Radioactive Waste Management Treatments: A Selection For The Italian Scenario

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Abstract – *The increased attention for radioactive waste management is one of the most peculiar aspects of the nuclear sector considering both reactors and not power sources. The aim of this paper is to present the state-of-art of treatments for radioactive waste management all over the world in order to derive guidelines for the radioactive waste management in the Italian scenario. Starting with an overview on the international situation, it analyses the different sources, amounts, treatments, social and economic impacts looking at countries with different industrial backgrounds, energetic policies, geography and population. It lists all these treatments and selects the most reasonable according to technical, economic and social criteria. In particular, a double scenario is discussed (to be considered in case of few quantities of nuclear waste): the use of regional, centralized, off site processing facilities, which accept waste from many nuclear plants, and the use of mobile systems, which can be transported among multiple nuclear sites for processing campaigns .At the end the treatments suitable for the Italian scenario are presented providing simplified workflows and guidelines.*

I. INTRODUCTION AND DEFINITIONS

Radioactive waste management is one of the most peculiar aspects of nuclear applications: power plants, medicine and military. Therefore, theoretical studies and practical/experimental applications of waste management are performed in many countries. This work aims to analyses the state-of-art of these studies in order to define the guidelines to manage as best as possible the nuclear waste in Italy. It starts from a wide view of all the treatments, narrowing the perspective according to (1) current availability (2) and their suitability for Italy. The paper ends providing a road map for the implementation of each treatment in Italy and general guidelines.

I.A. General Overview of Radioactive Waste Life Cycle

As the IAEA points out, the difference between pre-treatment, treatment and conditioning is country specific, but according to the IAEA Radioactive Waste Management Glossary, it is possible use the following definitions[1]:

- Pre-treatment: any operations prior to treatment, such as collection, segregation, chemical adjustment or decontamination. The main goals of pre-treatment are[2]:
    - segregate the waste into active and non-active streams in order to reduce the volume;
    - separate the active stream into components or to convert the waste into a form easy to treat.
- Treatment and conditioning processes are used to convert radioactive waste into a form that is suitable for its subsequent management, such as transportation, storage and final disposal. Therefore the main goals are:
    - minimise the volume of waste requiring treatments;
    - removal of radionuclides from the waste;
    - change of composition;
    - reduce the potential hazard of the waste by conditioning it into a stable solid form that can be safely handled during transportation, storage and final disposal.
- Conditioning: operations to produce a waste package suitable for handling, transportation, storage and/or disposal. Conditioning may include the solidification of liquid waste, enclosure of the waste in containers and their sealing. Packaging of radioactive is an important pre and post treatment operation and it has to satisfy the transport regulation[3].

It is important now to point out the meanings of two key words "Clearance" and "Exemption". According to IAEA Radioactive waste management glossary 2003:

Clearance. "*Removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory body.*"

Exemption. "*The determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure (including potential exposure) due to the source or practice is too small to warrant the application of those aspects.*"

"*Conceptually, clearance is closely linked to exemption, which means the determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure (including potential exposure) due to the source or practice is too small to warrant the application of those aspects. However, clearance can be seen as the process of relinquishing regulatory control, while exemption is the process of deciding that no regulatory control is necessary from the outset*" [4]. For exemption the threshold values[5,6] have international consensus, but these values have limited applications in terms of quantities (e.g. 1 tonne of radioactive materials), so their general application on superior amounts 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 and treatment.

I.B. Selection criteria

In order to select the best treatments three criteria have been considered:

1. Technical: according to this criterion we selected the treatments with the most proven and reliable technology. If it was possible we avoided treatments in the research, pilot and demonstration phase. In this selection we considered the peculiarities of the Italian scenario (e.g. no desert, high population density etc…).
2. Economical: According to this criterion we selected, for each type of waste, the most economical treatments among those with the same technical feasibility.
3. Social (i.e. public acceptability): The introduction of a waste management facility within a country requires public participation in order to gain public acceptance. The absence of an information program can undermine the development of a waste management facility, due to an opposition from the local community or political decision-makers. Such opposition could be avoided by involving them into the selection of site and, at a certain extent, technology. This "social approach" is the main argument of Aarhus convention[7] that ensures the availability and accessibility of information and the right for the public to be involved in a decision making process.

Table 1, in the appendix, shows the application of these criteria.

II. LITERATURE REVIEW

The literature review is organised in four main areas: (II.A) how the waste is classified (II.B) the peculiarities of the Italian scenario (II.C) how different countries (in particular European countries) deal with the nuclear waste (II.D) which treatments and strategies are available. In order to provide state-of-art road-maps and guidelines this work is based on official documents from international authorities, national waste management companies, official websites, technical reports, scientific papers, mainly of these last years. The most important are quoted in the references section.

II.A. Waste typologies

Since there are many types of waste it is useful to adopt the classification and definition from the IAEA Radioactive waste management glossary 2003.

High Level Waste, (HLW). The radioactive liquid containing most of the fission products and actinides present in spent fuel — which forms the residue from the first solvent extraction cycle in reprocessing — and some of the associated waste streams; this material following solidification; spent fuel (if it is declared a waste); or any other waste with similar radiological characteristics. Typical characteristics of HLW are thermal powers above about 2 kW/m^3 and long lived radionuclide concentrations exceeding the limitations for short lived waste.

