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Recycle and reuse of materials and components from waste streams of nuclear fuel cycle facilities

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RECYCLE AND REUSE OF MATERIALS AND COMPONENTS FROM WASTE STREAMS OF NUCLEAR FUEL CYCLE FACILITIES
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FOREWORD

All nuclear fuel cycle processes utilize a wide range of equipment and materials to produce the final products they are designed for. However, as at any other industrial facility, during operation of the nuclear fuel cycle facilities, apart from the main products some byproducts, spent materials and waste are generated. A lot of these materials, byproducts or some components of waste have a potential value and may be recycled within the original process or reused outside either directly or after appropriate treatment.

The issue of recycle and reuse of valuable material is important for all industries including the nuclear fuel cycle. The level of different materials involvement and opportunities for their recycle and reuse in nuclear industry are different at different stages of nuclear fuel cycle activity, generally increasing from the front end to the back end processes and decommissioning. Minimization of waste arisings and the practice of recycle and reuse can improve process economics and can minimize the potential environmental impact.

Recognizing the importance of this subject, the International Atomic Energy Agency initiated the preparation of this report aiming to review and summarize the information on the existing recycling and reuse practice for both radioactive and non-radioactive components of waste streams at nuclear fuel cycle facilities. This report analyses the existing options, approaches and developments in recycle and reuse in nuclear industry.

The initial draft of this report was prepared by the Secretariat with the assistance of external consultants. The initial draft was then discussed and revised at a Technical Committee meeting and three consultants meetings. The IAEA wishes to express its thanks to all those who took part in the drafting and revision of this report. The IAEA officers responsible for preparation of the report were A.F. Tsarenko and V.M. Efremenkov of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Nuclear fuel cycle facilities generate, at all stages of their life ranging from operation, maintenance and modification through to decommissioning, a number of arisings (byproducts, spent and abundant process materials, plant components and equipment, etc.) that are classified as wastes and which may be contaminated with radionuclides. These arisings, regardless of their potential value, must be properly managed to ensure that the whole fuel cycle is as cost effective as possible and the environmental impact is minimized.

Recognizing that waste minimization is an integral part of a comprehensive waste management strategy, this has been the subject of a number of important reviews. Minimization of radioactive waste from nuclear power plants and the back end of the nuclear fuel cycle was the subject of an IAEA report published in 1995 [1]. Minimization of waste from uranium purification, enrichment and fuel fabrication (back end of the nuclear fuel cycle) and waste from decontamination and decommissioning of nuclear facilities were covered in companion publications [2, 3]. Some of the factors influencing the selection of recycle and reuse for the minimization of decommissioning waste were also considered in an IAEA report published in 1988 [4] and the related principles for exemption from regulatory control were developed in Ref. [5].

An important element of waste minimization is recycle and reuse of valuable materials from potential waste streams. Recycle and reuse practices have been widely implemented in several nuclear fuel cycle processes since the early days of the commercial use of nuclear power. The economic advantages, coupled with reduced environmental impact and consideration of full cycle benefits, could provide a sound incentive to recycle and reuse.

1.2. OBJECTIVES

The purpose of this report is to review the available information related to recycle and reuse of radioactive and non-radioactive components of potential waste streams at nuclear fuel cycle facilities. The report is intended to provide Member States with an objective assessment of the potential opportunities for recycle and reuse and give information concerning various recycle and reuse options that have been utilized to date. The purpose of the report is to aid, rather than to prescribe, the decision making process for employment of recycle and reuse options as part of national, site or plant specific waste management policies and strategies.

The primary objectives of the report may be described as follows:

- To contribute to improvements in the efficiency of the overall nuclear fuel cycle;
- To assist Member States in improving current waste management practices with respect to recycle and reuse of process materials and plant components;
- To present the current status of recycle and reuse and the related issues involved in implementation of such practices;
- To discuss important criteria related to recycle and reuse.

1.3. SCOPE

The description of recycle and reuse in this report covers the main fuel cycle components, including refining uranium ore concentrate (or yellow cake), conversion-enrichment-reconversion of uranium, fuel fabrication, operation of nuclear power plants, reprocessing of irradiated fuel, operation of centralized (large scale) waste treatment facilities, and decommissioning of nuclear facilities. In view of the volume of materials involved, the assessment of recycle and reuse also covers so called “historic wastes”, or waste from the previous activities, which is stored at temporary facilities. The report also discusses methodologies for evaluating whether recycle and reuse is a feasible option for the disposition of materials, one that Member States might adopt.

Recycle and reuse of fissile material in fuel has been the subject of other extensive reviews and discussions [6, 7]. The use of uranium and plutonium recovered from irradiated fuel for production of mixed oxide fuels for thermal or fast neutron reactors is not considered in this report, nor are they widely considered as wastes. In addition there are fuel cycles based on thorium, but the thorium cycle represents a relatively small contributor to overall energy productions and thus also is not considered in the report.

