

For liquid waste there is the widest set of treatments. Most of them require just an immobilisation phase before storage, whilst further steps are needed for others (Figure 20).

For incineration, a removal of inorganic material is suitable as pre-treatment while off-gas cleaning and release system is required.

The end products of ion-specific filtration are liquid effluent – which will be immobilised – and spent resins that undergo to relative treatments for this type of waste (see next paragraph).

After alkaline hydrolysis, flocculation and cementation – as immobilisation method – are needed before disposal ([97] pg. 46, 47).

Although vitrification is a process more suitable for HLW, some commercial plants also employ it for calcined LLW/ILW; however, vitrification remains generally applied to HLW, due to its complexity and high cost.

The immobilisation techniques after alkaline hydrolysis and calcination are specific and they are respectively cementation (along with a flocculation process) and vitrification.

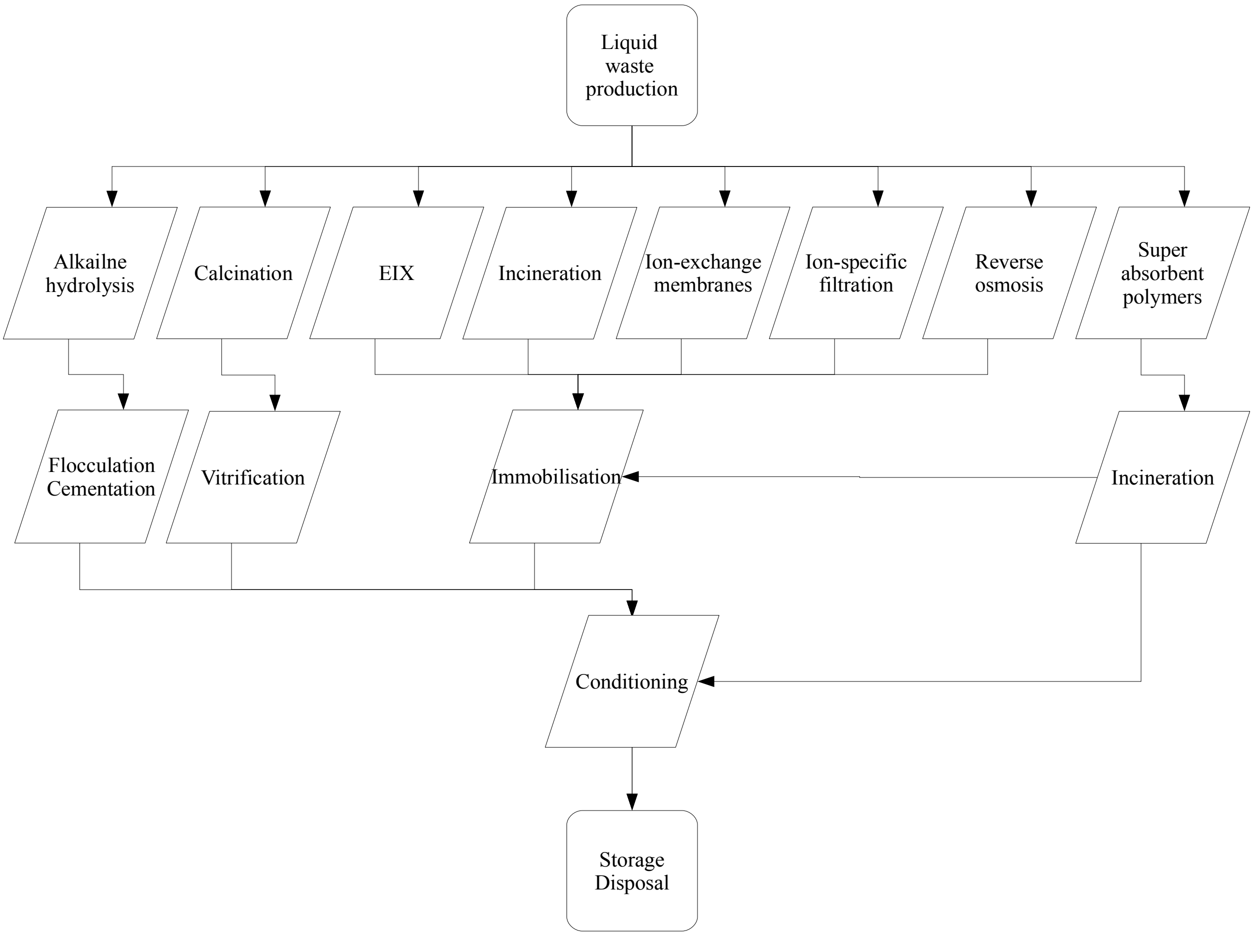


Figure 20: Diagram of the processes for liquid waste

6.1.2 Resins

Also in this case, we have several possibilities for resins treatments, some with pre-treatments, some with post-treatments before storage.

In drum drying, there is a loading into 200 litres drum before drying with an end product adapt for direct storage. Concerning about its implementation, it is possible locally (plant specific), at an off site central processing facility, or as a mobile processing facility.

In hot isostatic pressing, spent resins are first dewatered or dried to a residual water content of between 12 and 50%. Spent ion exchange resins may also be mixed with other radioactive waste, such as sludges and evaporator bottoms, with high water contents. After processing, the compacted pellets must, however, be packed into watertight packages in order to avoid the resins swelling owing to contact with water.

For incineration, the same indication of liquid waste exist, with locally implementation (plant specific), at an off site central processing facility, or as a mobile processing facility (one has been developed to incinerate steam generator chemical cleaning solutions) ([1] pg. 34).

The treatment of ion exchange resins with pelletization requires a chemical binder, whereas other waste types may not. After pelletization, the pellet are put into final storage container ([21] pg. 82). Implement locally (plant specific), or at an off site central processing facility (although off site processing may not be feasible for evaporate concentrates due to difficulty in transport).

With pyrolysis the end product is easily managed (although highly concentrated) and can either be directly disposed, vitrified, or solidified with cement, plastic polymers, wax, etc... and can be suited to elemental separation for recycling. The choice of pyrolyzer is related to specific waste feed. Waste pre-treatments are often necessary; the resultant dry product can be either directly stored in an appropriate container or immobilized immediately for long term storage or final disposal. Although the cost is comparable with a conventional incinerator system, the application of the technology is more complex than other incineration technologies. Implement at an off site central processing facility.