Low and Intermediate Level Waste, (LILW). Radioactive waste with radiological characteristics between those of exempt waste and high level waste. These may be long lived waste (LILW-LL) or short lived waste (LILW-SL). Typical characteristics of LILW are activity levels above clearance levels and thermal powers below about 2 kW/m^3. Many States subdivide this class in other ways, for example into low level waste (LLW) and intermediate level waste (ILW) or medium level waste (MLW), often on the basis of waste acceptance requirements for near surface repositories.

Very Low Level Waste, (VLLW). Radioactive waste considered suitable by the regulatory body for authorized disposal, subject to specified conditions, with ordinary waste in facilities not specifically designed for radioactive waste disposal.

Conventional industry, such as food processing, chemical, steel, produces **Very Low Level Waste, (VLLW)** as a result of the concentration of natural radioactivity present in certain minerals used in their manufacturing processes. The waste is therefore disposed as standard industrial waste, although countries such as France are currently developing facilities to store VLLW in specifically designed VLLW disposal facilities[17]. There is the presence of VLLW also in more common devices as used radioactive sources, some types of lightning rod, smoke detectors, contaminated metallic scrap.

The production of electricity by nuclear reactors creates two main groups of waste: Spent Nuclear Fuel (SNF) and Decommissioning & Decontamination (D&D) waste. Nuclear Power Plants (NPPs) operation produce SNF containing more than 95% of its original energy, but with the open fuel cycle, this potential energy is wasted. There are three main approaches to SNF reuse and they change with the relative fuel cycle: thermal reactors without reprocessing, thermal reactors with reprocessing and fast reactors. A 1.000 MWe thermal reactor generates more than 100 tons of SNF a year, while a fast reactor with the same electrical capacity produce a little more than one ton of fission products, in addition to traces of Transuranic (TRU) atoms.

The other main source of waste from NPPs is the D&D phase. In this phase it is necessary to: (1) decontaminate the plant's structures in order to facilitate access to working areas and the manipulation of components and equipment; (2) reduce the radioactivity of plants and equipment to facilitate cutting and handling; (3) satisfy the standards on waste disposal or return this material to the public domain; (4) to prepare the plant's structures for transport and future management. A basic IAEA principle about waste management states "generation of radioactive waste shall be kept to the minimum practicable"[23]. It implicitly promotes reuse or recycles of waste within nuclear field and, for other less radioactive material, the removal from regulatory control ("clearance") for conventional reuse or recycling.

From medical field 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 authorized firms for the disposal. Pharmacological and biomedical research centres uses radioactive materials as tracers, normally medium-lived and long-lived nuclides with low or medium activity usually mixed with other substances.

The problem of waste management has a double aspect: if the most radioactive material i.e. HLW and SNF arises with a relative small amount, other waste i.e. Low Level Waste (LLW) and Intermediate Level Waste (ILW) has a much greater volume. For this reason, clearance and recycle[18] are key concepts concerning LLW/ILW production. The removal of LLW 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) reduces the final disposal respecting the principle "the generation of radioactive waste shall be kept to the minimum practicable".

II.B. The Italian scenario

Italy has not active commercial NPPs since the four former commercial Italian reactor are now in the D&D phase. Some research reactor is active; some other is in the D&D phase. Moreover there are other laboratories and facilities containing activated material. As preliminary inventory:

The Italian NPPs were the followings:

- Garigliano: 1 BWR (150 MWe);
- Latina: 1 MAGNOX (153 MWe);
- Trino: 1 PWR (260 MWe);
- Caorso: 1 BWR (860 MWe).

The radioactive waste inventory (not SNF) in Italy includes:

- LLW/ILW: about 25.000-28.000 m^3 currently existing and 40.000 m^3 to be produced by NPPs decommissioning;
- High Level Waste (HLW): 7.500 m^3, included the reprocessed waste from overseas. [10, 11, 12, 13]

SNF is sent overseas for reprocessing UK and in France (with the exception of some "exotic fuel"), the following amount should come back[44, 45]:

- 936,2 tons of MTHM (uranium and plutonium dioxide) before 1978 ;
- 678 tons of MTHM (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 overseas after 1978. The SNF reprocessed abroad will return in the following amounts:

- 16,6 m^3 of vitrified waste (0,074 m^3 for each ton of SNF);
- 196 m^3 of ILW/HLW cemented waste (0.871 m^3 for each ton of SNF);
- 1405,7 m^3 of LLW cemented waste (6,248 m^3 for each ton of SNF).

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 ILW/HLW;
- 6.838 m^3 of LLW.

Italy currently has no final repository for LLW/ILW and HLW generally wastes are stored temporarily on-site; medical and industrial LLW are stored in a few centres satisfying Waste Acceptance Criteria, in order to condition the wastes and to further improve their safety.