A further exception, implied by the title of the report, is that all waste originating from beyond the nuclear fuel cycle is not addressed. An example of this is naturally occurring radioactive materials (NORM), such as oil field piping contaminated with natural radioactive scale (radium). However, the options and principles of recycle and reuse described in this report may be applied to materials contaminated by NORM or to other non-fuel cycle radioactive materials (e.g. waste from different nuclear applications) and thus may provide guidance to owners of such materials or waste.

Partition and transmutation (P&T) is also being considered as a potential waste minimization strategy [8] to reduce the inventory of long lived radionuclides in waste. However, P&T is not generally considered as a recycle and reuse opportunity except in the context of reuse of uranium and plutonium in MOX fuel.

1.4. STRUCTURE OF THE REPORT

The report consists of 12 sections. Following this introductory section, Section 2 provides general description of nuclear fuel cycle, options for waste minimization and indicates the role of recycle and reuse in waste minimization.

The bulk of the report is made up of examples and discussion of recycle and reuse opportunities across the nuclear fuel cycle (Sections 3 to 10). Against particular activities in the fuel cycle the report is divided in this way to accommodate Member States who participate in some, but not all, of the stages of the nuclear fuel cycle.

Section 11 presents some of the criteria that will aid in the consideration of options for the disposition of arisings, which allow an evaluation of the practicability of recycle and reuse in order to decide whether to deploy this practice. This section also includes discussion of methodologies by which option selection may be carried out. It should be noted that Member States should select a methodology and prioritize criteria that most closely suit their own requirements. The conclusions of the report summarize how the objectives of the report have been addressed.

2. NUCLEAR FUEL CYCLE AND WASTE MINIMIZATION OPTIONS

2.1. NUCLEAR FUEL CYCLE

There are two nuclear fuel cycle concepts. The first is the open fuel cycle, where the fuel material makes a once through passage from uranium ore to disposal of the irradiated fuel. The second is the closed fuel cycle in which fissile material is recovered from the irradiated fuel and re-utilized for the new fuel fabrication. The main difference between the open and closed cycle lies in the reprocessing of irradiated fuel and use of recovered fissile materials in a new fuel.

There are two distinct fuel cycles in existence worldwide, the most important is based on uranium and plutonium, which can be recovered and reused in either thermal or fast neutron reactors, while the second, much less common cycle, is based on thorium. An example of the latter is a small experimental test reactor (MINI) in India based on ^{233}U fuel which has recently been made critical. The ^{233}U in this reactor has been recovered from the reprocessing of irradiated fertile thorium fuel elements [9].

National need or policy dictates to Member States whether the closed or open nuclear fuel cycle is practiced. The front end activities are common to both open and closed cycles and include:

- refining of mined uranium,
- conversion of the uranium to fuel material (metal or oxide), or
- conversion to uranium hexafluoride for enrichment if required and subsequent reconversion to fuel material,
- fabrication into fuel for utilization in power plant.

Both cycles (open and closed) involve handling and storage of irradiated fuel, and both cycles require decommissioning of facilities after the end of their operating lifetime and treatment of arisings prior to disposal of the residual materials as waste. In open and closed nuclear fuel cycles the scope and challenge of waste management is different principally by virtue of reprocessing and handling of the plutonium product in the closed cycle. Nonetheless in all manifestations of the fuel cycle and its component parts, recycle and reuse of valuable materials and components ensure efficient use of materials and resources. The components of contaminated material flow in the closed nuclear fuel cycle are shown in Fig. 1.

A major activity in the nuclear industry, in terms of both cost and volumes of materials is the treatment of historic waste (i.e. stored waste or waste in unsatisfactory disposal facilities). Treatment of historic wastes may also represent a significant recycle and reuse opportunity.

2.2. WASTE MINIMIZATION OPTIONS

As it was indicated in the Introduction, waste minimization is recognized as an integral part of a responsible waste management strategy [1–4]. Considerable efforts are underway worldwide to reduce the volume of waste from different processes in the nuclear fuel cycle. The main elements of waste minimization and volume reduction are shown in Fig. 2 [1] and include:

– Source reduction, both volume reduction and prevention of contamination;
– Recycle and reuse of valuable materials from waste streams;
– Optimization of waste processing.

This report addresses one of these elements, namely recycle and reuse, across the entire nuclear fuel cycle.