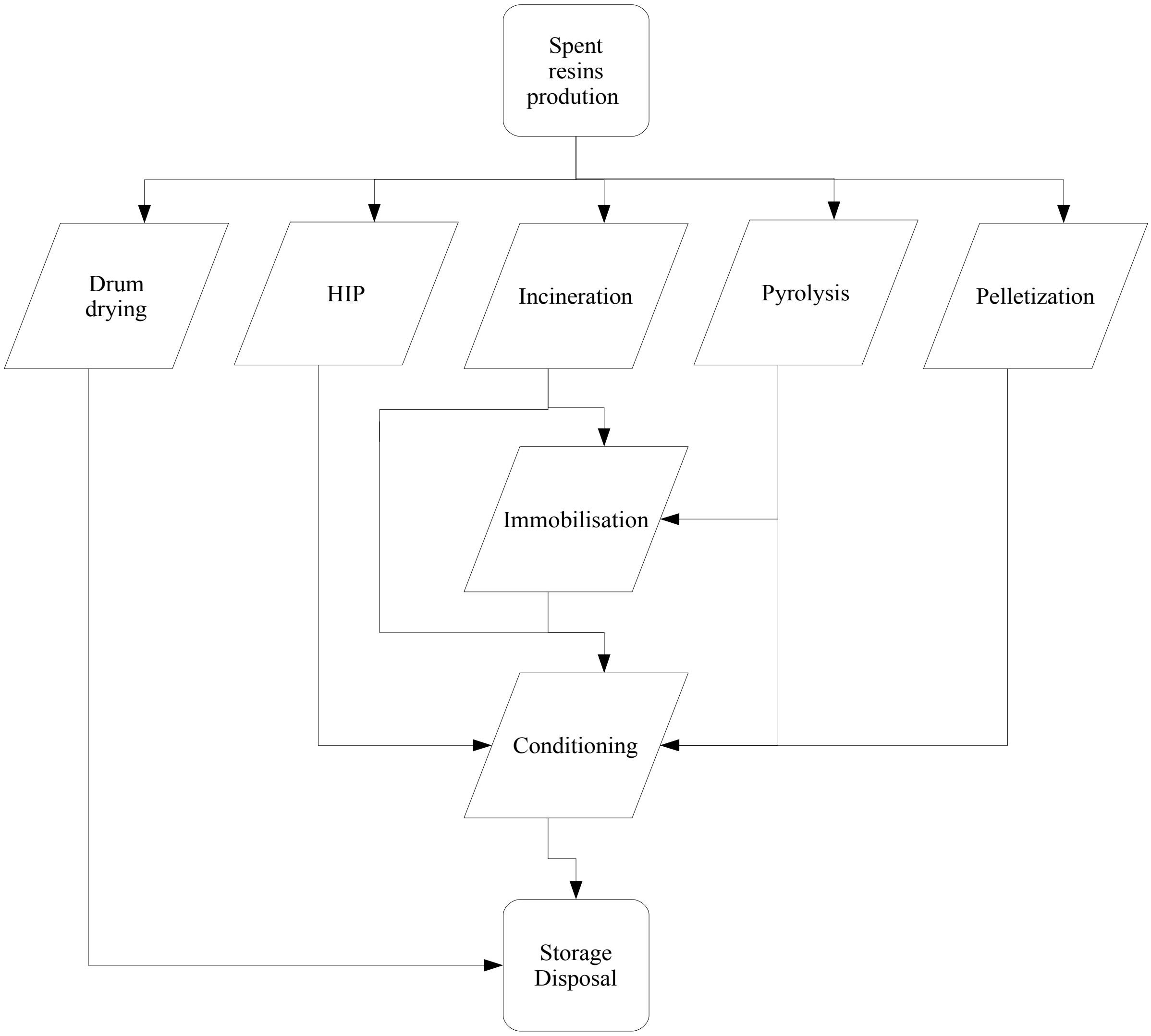


Figure 21: Diagram of processes for spent resins

6.1.3 Combustible waste

Incineration with fluidised bed combustion require pretreatment to improve homogeneity prior to combustion of heterogeneous waste. Plants costs are significant (high electric power usage) as FBC is only economical on a relatively large scale.

PVA dissolution is suitable for combustible made from PVA. The end product is a completely dissolved liquid which can be discharged or directed to a bioreactor for further treatment of any organics. Relatively inexpensive to construct and operate, it can be implemented at a large, multi-reactor plant site or at an off site central processing facility.

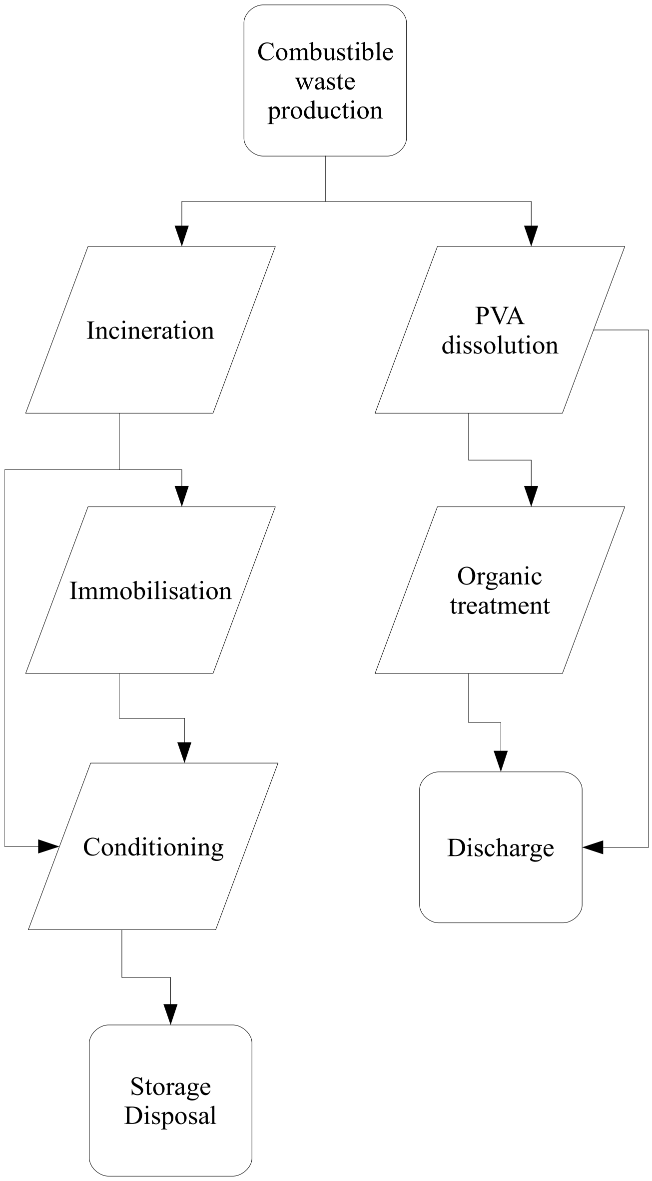


Figure 22: Diagram of processes for combustibles waste

6.1.4 Filters

The high capital cost for incineration involves a sufficient annual waste input to be economically competitive and, as usual, sorting and segregation is a required pre-treatment.

Liquid cartridge filter shearing and shredding is a very low cost technology to construct and operate. Shearing and shredding have the potential for airborne contamination and spreading of loose surface contaminates, with shredding generally having a higher potential than shearing. It' possible to implement it locally (plant specific), at an off site central processing facility or as a mobile processing facility.