ENEA (Ente per le Nuove Tecnologie, l'Energia e l'Ambiente) initiated efforts for siting and design a national repository since the '90ties and created a Task Force, that produced a large number of studies. In 2003, in a wider effort to solve nuclear criticalities, Italian Government started a siting process, but, because of public acceptability issues the initiative cannot reach the objective. The Italian urgent need for a disposal site, at least for LILW, and the possible nuclear renaissance led current Government to restart the process. The 2 most important legislative acts are: Law 99/09. Legislative Decree 31/2010. Sogin (SOcietà Gestione Impianti Nucleari) becomes responsible for the siting, design, construction and operation of the Nuclear Technology Park where also the national repository for radioactive waste will be located. In particular the "Technology Park" should be an advanced R&D compound devoted to research activities in the field of waste management, nuclear fuel fabrication, radioprotection and associated fields. Also high level training facilities will be included to foster the nuclear field workforce. Sogin, as part of the Technology Park, designs, builds and operates the national repository for LLW/ILW and, on the same site, the interim storage for HLW. It promotes and implements extended and detailed communication campaigns and manage the licensing process for operating the storage and disposal facility may allow its start of operation between 2018 and 2020.

II.C. International overview

Respect to the Italian scenario some European countries deserve a particular attention because:

1. have similar territories (with high density and the absence of deserts)
2. some scenarios foreseen a radioactive waste disposal and/or waste processing facilities in a regional plant (in a certain country) to process the waste of that countries and its neighbourhoods[8].

However the management of radioactive waste is still a "national issue" since according to the European disposal regulation, member States would be required to establish, implement and keep updated "national programs" to manage their own wastes[9].

Other non-European countries have been analysed because of their strong nuclear infrastructure – e.g. USA and South Korea. Such countries have an important role for the development of new technologies and the implementation of well-proven treatments.

These preliminary analyses show that:

- NPPs are the main origin field for nuclear waste;
- The military (nuclear) history of a country implies a waste production having non-negligible consequences in today waste management (e.g. weapon-grade material production, reprocessing plants, navy reactors and military research laboratory).

Let's focus now on The European Countries.

Netherlands has fewer nuclear reactors than Italy with two nuclear sites (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[14,15] it can represent a good example for small amount waste management.

In **Finland** there are 4 reactors in operations: 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). Particularly relevant is the deep geological repository under construction in Olkiluoto.

More electricity is produced by nuclear fission in **Belgium**, with its 2 nuclear sites having 7 PWR total. There is a good know-how of waste management from PWR exploitation and decommissioning.

Switzerland has a nuclear fleet somehow similar to Italy**,** although with more power installed and without a MAGNOX technology. Switzerland has 4 sites and 5 reactors (3 PWRs and 2 BWRs). The amount of waste should be similar to Italy since the greater size of Swiss reactors is balanced by the Italian GCR, (i.e. the MAGNOX in Latina), producing more waste than other technologies.

More reactors are currently in operation in **Spain** (6 PWRs, 2 BWRs) and in Sweden (7 BWRs, 3 PWRs and other 2 BWRs shut-down) that involve 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.

England is another relevant country for what it concerns GCR. In operation there are 2 Magnox reactors, 14 AGR and 1 PWR. Solid low-level wastes are disposed of in the 120 ha Low Level Waste Repository (LLWR) at Drigg in Cumbria, near Sellafield, which has operated since 1959. Intermediate-level waste is stored at Sellafield and other source sites, pending disposal. High-level waste (HLW) arising from reprocessing is vitrified and stored at Sellafield, in stainless steel canisters in silos. All HLW is to be stored for 50 years before disposal, to allow cooling. There are plans to develop a deep geological repository for high and intermediate-level wastes and evolve into the entity that builds and operates it. The Geological Disposal Facility is expected to cost around £12 billion undiscounted from conception, through operation from about 2040, to closure in 2100.

In **France** there are 59 PWR in operation; 13 experimental and power reactors are being decommissioned in France, nine of them first-generation gas-cooled, graphite-moderated types, 6 being very similar to the UK Magnox type. Used fuel from the French reactors and from other countries (Italy included) is sent to Areva NC's La Hague plant in Normandy for reprocessing. The treatment extracts 99.9% of the plutonium and uranium for recycling, leaving 3% of the used fuel material as high-level waste which are vitrified and stored there for later disposal. The plutonium is immediately shipped to the 195 ton/yr Melox plant near Marcoule for prompt fabrication into about 100 tonnes of mixed-oxide (MOX) fuel, which is used in 20 of EdF's 900 MWe reactors. The authority indicated a deep geological disposal as the reference solution for high-level and long-lived radioactive waste, and sets 2015 as the target date for licensing a repository and 2025 for opening it.

II.D. Treatments and Strategies

In general LLW/ILW (with VLLW subcategory) have more available and under development treatments than HLW. For most of solid LLW generated from operations and decommissioning, the current baseline treatment technology is high-force compaction (where applicable) followed by encapsulation (by grouting) prior to disposal. The use of blasting as a pre-treatment, followed by melting, can allow a wider envelope of material to be recycled[19]. For liquid form, the current choices are for example (see Table 1 in appendix) ion-exchange techniques, alkaline hydrolysis, reverse osmosis.

Thermal treatment of waste, both solids and liquids, refers to the use of heat to stabilize and reduce the waste volume; typical examples are the incineration of VLLW/LLW, pyrolysis, plasma arc processes and melting. These processes reduce significantly the volume of waste and remove some of the volatile and hazardous components of the waste[20]. Cementation exploiting specially formulated grouts is used to immobilize sludge and precipitates/gels (flocks). In general the solid wastes are placed into containers.