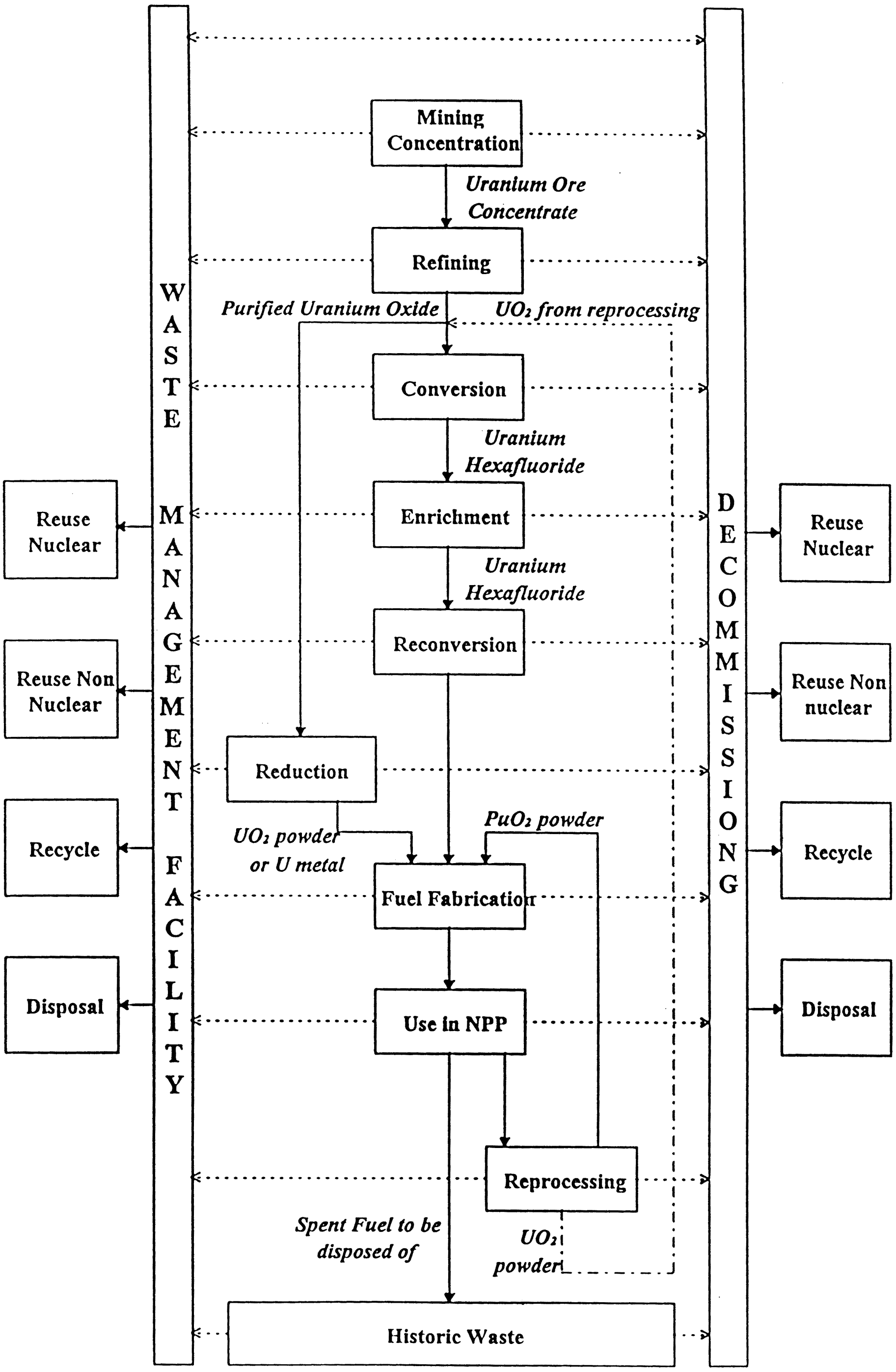

FIG. 1. Depiction of the nuclear fuel cycle based on contaminated material flow.

Fig. 2. Elements of waste minimization.

The applicability of recycle and reuse options in the nuclear fuel cycle are determined by consideration of a very wide range of factors. These are discussed in some details in Section 12 of this report but may include factors such as:

- Availability of appropriate clearance/release criteria;
- Consideration of cost;
- Technical feasibility;
- National waste management policy and strategy;
- Public acceptance of recycle and reuse options.

The inter-relationship between these criteria is complex, and as yet recycle and reuse is not always selected as a way of dealing with waste or contaminated materials. However, a series of projects that demonstrate the opportunity presented by recycle and reuse are referred to details in the following sections.

Many definitions of terms related to waste safety and waste technology are now in the process of discussion by the IAEA and Member States for their clarification and agreement, so several terms and their interpretation in this report may be changed or modified in the future IAEA publications. For the purpose of this report r*ecycling* is defined as the reutilization of materials and equipment for their original purpose in the original form or after being treated or reworked [3]. An example of recycling is recovery of nitric acid from the gaseous arisings (NO_x) at a reprocessing facilities, from metal or oxide dissolution processes and returning that acid to the original dissolution stage.

Reuse is defined as reutilization of materials and equipment again in their original form or after being treated or reworked for purposes different to their original use [3]. Reuse can be applied to return of material to the nuclear fuel cycle, for example, the use of lightly contaminated metal scrap from decommissioning of nuclear facilities to fabricate waste containers. Reuse can also be applied to material that is used outside the nuclear fuel cycle.

The concept of reuse of materials and equipment may involve two categories of release from regulatory control:

Unrestricted release, or clearance, is referred to as "… a designation, by the regulatory body in a country or state, that enable the release or use of equipment, materials buildings or site without radiological restriction" [10]. The term *clearance* is often used to mean the removal of restrictions from materials which, before clearance, are a part of sources and practices that are subject to notification and authorization requirements. The general concept of clearance from regulatory control implies a complete removal of control to the extent that cleared material is treated as if it is not radioactive. By this definition, the subject material is distinguished from sources of radiation that are never subject to regulatory requirements. These sources are said to have been *exempted* from the requirements of national regulations. Examples of sources which could be exempt from regulatory control include tracers used in research, calibration sources, and some consumer products that contain small sources (e.g. smoke detectors).