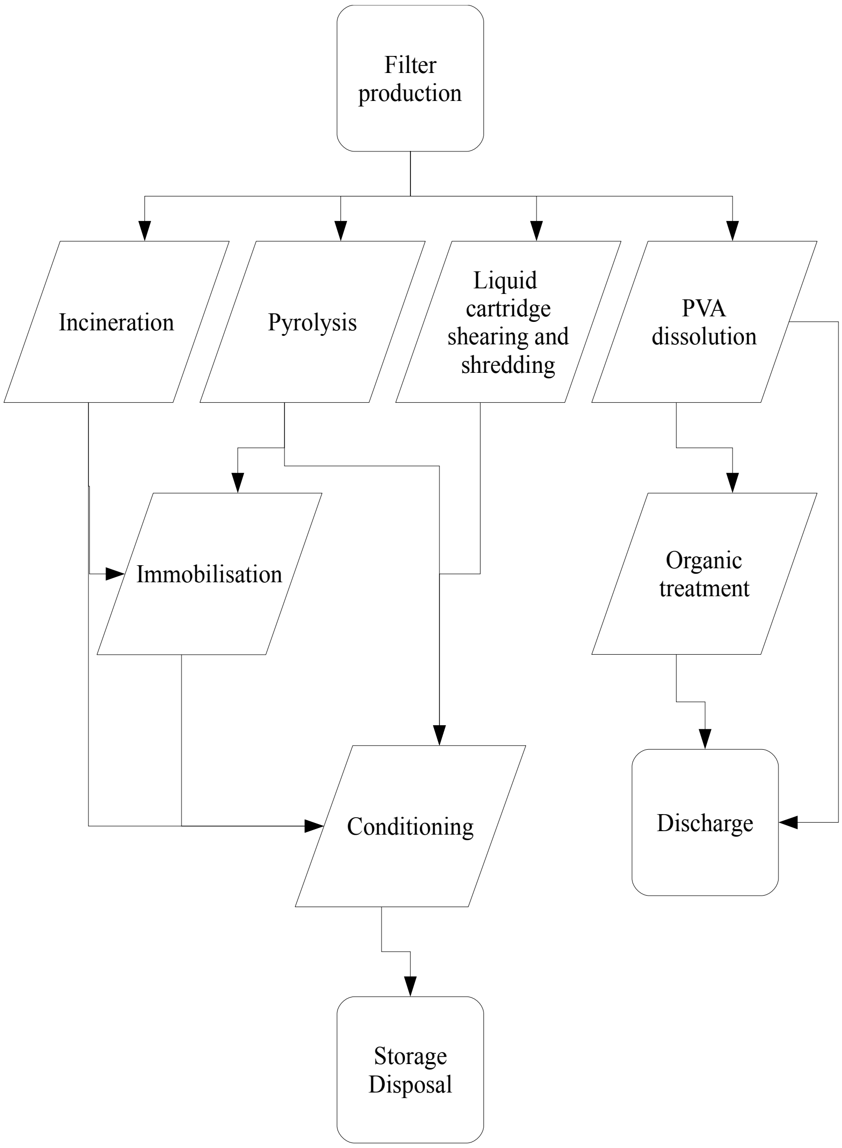


Figure 23: Diagram of processes for filters

6.1.5 Evaporator concentrates

Available technology for evaporator concentrates, cold crucible vitrification requires a large input volume (and relative high throughput) to support continuous, cost efficient operation, and therefore is more suited to use in a centralised processing facility. Its implementation can be local (plant specific) or at an off site central processing facility. To avoid continuous operation when only small waste input volumes are available, campaign processing should be considered.

Crystalization is suitable for for high salinity solutions and it's commonly used for liquid waste containing boric acid. Its implementation is local at plant site.

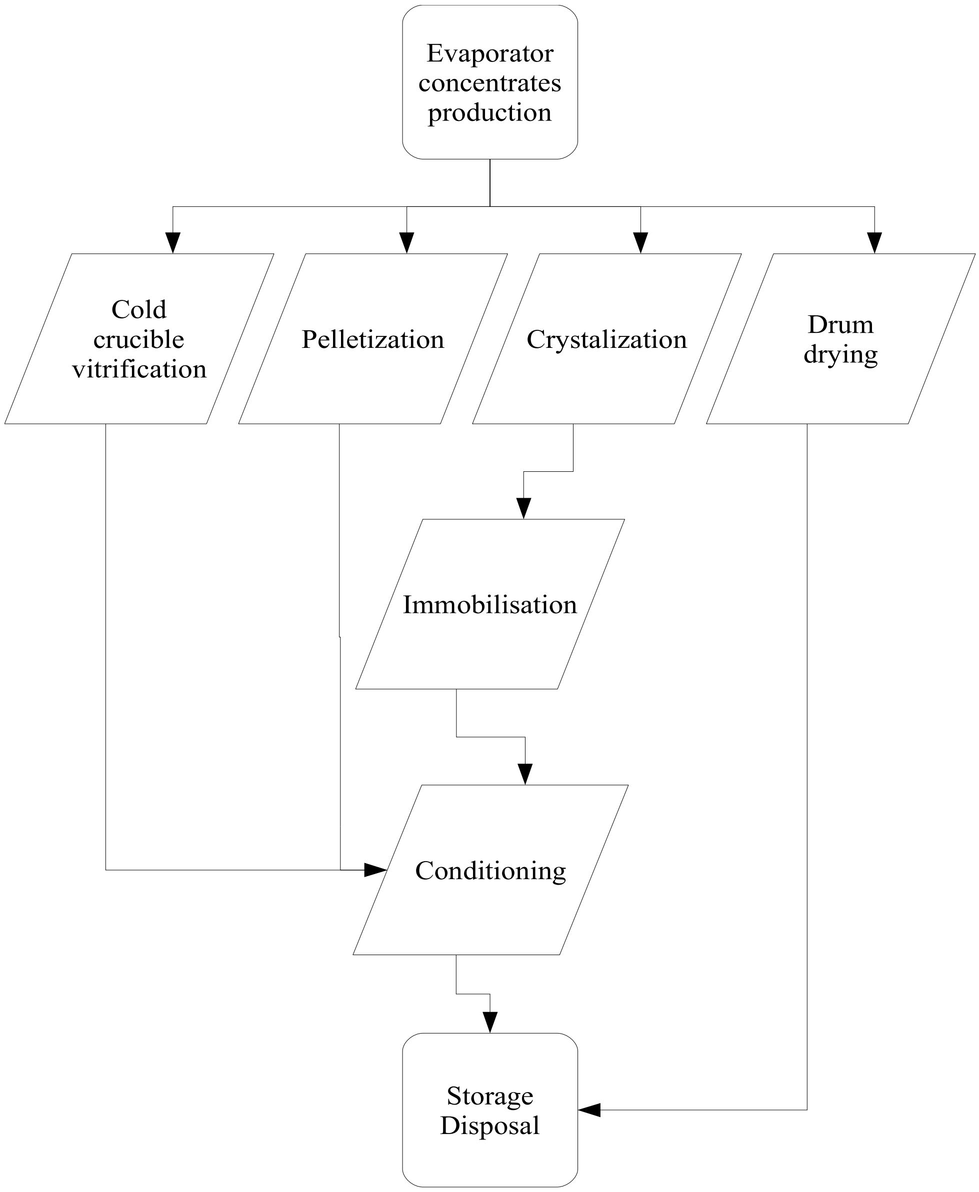


Figure 24: Diagram of processes for evaporator concentrates

6.1.6 Ashes

For the sole treatment suitable for ashes – pelletization – the same considerations of spent resins are valid. Ash is a typical end product of destructive treatments such as incineration.