Considerable quantities of waste are very difficult to incorporate in glass by vitrification. Synroc is a technology to incorporate such waste into its crystal structures; nearly all of the elements present in HLW can be processed and immobilized. In particular the waste suitable for Synroc is HLW (containing Am, Cm, Cs, Sr, Tc, Pu), rare earths, calcined waste as well as ILW [21, 22].

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 as shown in Table 1 (see appendix). An important difference for the treatments described above is the characteristic of their end product. If some processes need further treatments to adapt the end product for pre-disposal conditioning, other have as output a waste already suitable for the disposal (e.g. see Figure 2, Figure 3).

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 VLLW.

Volume reduction systems by pressure (e.g. hot isostatic pressing or compaction) it used for waste already treated. The goal is to reduce the disposal space without further treatments, whereas 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. However generally they have a large employment, although they have high capital cost.

HLW has more specific treatments suitable just for its higher radioactivity level, except for pyrolysis that, as said above, is one of the treatments with widest-range applicability, and calcination followed by vitrification, that can be used also for liquid LLW/ILW but originally developed for HLW. Vitrification produces an apt output for conditioning and then for disposal, whilst other treatments usually have the immobilisation step in their flow chart before conditioning.

In any case, final disposal recourse is unavoidable, both for LLW/ILW and HLW treatments.

III. SELECTION OF TREATMENTS

This paragraph presents a treatments selection based on economical, technical and social aspects. As stated in section I all the methods in research, pilot or demonstration phase or non-suitable with the criteria of above, are washed out although they have a good potential development for future use. The goal of this section is to present the guidelines for the judgments in Table 1, Table 2 and Table 3 (see appendix).

III.A. First selection: currently available treatments

According to the IAEA 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 first option is the use of regional, centralized, off site processing facilities that 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 that can be transported among multiple nuclear sites for processing campaigns. Typically such 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 super-compactor to recover some of the storage capacity of a ten-year accumulation of drummed and stored waste)[38].

There is a difference in terms of implementation between mobile and fixed plants. "Mobile plants" are advantageous when there isn't the possibility to move the waste to a central plant or the amount existing in a singular site doesn't validate a central implementation; generally these techniques are low-cost. "Fixed plants" (site-specific or centralized) can be chosen when the amount of the waste to be treated is large, even if the capital cost is high. According to "scope-economy" a singular plant able to create synergies in the process a set of N wastes has a relative costs for each treatment lower than N plants to treat N wastes[24,25,26,27]. Therefore the goal should be the developments of plants able to treat as many types of waste as possible. Examples of wide range treatments are incineration, drum drying or hot isostatic pressing[28,29]. Sometimes these "wide range" processes are adopted, waiting for new development of more innovative, specific, approaches. 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. In fact many specific treatments are developed and therefore currently employed. An example is 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 treaded with specific procedures are resins (pelletization), combustibles (PVA dissolution), filters (liquid cartridge filter shearing and shredding and PVA dissolution), sludge (oil solidification), oils (oil solidification, oil filtration), superabsorbent polymers, contaminated land (thermo-chemical/advanced thermo-chemical 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 a reasonable choice[30] . The advantages of this approach are (1) the flexibility and (2) the possibility to adopt new technologies as they will be developed (3) to avoid waste transportation.

On the other hand also a central facility can exploit the economy of scale. The main characteristics of these plants (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. These aspects lead to prefer a centralized waste processing plant. To compensate their capital cost, these facilities need to receive radioactive waste not only from local national nuclear sites, but also from sites in a designed regional zone (both national and international). Therefore a strong international cooperation (e.g. about studies, research...) and regulation harmonization (about radioactive waste categories, transportation) is needed. This is fundamental in Europe, where several countries in a relative small space use or have used nuclear energy.

The literature shows as the most relevant issues are related to asbestos, concrete and graphite. In these cases, also well-proven applications, such as pyrolysis or thermo-chemical treatments, are not developed for these waste typologies, because of their particularity[31,32]. HLW has several possible treatments most of them ad-hoc developed just for this kind of radioactivity levels (e.g. calcination, vitrification). The usage of these methods is spread to LLW/ILW. Other methods have a natural wide application: pyrolysis and hot isostatic pressing, are used for HLW and LLW/ILW [33, 34]. Partitioning and transmutation are the most innovative and potentially the best HLW management techniques, but their ideal adoption requires an advanced fuel cycle that is not currently developed[37]. They are the only treatments that can reduce the radiotoxicity of HLW and, therefore, its confinement time.

Widely used immobilization methods, suitable for LLW/ILW as well as HLW, such as cementation, compaction, Synroc (more recent) and vitrification, are considered because of their suitability for many waste feeds. Even if a treatment can be theoretically applied to different waste, it might be not the suitable method for all of these. Complete dissolution, chemical separation and corrosion facilities do not currently exist on a significant scale whereas 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[23]. The results of this analysis are reported in appendix and integrate the contribution form an ENEA document[43].

IV. RESULTS: FEASIBILITY FOR ITALY

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. For what it concerns back-end operations, just interim storage and disposal (vitrified waste disposal) are important since reprocessing and vitrification are currently operated abroad. This is not a negligible aspect: one of the main activities generating liquid HLW is SNF reprocessing. Therefore even if sending abroad SNF for reprocessing is costly, there is the advantage of dealing with only vitrified HLW.