Alternatively, the potential uses of material after clearance my be restricted in some way. If the fate of material being considered is known, clearance levels can be derived based on a limited number of exposure routes that must be considered. Moreover, site specific data and realistic assumptions can be introduced in the dose calculations. As a result, release requirements that are less restrictive than those required for unconditional use might now be applied. This type of situation is called r*estricted release or restricted clearance*. For example, during decommissioning or routine maintenance of nuclear facilities, discrete pieces of contaminated equipment can be cleaned such that restricted reuse in the nuclear industry might be permitted. Contaminated equipment could include tools, motors, pumps, tanks and containers. Rooms with fixed equipment, in the same way, might be adequately cleaned to allow further activities involving radioactive substances.

Interpretation of other special terms used in the report is derived from the IAEA Radioactive Waste Management Glossary [10] and the report is consistent with the concepts introduced in the earlier IAEA publications [1–3].

3. REFINING OF URANIUM

The refining process takes uranium ore concentrate (UOC or yellow cake), and converts it to a form of appropriate purity for use as uranium oxide or for further conversion to uranium hexafluoride. The refining process options and outputs are depicted in Fig. 3.

3.1. PROCESS DESCRIPTION

The detailed process stages are described elsewhere [11] but may be summarized as:

- Dissolution of the UOC in nitric acid (HNO_3);
- Solvent extraction of uranyl nitrate using Tributylphosphate (TBP), with an alkaline diluent to remove impurities such as thorium;
- Uranium oxide formation via one of the following methods:
  - Thermal denitration of uranyl nitrate to uranium trioxide, UO_3 (TDN process);
  - Precipitation as ammonium diuranate by reaction with NH_3 or NH_4OH followed by calcination to UO_3 (ADU process);
  - Precipitation as ammonium uranyl carbonate followed by calcination under hydrogen (H_2) to give uranium dioxide, UO_2 (AUC process).

3.2. MATERIALS USED IN THE PROCESS

Materials fed to the process are:

- Drums for UOC transportation;
- Nitric acid for dissolution of yellow cake;
- Solvent (TBP plus diluent) for extraction;
- Caustic solution for raffinate neutralization and uranium recovery;
- Ammonia for precipitation (ADU and AUC);
- Carbon dioxide (CO_2), to precipitate ammonium uranyl carbonate (AUC);
- H_2 as a reductant in the AUC process.

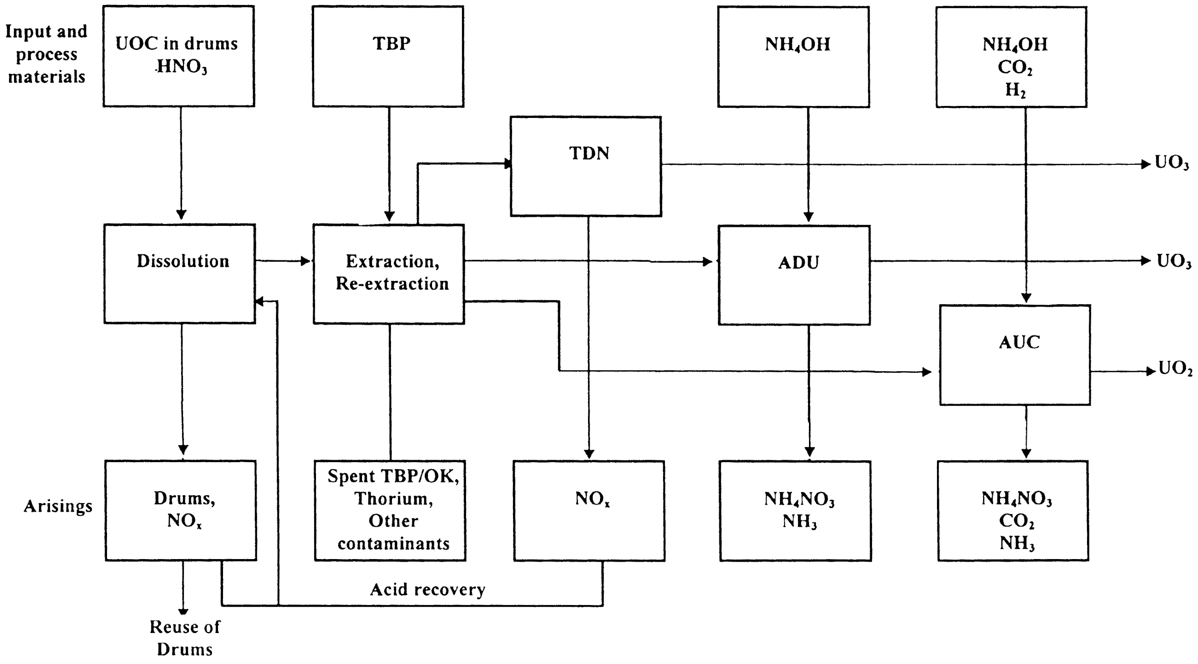

FIG. 3. Refining material flow.