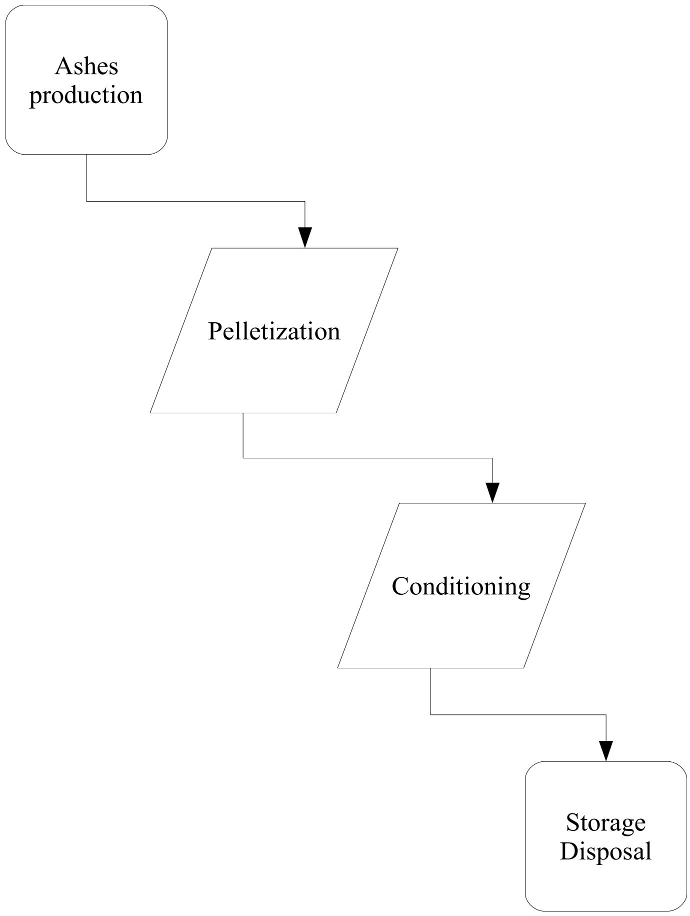


Figure 25: Diagram of processes for ashes

6.1.7 Plastic waste

As in the case of filter waste, here we have incineration and pyrolysis options that can obtain an end product suitable for an immobilisation step or for direct conditioning before storage/disposal.

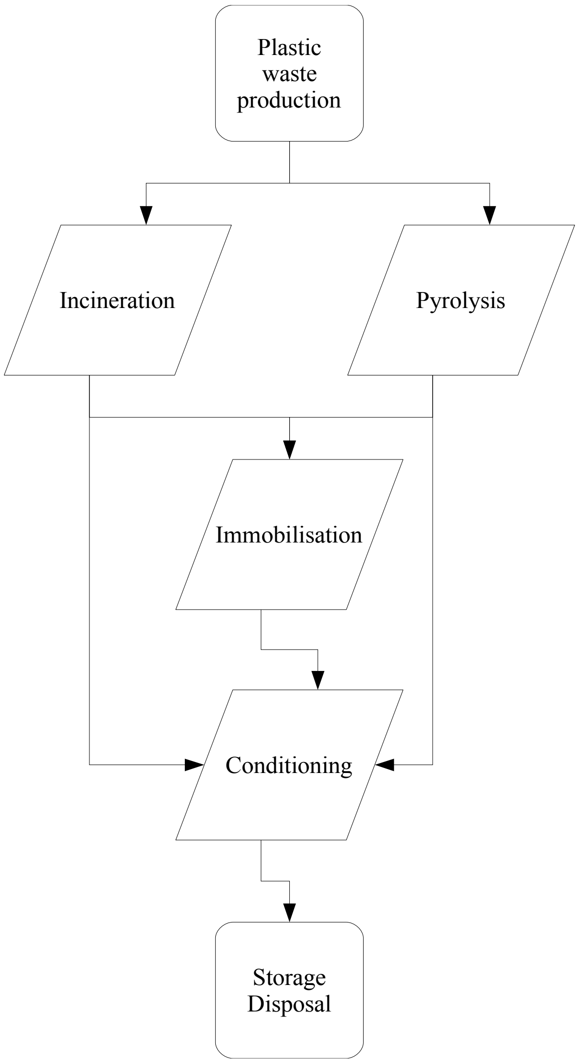


Figure 26: Diagram of processes for plastic waste

6.1.8 Sludge

The end product of oil solidification is a solid monolith and the implementation is plant specific using typical cement solidification equipment, or at an off site central processing facility, or using mobile solidification equipment.