Besides SNF, metals and concrete account for most of the waste. These two waste streams have a 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. The development of the guidelines for managing the Italian has to be specific for the Italian scenario since consider:

- waste typologies effectively existing in Italy;
- amount of waste.

Starting from these evidences and the literature review Table 1 provides the main set of results: the linkages between Wastes and Treatments suitable for the Italian scenario. This table presents a taxonomy of the nuclear waste bases on its specific state (liquids, resins etc…). Than for each waste are presented all the possible treatments, their implementation strategies and, according to the criteria in section I.B, Strengths and Weaknesses.

In order to show the "economy of scope" and "economy of scale" synergies discussed in III.A

Table 2 present the linkage between all the waste and the treatments. From this table is clear as Incineration and Pyrolysis are among the most interesting options. Table 3 select for all the nuclear waste the suitable treatments.

More details about the possible implementation of each treatment are provided by ad-hoc flow charts. Figure 1, Figure 2 and Figure 3 are example of these flow charts (all the other road-maps are available upon request). These flow charts show for each waste the suitable treatments, the end products, and the relative immobilization options before the storage/disposal[43]. Indeed some methods need further treatments if their end-product is not suitable for storage or disposal.

V. CONCLUSIONS

Dealing with nuclear waste is a fundamental responsibility that each country with nuclear reactors needs to face. Today, even if there is not a definitive solution, many options are available and more under development. Therefore a reasonable strategy can be the waste immobilisation and storage for future treatments. This solution is particular suitable for HLW, whereas LLW already have some treatments able to handle these waste.

Italy needs to treat and dispose its nuclear waste. Most of such waste comes from the Italian reactors and facilities, now in the decommissioning phase. Even if there have been only 4 commercial reactors the amount of waste is not negligible. Since such waste has been (1) sent abroad and therefore will come back and (2) stored in aging facilities, it is important to define a strategy do deal with this issue. In particular a critical point is the management of waste such as concrete, arising in large amount, which have not current available treatments. The other critical waste types are graphite and asbestos, but with less impact in Italy due to their amount. The SNF represents an issue mainly for what it concerns it storage. We think that the following guidelines should be applied for the Italian scenario:

1. Continue the policy of sending abroad the waste for reprocessing: this allow taking advantage from the facilities and know-how of countries like UK and France.
2. Develop feasibility studies to assess the opportunity to exploit "mobile plants".
3. Collaborate in research projects to develop methodologies to reprocess the critical waste as graphite and asbestos.
4. Design and start the process for the construction of the final repository.

This later point seems the most critical. The previous project failed because of public acceptability. Engineers, physics and policy makers have to collaborate together to explain to the population the reasons beyond the construction of such facility, its safety and the potential benefits for the local community. The recent experiences in Finland and Sweden represent very good references.