3.3. PROCESS ARISINGS AND OPTIONS FOR RECYCLE AND REUSE

At the refining stage apart from oxides of uranium produced for direct use or suitable for fluorination some other by-products and waste are generated:

- Nitrogen oxides (NO_X);
- Spent solvent (TBP and diluent);
- Ammonia and ammonium nitrate;
- Sodium nitrate;
- Contaminated UOC drums;
- Thorium and other UOC contaminants.

Where economical these materials are already recovered for recycle and reuse, for example the recycle/reuse of UOC drums, recovery and recycling of nitric acid and TBP, free release for reuse of sodium and ammonium nitrate solutions, etc. Many of the additional arisings are of relatively low value or have low environmental impact when disposed of (e.g. sludges and filters), and do not economically justify their recycle and reuse. An exception to this is thorium and some other waste components that are recovered from waste following the purification process. Thorium may be used in alternative fuel cycles [12] but this possibility is not explored in this report. An imaginative attempt to define an opportunity to use these materials would contribute to waste minimization for refining process, for example new, non-nuclear uses for thorium.

Some particular examples of recovery of materials for recycle and reuse are described below.

Nitric acid recovery

Nitrogen oxide gases (referred to as NO_x) are produced at each process stage. The NO_x is removed by a scrubber and the dilute nitric acid solutions produced by the scrubber are recycled to the dissolution process.

TBP recovery

Over time, the TBP solution used in the solvent-extraction process gradually degrades due to hydrolysis, oxidation and polymerization in the aqueous phase. To maintain the quality of the TBP solvent and to avoid formation of interfacial cruds, a small stream of solvent is withdrawn from the process. This TBP stream is then treated with a sodium carbonate solution to neutralize it and precipitate the high molecular weight organic impurities, and the TBP solution is returned to the process. In the Nuclear Fuel Complex, India, the interfacial cruds from solvent extraction are treated with HF. The recovered dilute TBP free of fluoride is returned to the process [12].

Ammonium nitrate and sodium nitrate recovery

The main waste stream arises from the purification stage and consists of the aqueous acid phase from which uranyl nitrate has been extracted by TBP. This very complex solution (it contains alkali metals, alkaline earths, transition group metals, sulfates, chlorides, silica, etc.) is neutralized with lime. The resulting sludge is allowed to settle. The decanted product has no use but the decantate that is rich in nitrates of alkalines and alkaline earths, has a good fertilizing potential (its uranium content is under 1 ppm). Nevertheless, this potential is not always exploited. In some countries, for example, in India, the high content of the above mentioned salts and large volume of effluent have commercial sale value.

Drum decontamination

Steel drums used for transportation of UOC are treated by different ways depending on their conditions. Drums found to be in good condition after emptying are returned to the ore concentrate suppliers for recycle where economically feasible. In India the drums are not only returned to the supplier but are also returned filled with a precipitate of uranyl nitrate raffinate cake (UNRC) arising from the refining of yellow cake, so it can be treated for uranium recovery.

Drums which cannot be recycled, either due to their condition or because it is economically not justified, are treated as waste. The drums may be washed and the recovered uranium returned to the process. The drums are then checked for contamination and either consigned, after size reduction (cutting the base first and then crushing), to low level waste disposal, or sent to a metal treatment facility for free release or reworking into lightly contaminated artifacts following appropriate certification (reuse of metal).

Ammonia

Although ammonia as ammonium hydroxide could be recovered and recycled in the precipitation process there is no current practice for its recovery because economically it is not justified.

Table I shows typical arisings from ADU process and some of the recycle and reuse opportunities.

TABLE I. TYPICAL ARISINGS FROM URANIUM ORE CONCENTRATE REFINING (FOR 1000 t URANIUM OXIDE), ADU PROCESS

Arising	Quantity	Recycle and Reuse Potential	Comments
Liquid			
Process effluent	3000–10000 m^3	300 t of nitrates having a fertilizing potential	300 t of decanted materials stored as waste
Ammonium nitrate	450–1000 m^3	Yes	Unconditional release
Sodium nitrate	4500 m^3	Yes	Unconditional release
Solvent (TBP)		Yes	Recycled to process
Solid			
Uranyl nitrate raffinate cake (UNRC)	1500 t	Yes	Transported to mine for uranium recovery & back-filling
Drums	3300–9000 pcs (~ 100 t of steel)	Yes, about 95% is recycled to the steel mill	Transport container for UNRC
Cotton wastes	30 t	Yes	Incinerated, uranium recovered from ash
Other metallic	6 t	Yes	Send to the steel mills after decontamination
Gaseous			
Nitrogen oxides (NO_x)		Yes	Nitric acid recovery

4. URANIUM CONVERSION, ENRICHMENT AND RECONVERSION

This stage of the nuclear fuel cycle covers those operations in which the uranium oxide is fluorinated, enriched in fissile content (^{235}U), and then 'reconverted' or processed to oxide or uranium metal as a fuel material. The process(es) and associated arisings are generically as described in Fig. 4.