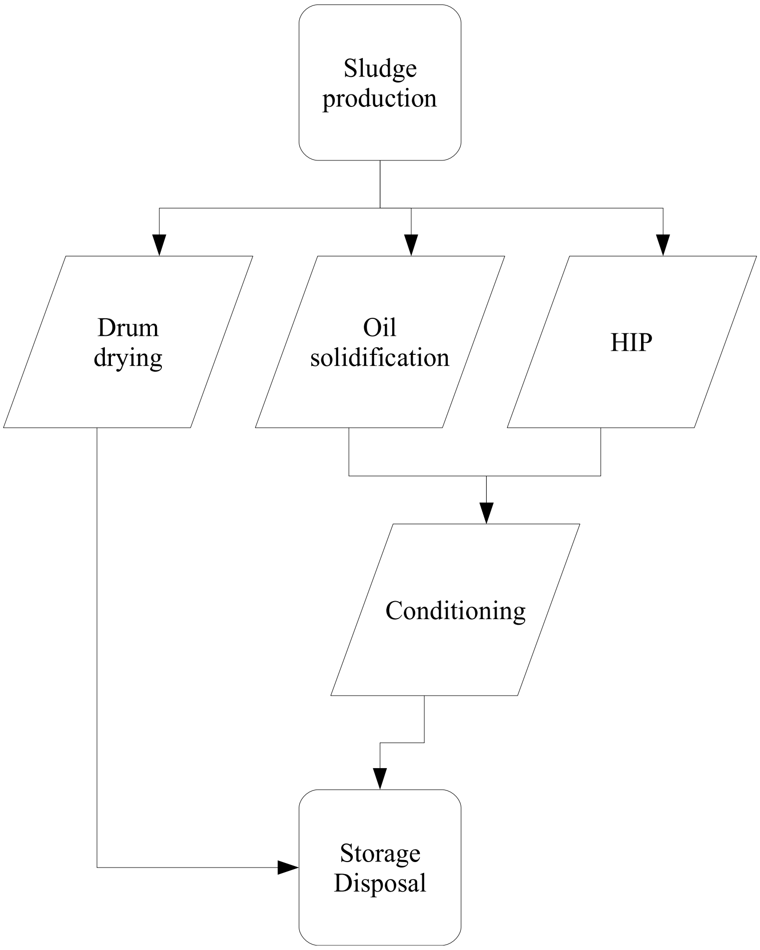


Figure 27: Diagram of processes for sludge

6.1.9 Oils

Super absorbent polymers implementation is normally local, at generating plant site, but can be used at a central location. Can be implemented as a mobile process with very simple equipment.

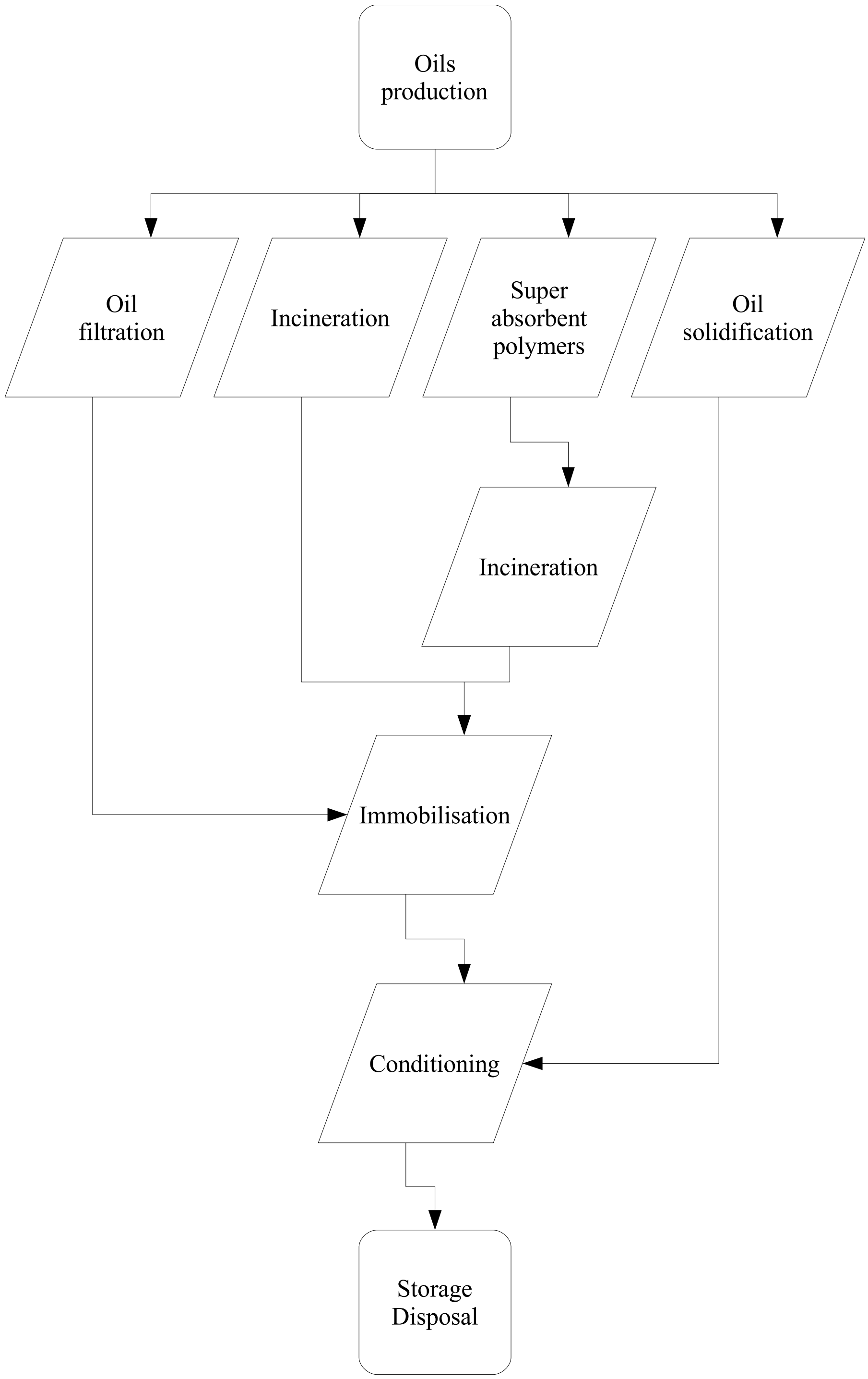


Figure 28: Diagram of processes for oils

6.1.10 Contaminated land

The resulting product of thermochemical treatment process, used also for decontamination of organic surfaces such as asphalt, is solid slag or ash.

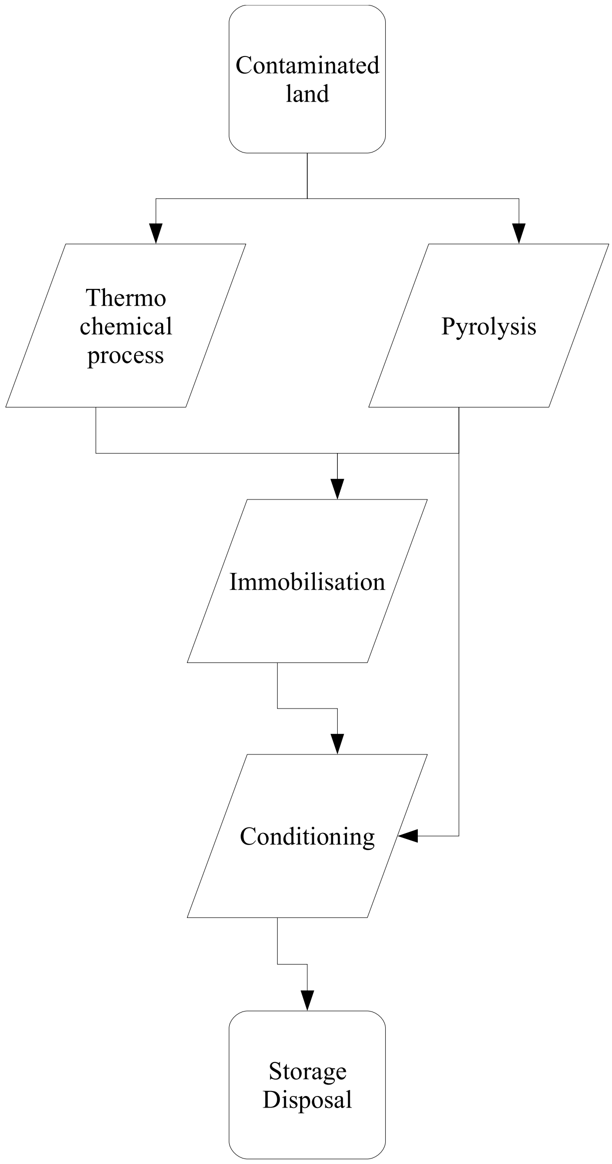


Figure 29: Diagram of processes for contaminated land

6.1.11 Metals

The same consideration for plastic waste, for which the sane treatments are suitable, are valid.