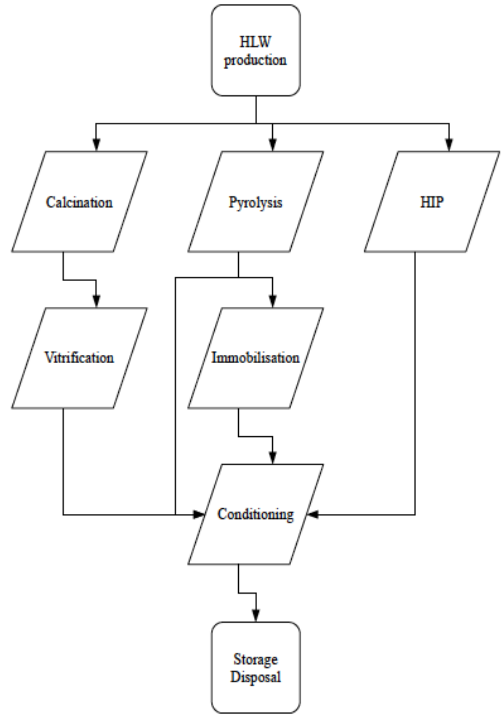

Figure 1: Diagram of processes for HLW

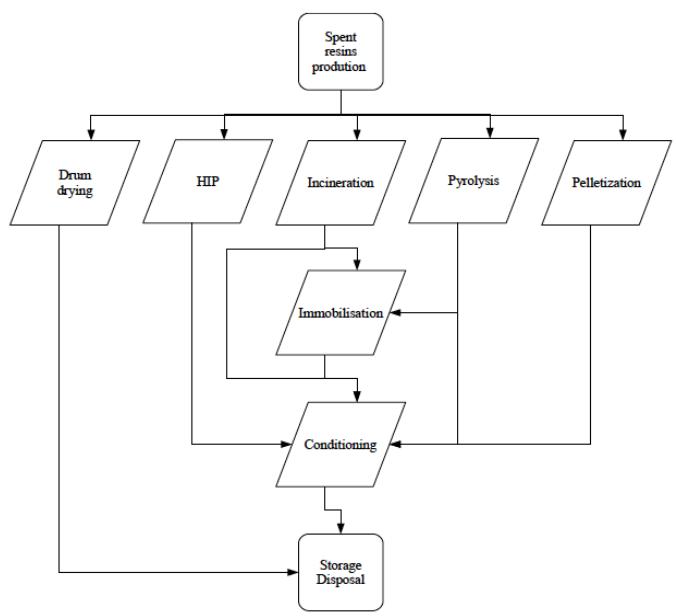

Figure 2: Diagram of processes for spent resins

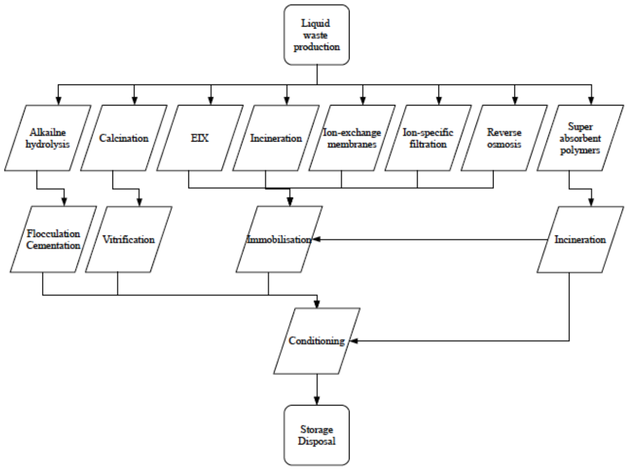

Figure 3: Diagram of processes for liquid waste

NOMENCLATURE

AGR: Advanced Gas Reactor
BWR: Boiling Water Reactor
D&D: Decontamination and Decommissioning
EDF: Electricité de France
EIX: Electrochemical Ion Exchange
ENEA: Ente per le Nuove Tecnologie e l'Ambiente
GCR: Gas Cooled Reactor
HLW: High Level Waste
HTGR: High Temperature Gas Reactor
HWGCR: Heavy Water Gas Cooled Reactor
IAEA: International Atomic Energy Agency
ILW: Intermediate Level Waste
LL: Long Lived
LLW: Low Level Waste
NPP: Nuclear Power Plant
MAGNOX: Magnesium Non-Oxidising
MWe: Mega Watt Electrical
MTHM: Metric Ton of Heavy Metal
MOX: Mixed Oxide Fuel
NDA: Nuclear Decommissioning Authority
NEA: Nuclear Energy Agency
PVA: PolyVinyl Alcohol
PWR: Pressurised Water Reactor
R&D: Research and Development
SL: Short Lived
SNF: Spent Nuclear Fuel
TRU: Transuranic
UNGG: Uranium Naturel Gaz Graphite
VLLW: Very Low Level Waste
VVER: Vodo-Vodyanoi Energetichesky Reactor
WNA: World Nuclear Association