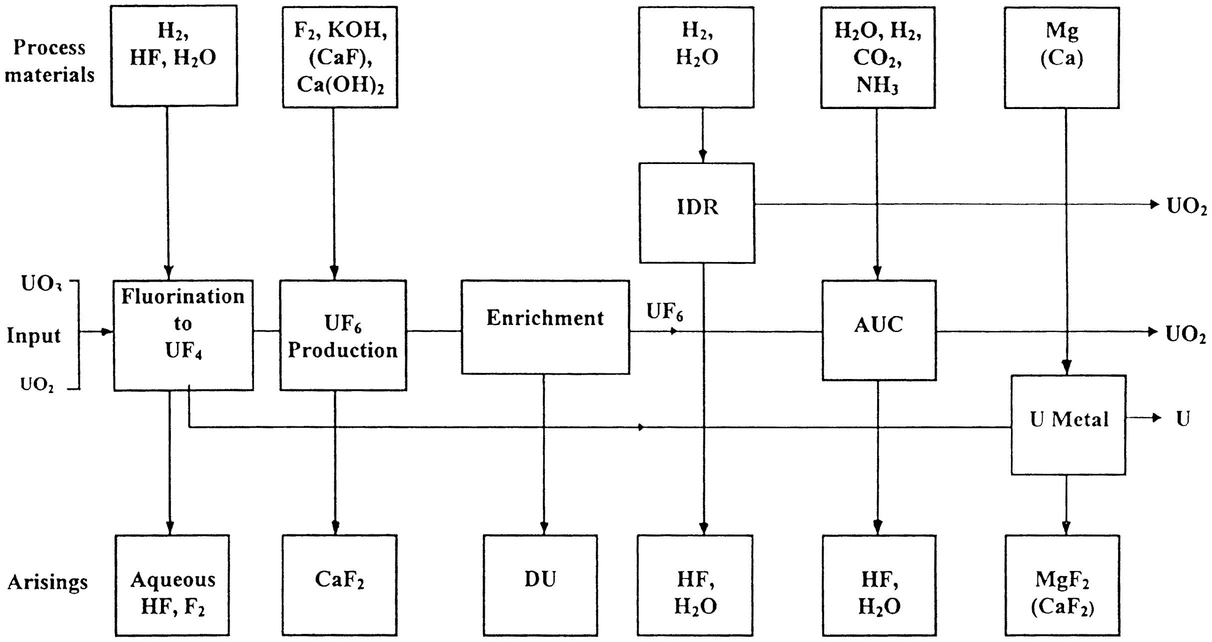

FIG. 4. Conversion, enrichment, reconversion.

4.1. PROCESS DESCRIPTION

Conversion of uranium oxides (UO_3 and UO_2), to uranium hexafluoride includes the following processes:

- Reduction of uranium trioxide (UO_3), using hydrogen gas, to produce uranium dioxide;
- Wet route production of uranium tetrafluoride (UF_4) by precipitation following reaction of aqueous hydrogen fluoride (HF), and UO_2 ; or
- Dry route production of UF_4 by reaction of UO_2 directly with anhydrous gaseous hydrogen fluoride;
- Production of uranium hexafluoride (UF_6) by reaction of UF_4 with fluorine gas. This can be achieved either in a flame reactor or in a fluidized bed. Excess fluorine may be scrambled with potassium hydroxide to give the fluoride. The potassium fluoride may be regenerated by reaction with lime (calcium hydroxide), to provide insoluble calcium fluoride.

The flow diagram of the specific process of uranium hexafluoride production from UOC used by BNFL is presented in Fig 5.