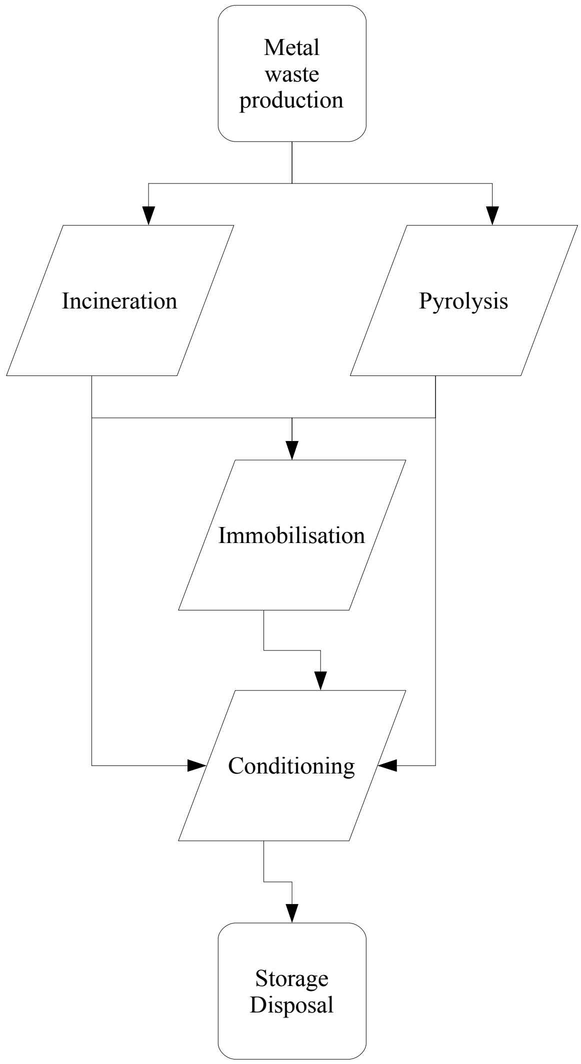
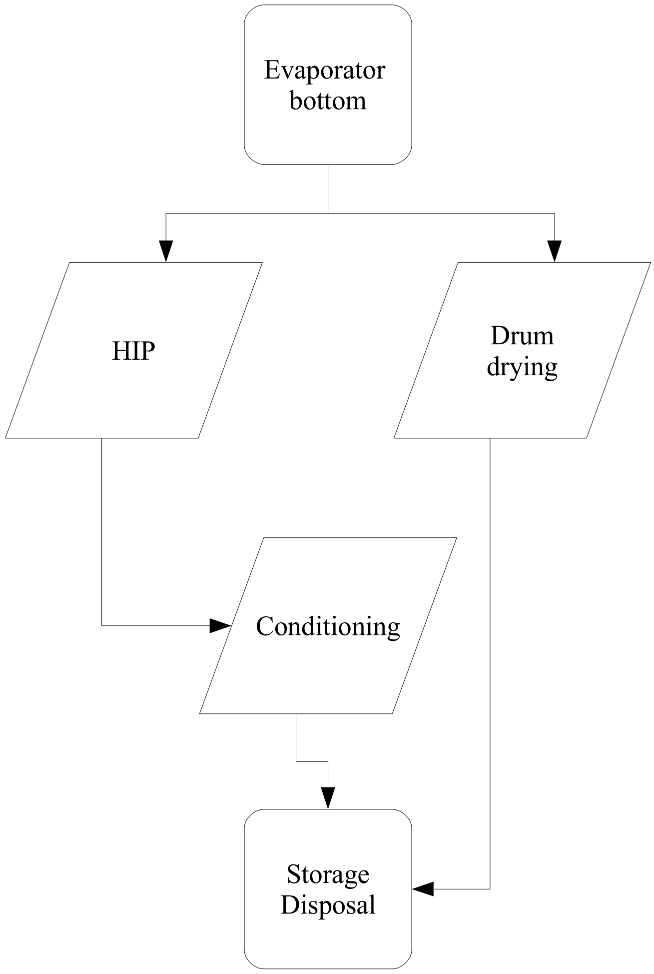


Figure 30: Diagram of processes for metallic waste

6.1.12 Evaporator bottom



6.1.13 HLW

Although here we deal with this waste typology as HLW and not as liquid, metallic, combustible and so on, like in the previous paragraphs, the same consideration about these treatments are sound. For pyrolysis, fixed plants are capable of processing HLW and post-treatment immobilisation can be made by vitrification or cementation as well.