REFERENCES

1. IAEA, *Innovative waste treatment and conditioning technologies at nuclear power plants*, TECDOC-1504, p. 27 (2006).
2. IAEA, *Selection of efficient options for processing and storage of radioactive waste in countries with small amounts of waste generation*, TECDOC-1371, p. 22 (2003).
3. IAEA, *Selection of efficient options for processing and storage of radioactive waste in countries with small amounts of waste generation*, TECDOC-1371, p. 23, 24 (2003).
4. NEA, *Release of Radioactive Materials and Buildings from Regulatory Control*, p. 9 (2008).
5. International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources.
6. Directive 96/29/Euratom.
7. United Nations Economic Commission For Europe, *Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters, Aarhus, Denmark*, (1998).
8. IAEA, *Innovative waste treatment and conditioning technologies at nuclear power plants*, TECDOC-1504, p. 4, 5 (2006).
9. European Foundation, http://www.europeanfoundation.org/my_weblog/2010/11/brussels-tointerfere-with-radioactive-waste-disposal.html, (2011).
10. R. Bove et al., *Revisione critica dell'inventario nazionale dei rifiuti radioattivi ai fini dello smaltimento*, ENEA, Ministero dell Sviluppo Economico, p. 10, 21 (2009).
11. A. Taglioni, *Radioactive Wastes: from an Emotional Approach to a Rational Evaluation*, p. 6 ENEA, (2010).
12. ENEA,http://www.enea.it/focus-fissione-nucleare/situazione-italia.html, (2011).
13. EnergyLab Foundation, *Rapporto preliminare sulle condizioni per il ritorno all'energia elettronucleare in Italia*, p. 143, 144 (2010).
14. COVRA, *Radioactive waste management in the Netherlands: a practical solution in full operation*, p. 3.
15. NEA, *Radioactive waste management programmes in OECD/NEA member countries. Netherlands*, p. 2 (2008).
16. WNA, *Radioactive Waste Management*, p. 50 (2009).
17. WNA, *Radioactive Waste Management*, p. 1 (2009).
18. NEA, *Release of Radioactive Materials and Buildings from Regulatory Control*, p. 9 (2008).
19. NDA/LLW Repository Ltd., *LLW Repository: LLW Strategic Review*, p. 51, 77, 83, 190, 192 (2009).
20. NDA, *UK Strategy for the Management of Solid Low Level Radioactive Waste from the Nuclear Industry*, p. 24 (2010).
21. WNA, *Synroc waste form*, p. 8, 23, 30, 37 (2010).
22. IAEA, *New Developments and Improvements in Processing of 'Problematic' Radioactive Waste*, TECDOC-1579, p. 1, 5 (2007).
23. NDA/LLW Repository Ltd., *LLW Repository Compendium of Strategic Technical Briefs Volume 1*, NLWS/LLWR/04, p. 134 (2009).
24. NDA/LLW Repository Ltd., *LLW Repository Compendium of Strategic Technical Briefs Volume 1*, NLWS/LLWR/04, p. 75 (2009).
25. IAEA, *Innovative waste treatment and conditioning technologies at nuclear power plants*, TECDOC-1504, p. 27 (2006).
26. IAEA, *Application of Thermal Technologies for Processing of Radioactive Waste*, TECDOC-1527, p. 30-37 (2006).
27. IAEA, *Predisposal Management of Organic Radioactive Waste*, TECHNICAL REPORTS SERIES N. 427, p. 44, 45 (2004).
28. IAEA, *Innovative waste treatment and conditioning technologies at nuclear power plants*, TECDOC-1504, p. 27 (2006).
29. NDA/LLW Repository Ltd., *LLW Repository Compendium of Strategic Technical Briefs Volume 1*, NLWS/LLWR/04, p. 71-74 (2009).
30. IAEA, *Innovative waste treatment and conditioning technologies at nuclear power plants*, TECDOC-1504, p. 27 (2006).
31. IAEA, *Application of Thermal Technologies for Processing of Radioactive Waste*, TECDOC-1527, p. 33, 37 (2006).
32. J.B. Mason, D. Bradbury, *Pyrolysis and its potential use in nuclear graphite disposal*, p. 8, IAEA (2006).
33. IAEA, *Innovative waste treatment and conditioning technologies at nuclear power plants*, TECDOC-1504, p. 27 (2006).
34. IAEA, *Application of Thermal Technologies for Processing of Radioactive Waste*, TECDOC-1527, p. 33, 37 (2006).
35. IAEA, *Application of Ion Exchange Processes for the Treatment of Radioactive Waste and Management of Spent Ion Exchangers*, TECHNICAL REPORTS SERIES N. 408, p. 58 (2002).
36. Mikael Höök, *Partitioning and transmutation*, Global Energy Systems,p. 3 (2008).
37. IAEA, *Innovative waste treatment and conditioning technologies at nuclear power plants*, TECDOC-1504, p. 27 (2006).
38. IAEA, *Selection of efficient options for processing and storage of radioactive waste in countries with small amounts of waste generation*, TECDOC-1371, p. 37 (2003).
39. IAEA, *Innovative waste treatment and conditioning technologies at nuclear power plants*, TECDOC-1504, p. 27 (2006).
40. IAEA, *Application of Thermal Technologies for Processing of Radioactive Waste*, TECDOC-1527, p. 12-70 (2006).
41. IAEA, *Application of Ion Exchange Processes for the Treatment of Radioactive Waste and Management of Spent Ion Exchangers*, TECHNICAL REPORTS SERIES N. 408, p. 37, 38, 49-55, 62-65 (2002).
42. IAEA, *Predisposal Management of Organic Radioactive Waste*, TECHNICAL REPORTS SERIES N. 427, p. 21-69 *(2004).*
43. R. Bove et al., *Revisione critica dell'inventario nazionale dei rifiuti radioattivi ai fini dello smaltimento, ENEA, Ministero dello Sviluppo Economico*, p. 10-14, 523-625 (2009).
44. R. Bove et al., *"Revisione critica dell'inventario nazionale dei rifiuti radioattivi ai fini dello smaltimento", ENEA, Ministero dell Sviluppo Economico*, p. 18-20 (2009).
45. APAT, *"Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management",* p. 12 (2006);.

APPENDIX

Table 1: Selection of treatments with their implementation (L: Local; C: Central; M: Mobile)