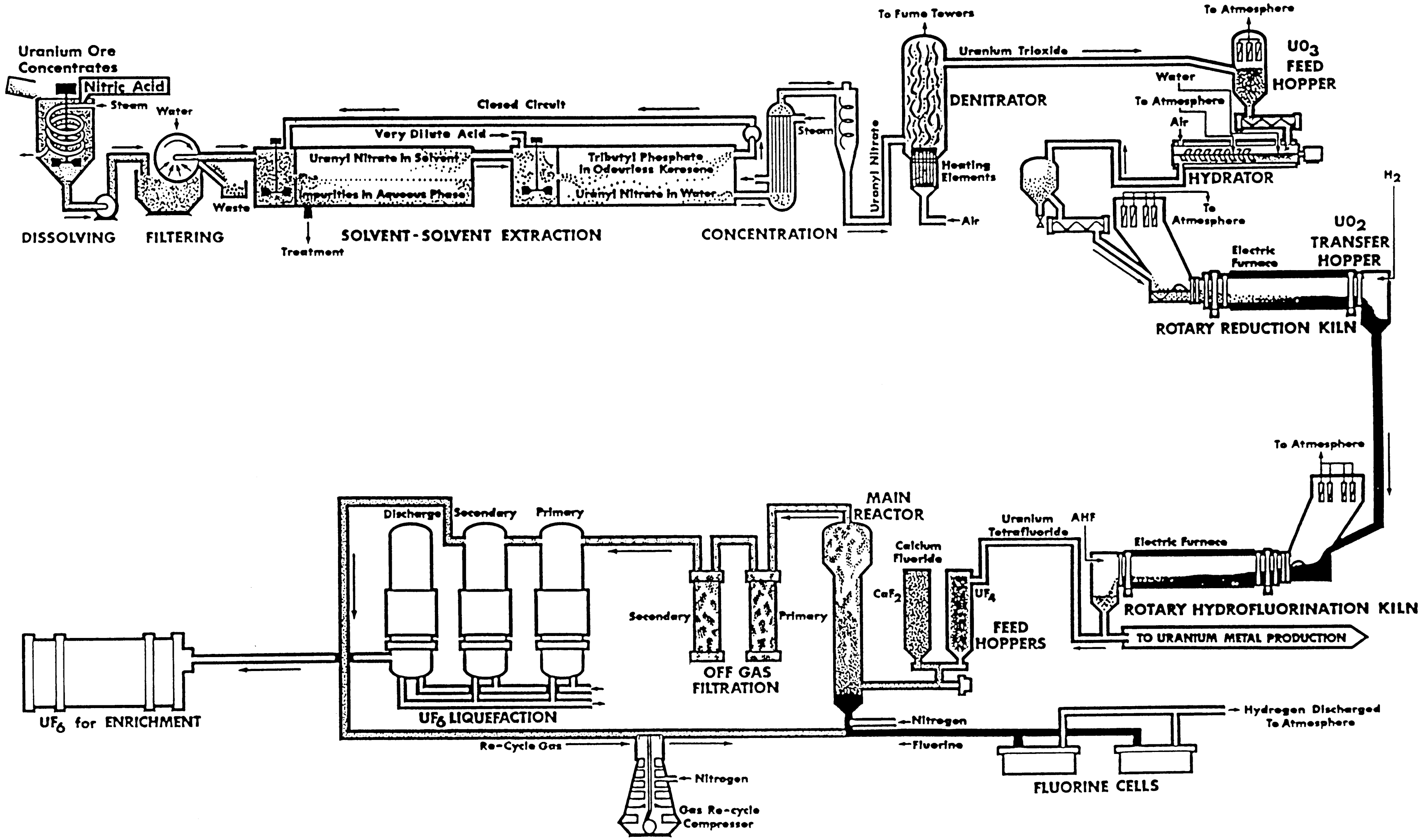

FIG. 5. Uranium hexafluoride production at Springfields , UK.

Gaseous diffusion enrichment is based on different diffusion rate of gaseous $^{235}UF_6$ and $^{238}UF_6$ through membranes. The lighter $^{235}UF_6$ diffuses slightly quicker than the $^{238}UF_6$. Repetition of the operation in cascade diffusion columns leads to increasing degrees of the enrichment to the required level. Owing to the high number of steps needed to reach the desired degree of enrichment the plant tends to be very large, and the compression and circulation of the gases is very power intensive.

The main process currently in use worldwide for enrichment of uranium hexafluoride in the fissile isotope of uranium (^{235}U) is centrifugation in cascades of gas centrifuges. In this process enrichment is achieved by differential centrifugation. The lighter ^{235}U is separated from the heavier ^{238}U when injected as UF_6 into a high speed centrifuge. Cascade arrangement of centrifuges leads to a progressively enriched fractions. Centrifugation is more efficient than the diffusion process, thus the plant is smaller for the same output and the energy consumption is significantly lower.

An exciting, though commercially unproven process that has enjoyed considerable investment at a research level, is Laser Isotope Enrichment. In this process there is an opportunity for designing out the arisings of waste and removing the need for a reuse strategy. The use of lasers to enrich uranium has yet to be realized commercially.

Reconversion of UF_6 generates the materials that will be incorporated into fuel elements. This implies uranium metal, for Magnox type fuels, or more commonly UO_2 for the predominant reactor types. Uranium metal is produced by reaction of the UF_4 with an alkali earth metal using a thermite type process. In addition to uranium metal this produces uranium contaminated slags of the alkali metal fluoride. UO_2 can be produced by one of two routes, ammonium uranyl carbonate (AUC) process, and integrated dry route (IDR) process, where UF_6 is ‘burnt’ in steam under a reducing hydrogen atmosphere. Both processes give rise to hydrogen fluoride as a by-product.

4.2. MATERIALS USED

The main reagents and materials used for conversion and reconversion are [13, 14]:

- UF_6 , UO_3 and UO_2;
- HF (wet and dry); fluorine gas; (F_2);
- Scrubbing reagents (KOH and $Ca(OH)_2$);
- Carbon dioxide (CO_2) and ammonia (NH_3);
- Magnesium and calcium metals;
- H_2O, H_2;
- Calcium or magnesium fluoride slags.