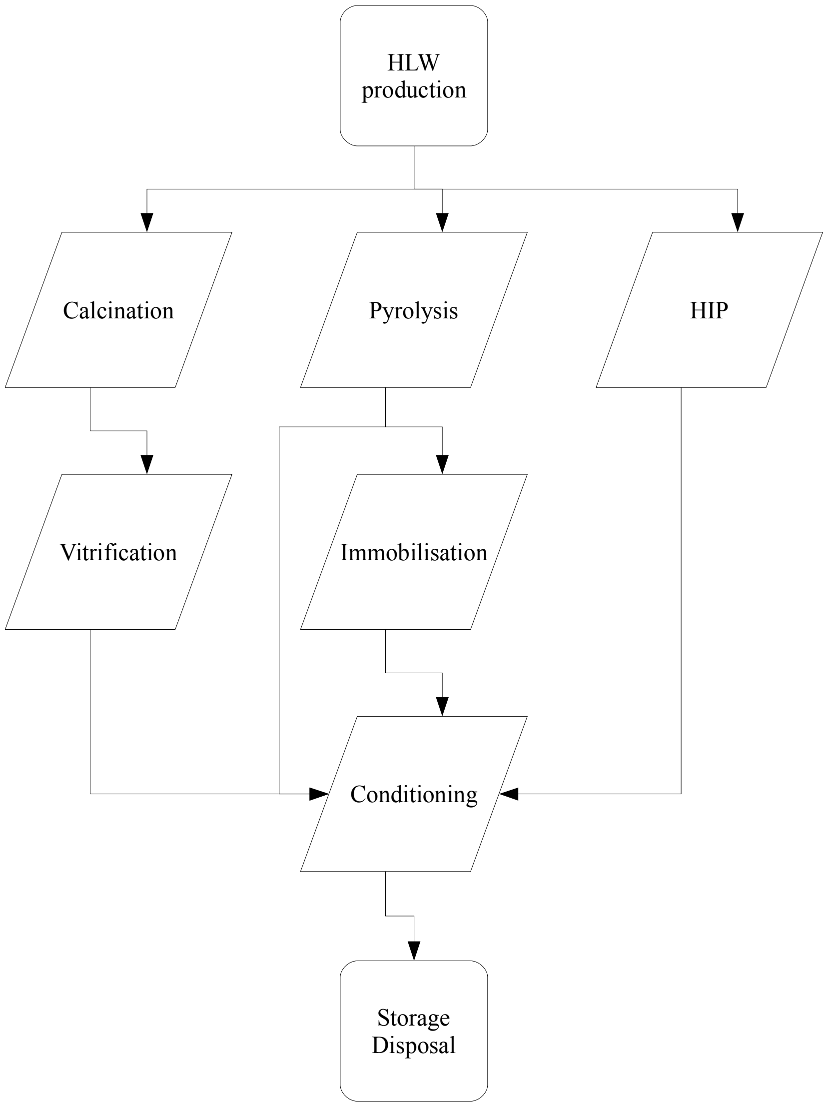


Figure 31: Diagram of processes for HLW

References

[1] IAEA, "Innovative waste treatment and conditioning technologies at nuclear power plants", May 2006;
[2] IAEA"Selection of efficient options for processing and storage of radioactive waste in countries with small amounts of waste generation", September 2003;
[3] WNA, "Treatment and Conditioning of Nuclear Wastes", 2011;
[4] NEA, "Release of Radioactive Materials and Buildings from Regulatory Control", 2008;
[5] NDA/LLW Repository Ltd., "LLW Repository Compendium of Strategic Technical Briefs Volume 1", March 2009;
[6] European Foundation, http://www.europeanfoundation.org/my_weblog/2010/11/brussels-to-interfere-with-radioactive-waste-disposal.html,July 2011;
[7] COVRA, “Radioactive waste management in the Netherlands: a practical solution in full operation”;
[8] NEA"Radioactive waste management programmes in OECD/NEA member countries. Netherlands", 2008;
[9] G. Stanford, "LWR recycle: necessity or impediment?", ANS, November 2003;
[10] W.H. Hannum, G.E. Marsh, G.S. Stanford, "Smarter use of nuclear waste", Scientific American 2005;
[11] NEA, "Cooperative programme on decommissioning", 2006;
[12] WNA, "Radioactive Waste Management", June 2009;
[13] WNA, "Natural Occurring Radioactive Materials", March 2009;
[14] P.J. O'Sullivan, "Libération des matériaux et bâtiments radioactifs du contrôle réglementaire", Revue Générale NucléaireJuly-August 2009;
[15] NDA/LLW Repository Ltd., "LLW Repository: LLW Strategic Review", January 2009;
[16] NDA, "UK Strategy for the Management of Solid Low Level Radioactive Waste from the Nuclear Industry", August 2010;
[17] IAEA, "New Developments and Improvements in Processing of 'Problematic’ Radioactive Waste", December 2007;
[18] WNA, "Synroc waste form", July 2010;
[19] "Application of Thermal Technologies for Processing of Radioactive Waste"December 2006;
[20] "Predisposal Management of Organic Radioactive Waste", July 2004;
[21] IAEA, "Application of Ion Exchange Processes for the Treatment of Radioactive Waste and

Management of Spent Ion Exchangers", June 2002;
[22] J.B. Mason, D. Bradbury, "Pyrolysis and its potential use in nuclear graphite disposal", IAEA, ;
[23] Mikael Höök, "Partitioning and transmutation", Global Energy Systems, May 2008;
[24] ONDRAF/NIRAS, http://www.nirond.be/engels/7.8_Inventaris_eng.html, July 2011;
[25] ONDRAF/NIRAS, http://www.nirond.be/engels/7.3_Verwerking_eng.html, July 2011;
[26] ONDRAF/NIRAS, http://www.nirond.be/engels/7.4_Opslag_eng.html, July 2011;
[27] ONDRAF/NIRAS, http://www.nirond.be/engels/7.5_Beheer_eng.html, July 2011;
[28] Jean-Paul Minon, "L'inventaire des passifs nucléaires répertoriés par l'ONDRAF durant la période 2003 – 2007", p. 15, ONDRAF/NIRAS, ;
[29] Belgoprocess, "Sustainability report - Annual report - 2009", p. 41, February 2010;
[30] NWMO, "Used Nuclear Fuel Inventory and Transportation Estimates", p. 10, 12, 14, August 2009;
[31] Ontario Power Generation, "Reference Low and Intermediate Level Waste Inventory for the Deep Geologic Repository", p. 22August 2008;
[32] Rolf Lidskog Ann-Catrin Andersson, "The management of radioactive waste A description of ten countries", SKB, 2002;
[33] NWMO, "Implementing Adaptive Phased Management 2010 to 2014", March 2010;
[34] Ontario Power Generation, "2009 Annual Report", 2010;
[35] Posiva Oy"Nuclear Waste Management at Olkiluoto and Loviisa Power Plants, Review of Current Status and Future Plans for 2010 –2012", February 2010;
[36] Posiva Oy"Safe Final Disposal of Spent Nuclear Fuel", April2010;
[37] ANDRA,"2009, Rapport d'activité", 2010;
[38] ANDRA, http://www.andra.fr/pages/fr/menu1/les-dechets-radioactifs/les-volumes-de-dechets-11.html, July 2011;
[39] ANDRA, http://www.andra.fr/andra-aube/pages/fr/menu4/le-centre-de-stockage-fma/les-dechets-de-faible-et-moyenne-activite-1087.html, July 2011;
[40] ANDRA, http://www.andra.fr/pages/fr/menu1/les-solutions-de-gestion/concevoir/un-centre-de-stockage-pour-les-dechets-ha-et-ma-vl-84.html, July 2011;
[41] ANDRA, http://www.andra.fr/international/pages/en/menu21/waste-management/waste-management-issues-at-national-level-1615.html, July 2011;
[42] ANDRA, http://www.andra.fr/pages/fr/menu1/les-solutions-de-gestion/transformer-13.html, July 2011;

[43] ANDRAhttp://www.socodei.fr/traitement-des-dechets/centraco/lincineration/, July 2011;

[44] ANDRA, http://www.andra.fr/international/pages/en/menu21/waste-management/financing-of-radioactive-waste-management-1623.html, July 2011;