TREATMENT	IMPL.	NOTES
Liquids		
Advanced oxidation processes		Pilot scale
Alkaline hydrolysis	L, C, M	SNF solvents; limited application with organics
Biological treatment		Pilot scale
Calcination	L, C	Low to medium cost
Direct chemical oxidation		Development phase
EIX	L, C, M	Recently developed
Incineration	C	Adapt to large scale; Low public acceptance; High cost
Ion exchange membranes	L, C, M	High cost
Ion-specific filtration	L, C, M	Innovative technology
Membrane filtration		Innovative technology; Not widely used
Molten metal		Wide use only in Japan
Plasma arc		Limited full-scale experience with LLW; High cost
Reverse osmosis	L, C, M	Low cost
Super absorbent polymers	L, C, M	
Supercritical water oxidation		Pilot scale
Thermochemical conversion		Development phase
Vitrification	C	Post-calcination Suitable for HLW
WETOX		Pilot scale
Resins		
Acid digestion		Expensive materials
Thermochemical/ Advanced thermochemical process		No broad implementation
Biological treatment		Pilot scale
Cold crucible vitrification		Development phase
Drum drying	L, C, M	
Geopolymerization		Research phase
Hot isostatic pressing	C	
Incineration	C	High cost; Low public acceptance
Microwave treatment		Demonstration phase
Molten metal		Wide use only in Japan
Molten salt oxidation		Development phase; High cost
Pelletization	C, L	
Plasma arc		Limited full-scale experience with LLW; High cost
Pyrolysis	L, C	High cost; Often applied to ILW; Good public acceptance; Limited application with inorganic materials
Supercritical water oxidation		Pilot scale
Thermochemical conversion		Development phase
WETOX		Not in commercial use; High maintenance
Combustible waste		
Cold crucible vitrification		Development phase
High temperature incineration		Used in Japan; High cost; Very sensitive to waste feed
Incineration	C	High cost; Low public acceptance
Molten metal		Wide use only in Japan
Plasma arc		Limited full-scale experience with LLW; High cost
PVA dissolution	L, C	Relative low cost
Pyrolysis	L, C	High cost; Not suitable for combustible LLW; Good public acceptance
Thermochemical conversion		Development phase
Filters		
Cold crucible vitrification		Development phase
Drum drying		Not suitable for filters
High temperature incineration		Used in Japan; High cost; Very sensitive to waste feed
Incineration	C	High cost; Low public acceptance
Liquid cartridge filter shearing and shredding	L, C, M	Low cost
Molten metal		Wide use only in Japan
Plasma arc		Limited full-scale experience with LLW
PVA dissolution	L, C	Relative low cost
Pyrolysis	L, C	Suitable for powder or granular form; Good public acceptance
Supercritical water oxidation		Pilot scale
Evaporator Concentrates		
Cold crucible vitrification	L, C	High cost
Crystallization	L	High cost
Drum drying	L, C, M	Low cost
Hydrothermal treatment		Pilot scale
Liquid concentrates volume reduction system		New technology developed in Hungary
Pelletization	L	
Ashes		
Cold crucible vitrification		Development phase
Geopolymerization		Research phase
Molten metal		Wide use only in Japan
Pelletization	L, C	
Plasma arc		Limited full-scale experience with LLW
Plastic Waste		
Thermochemical/ Advanced thermochemical process		No broad implementation
Incineration	C	High cost; Low public acceptance
Melt densification		Development phase
Microwave treatment		Demonstration phase
Pyrolysis	L, C	High cost; Suitable for powder or granular form; Good public acceptance
Sludge		
Drum drying	L, C, M	Low cost
Geopolymerization		Research phase
Hot isostatic pressing	C	
Microwave treatment		Demonstration phase
Oil solidification	L, C, M	
Oils		
Incineration	C	High cost; Low public acceptance
Oil filtration	L, C, M	Economical only in case of large volume to be treated
Oil solidification	L, C, M	
Super absorbent polymers	L, C, M	Low cost

Thermochemical conversion		Development phase
Contaminated Land		
Thermochemical/ Advanced thermochemical process	L	In development phase, but used for organic surfaces
EIX		Recently developed but for coolant and liquid effluent
Phytoremediation, phytostabilization		Research phase
Plasma arc		Limited full-scale experience with LLW; High cost
Pyrolysis	L, C	High cost; Good public acceptance; Limited experience with inorganics
Metals		
High temperature incineration		Used in Japan; High cost; Very sensitive to waste feed
Incineration	C	High cost; Low public acceptance
Molten metal		Wide use only in Japan
Plasma arc		Limited full-scale experience with LLW; High cost
Pyrolysis	L, C	High cost; Good public acceptance; More suitable for ILW;
Asbestos		
Molten metal		Wide use only in Japan
Plasma arc		Limited full-scale experience with LLW; High cost
Thermochemical conversion		Development phase
Vitrification		Suitable for HLW
Concrete		
High temperature incineration		Used in Japan; High cost; Very sensitive to waste feed
Molten metal		Wide use only in Japan
Plasma arc		Limited full-scale experience with LLW; High cost
Thermochemical/ Advanced thermochemical process		No broad implementation
Graphite		
Incineration		Research phase
Pyrolysis		Limited experience
Thermochemical/ Advanced thermochemical process		No broad implementation
Evaporator Bottom		
Hot isostatic pressing	C	
Drum drying	L, C, M	Low cost
HLW		
Calcination	L, C	Low to medium cost
Hot isostatic pressing	C	
P&T		Development phase
Pyrolysis	L, C	High cost
Vitrification	L, C	High cost

Table 2: Coupling Waste-Treatment suitable for Italy

	Asbestos	Ash	Concrete	Contaminated land	Evap. concentrates	Filters	Graphite	Liquid HLW	Liquids	Metals	Olis	Plastics	Sources	Resins	Sludge	U-waste
Alkaline Hydrolysis									X							
Calcination								X	X							
CCV					X											
Crystalization					X											
Drum Drying					X									X	X	
EIX									X							
HIP														X	X	
Incineration						X			X	X	X	X		X		
Ion-specific Filtration									X							
IX Membranes									X							
Liquid Cartridge shearing/shredding						X										
Oil Filtration											X					
Oil Solidification											X				X	
Pelletization		X			X									X		
PVA dissolution						X										
Pyrolysis						X		X		X		X		X		
Reverse Osmosis									X							
Super-abs polymers									X		X					
Thermochemical Adv. Thermochemical				X												
Vitrification								X								

Table 3:
Treatments according to waste feed existing in Italy

Waste stream	Treatment under development
Asbestos	Treatments under development
Ash	Pellettization
Contaminated land	Treatments under development
Evaporator concentrates	Cold crucible vitrification; Crystallization; Drum Drying; Pellettization
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
Plastic waste	Incineration; Pyrolysis
Radioactive sources	Conditioning (grouting, cementation) or decay for those ones with half-life < 100 d.
Resins	Drum drying; Hot isostatic pressing; Incineration; Pellettization; Pyrolysis
Sludge	Drum drying; Hot isostatic pressing; Oil solidification
Uranium waste	For U-contaminated metals: Immobilization; Minimisation/Recycling