[45] ANDRA, “Centre de stockage des déchets de faible et moyenne activité de l’Aube. Rapport annuel”, June 2010;

[46] BfS, http://www.bfs.de/en/endlager/abfaelle/abfall_prognosen.html, July 2011;

[47] GNS, “Competence for Nuclear Services”, 2010;

[48] Department of Nuclear Safety, “State and Development of Nuclear Energy Utilization in the Federal Republic of Germany 2009”, September 2010;

[49] BfS, http://www.bfs.de/en/transport/faq/faq_zwischenlager.html/#12, July 2011;

[50] Ministero de Industria, Turismo y Comercio, “Sixth General Radioactive Waste Plan”, June 2006;

[51] SKB, “Technical Report TR-07-12”, September 2007;

[52] SKB, “Technical Report TR-09-23”, December 2008;

[53] NAGRA, “Annual Report 2009”, April 2010;

[54] NDA, “Radioactive Wastes in the UK: A Summary of the 2007 Inventory”, March 2008;

[55] NDA/LLW Repository Ltd., "LLW Strategic Review Summary", October2008;

[56] LLW Repository Ltd., "Strategic BPEO study for VLLW", vol.1, August2009;

[57] LLW Repository Ltd. "Strategic BPEO study for VLLW", vol.2August2009;

[58] NDA, “UK Strategy for Radioactive Discharges”, July 2009;

[59] NDA, “The-main report of the 2007 Inventory”, March 2008;

[60] NDA, “NDA Business Plan 2010–2013”, March 2010;

[61] NDA/LLW Repository Ltd., "LLW Repository: LLW Strategic Review", January 2009;

[62] NDA, “Socio-Economic Policy”, 2008;

[63] OCRWM, “Supplemental Environmental Impact Statement”, June 2008;

[64] OCRWM, http://www.nrc.gov/waste/llw-disposal/licensing/statistics.html, July 2011;

[65] OCRWM, http://www.nrc.gov/reading-rm/doc-collections/nuregs/brochures/br0216/, July 2011;

[66] OCRWM, http://www.nrc.gov/about-nrc/regulatory/enforcement/public-involvement.html, July 2011;

[67] CORA, “Retrievable disposal of radioactive waste in The Netherlands”, February 2001;

[68] NRG, http://www.nrg.eu/product/re/radwaste/covra/index.html, July 2011;

[69] NRG, http://www.nrg.eu/product/re/radwaste/policy/index.html, July 2011;

[70] KHNP, http://www.khnp.co.kr/en/040203, July 2011;

[71] KHNP, http://www.khnp.co.kr/en/040201, July 2011;

[72] WNA, "Nuclear Power in South Korea", August 2010;

[73] JNES, "Current status of nuclear facility in Japan", 2009;

[74] NUMO, http://www.numo.or.jp/en/faq/main1.html, July 2011;

[75] NUMO, http://www.numo.or.jp/en/jigyou/new_eng_tab04.html, July 2011;

[76] RWMC, http://www.rwmc.or.jp/english/research_and_development_on_hi/, July 2011;

[77] Guillame De Roo, "Economics of nuclear fuel cycles: option valuation and neutronics simulation of mixed oxide fuels", Massachusetts Institute of Technology, August 2009;

[78] WNA, "Supply of uranium", December 2009;

[79] DbE, http://www.dbe.de/en/final-disposal/final-disposal-of-waste/index.php, July 2011;

[80] BfS, http://www.endlager-asse.de/cln_135/EN/2_WhatIs/_node.html, July 2011;

[81] IAEA, "Classification of radioactive waste", 2009;

[82] NRC, "Regulations: Title 10, Part 60", December 2010;

[83] DOE, "IMPLEMENTATION GUIDE for use with DOE M 435.1-1", July 1999;

[84] U.S Government Printing Office, http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=ccd18a19491a7792dbd5a160a87131f3&rgn=div5&view=text&node=40:24.0.1.1.2&idno=40, Part 191.11, July 2011;

[85] U.S. Nuclear Regulatory Commission, http://www.nrc.gov/about-nrc.html, March 2011;

[86] F. Berkhout, "Radioactive waste: politics and technology", 2003;

[87] D. E. Shropshire et al., "Advanced Fuel Cycle Cost Basis", INL, December 2009;

[88] ENRESA, http://www.enresa.es/activities_and_projects/low_and_intermediate_wastes/treatment_and_conditioning_of_radioactive_wastes, July 2011;

[89] ANDRA, http://www.andra.fr/international/pages/en/menu21/waste-management/waste-classification/short-lived-low—and-intermediate-level-waste-1609.html, July 2011;

[90] ENRESA http://www.enresa.es/activities_and_projects/low_and_intermediate_wastes/treatment_and_conditioning_of_radioactive_wastes, July 2011;

[91] C. Ahmed Bashaa et al., "Total dissolved solids removal by electrochemical ion exchange (EIX) process", Electrochimica ActaJuly 2008;

[92] Mark D. Neville et al., "The EIX process for radioactive waste treatment", AEA Technology, 1997;

[93] ANDRA, http://www.andra.fr/international/pages/en/menu21/waste-management/waste-classification/high-level-waste-and-long-lived-intermediate-level-1610.html, July 2011;

[94] DOE"Federal Register / Vol. 75, No. 1", January 2010;

[95] D. Gombert et al"Combined Waste Form Cost Trade Study", INL, November 2008;

[96] C. Rodriguez et al., "Deep-Burn: making nuclear waste transmutation practical", Nuclear Science and Design, December 2002;

[97] IAEA, "Predisposal Management of Organic Radioactive Waste", July 2004;

[98] Jan Deckers, "1Plasma treatment of Radioactive waste", Belgoprocess29 September 2010;

[99] IAEA, "Low and Intermediate Level Waste Repositories: Socioeconomic Aspects and Public Involvement", November 2005;

[100] M.I. Ojovan, O.G. Batyukhnova, "Glasses for nuclear waste immobilization", WM 2007 conference, February-March 2007;

[101] IAEA, "XRF Newsletter N°17", July 2009;

[102] F. Delage, C. Latge, P. Thouvenot, "Overview on graphite treatment processes in high temperature reactors", CEA, 22-24 September 2004;

[103] NEA Radioactive waste management programmes in OECD/NEA member countries-Italy", 2008;

[104] R. Bove et al., "Revisione critica dell’inventario nazionale dei rifiuti radioattivi ai fini dello smaltimento", ENEA, Ministero dell Sviluppo Economico, 2009;

[105] APAT, "Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management", April 2006;

[106] A. Taglioni, "Radioactive Wastes: from an Emotional Approach to a Rational Evaluation", ENEA, 2010;

[107] ENEA, http://www.enea.it/focus-fissione-nucleare/situazione-italia.html, July 2011;

[108] EnergyLab Foundation, " Rapporto preliminare sulle condizioni per il ritorno all'energi elettronucleare in Italia", 2010;