4.3. CURRENT MATERIALS RECOVERY PRACTICES

The uranium conversion, enrichment and reconversion is a well practiced and mature processes with responsible reuse and recycle of fluorine products. One of the most significant arising in the enrichment process is that of depleted uranium (DU), i.e. uranium residues after the ^{235}U has been concentrated into the minor stream. The depleted uranium represents ca 85% of input uranium to enrichment (ca 850 t DU per 1000 t of processed metal) and represents one of the major challenges for reuse. Other important arisings are hydrogen fluoride and calcium or magnesium fluoride slags. All residues of enriched uranium are collected and treated for recovery and recycling. An example of enriched uranium recovery plant is presented in Fig. 6. Other opportunities for reuse and recycle in conversion, enrichment and reconversion are utilisation of depleted uranium and fluorine products, especially the gaseous products.

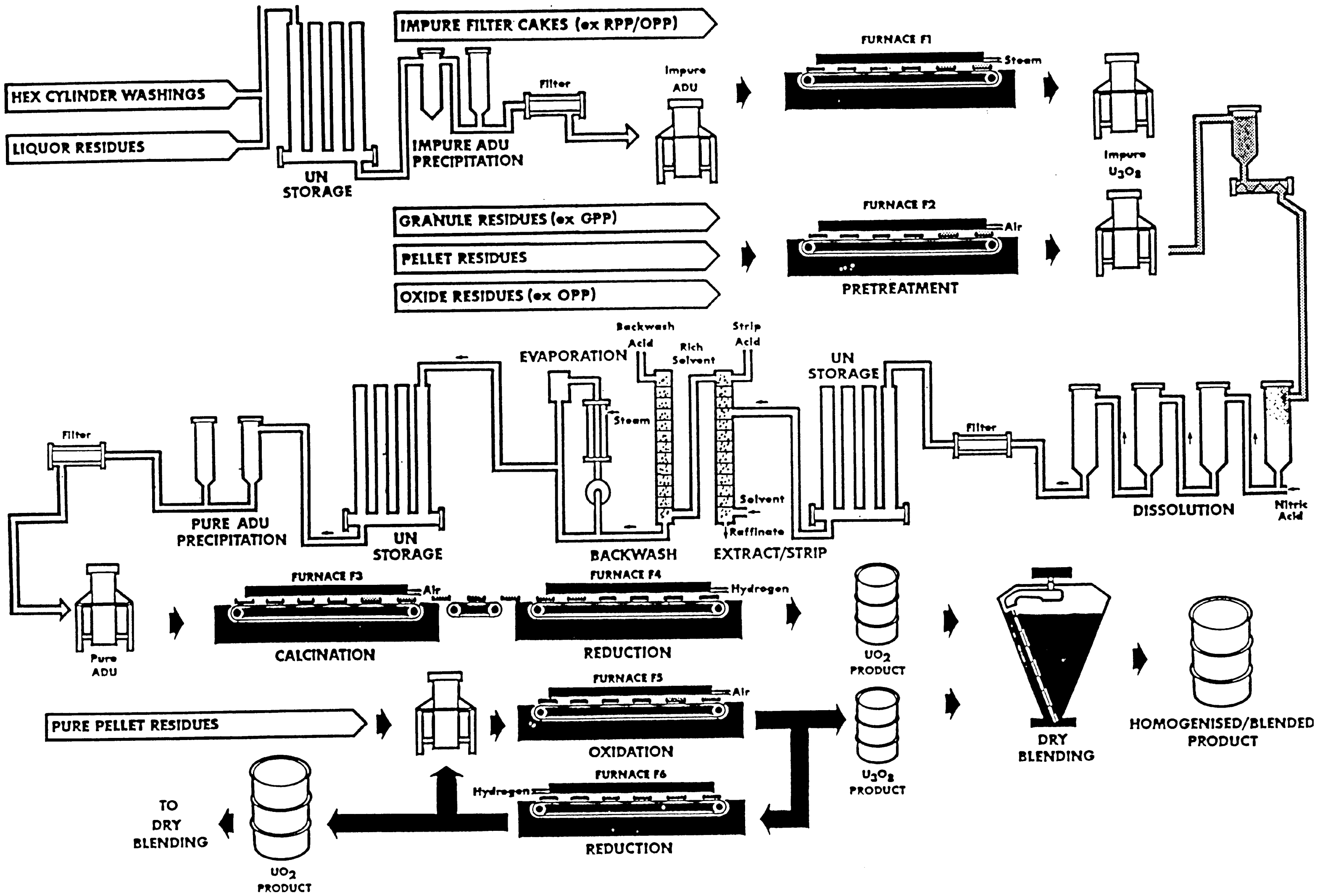

FIG. 6. Enriched uranium recovery plant at Springfields , UK.

Depleted uranium after reconversion finds many commercial nuclear and non-nuclear applications by virtue of its density and metallurgical properties (for example, in projectiles or ballast). Due to its high shielding capacity it may be fabricated into containers that contain highly radioactive materials. One of the more innovative application of DU is to use the uranium oxide as aggregate in concrete containers for radioactive waste, a concept that has been developed by Sierra Nuclear Corporation [15]. Stocks of DU are large and additional innovative products and processes are required to utilize the significant amounts of DU collected by the enrichment facilities.

The amount of highly enriched uranium (HEU) currently available due to the destruction of nuclear weapons has potential for reuse in nuclear power reactors. It may be mixed with tails of depleted uranium to use as a feed for the fabrication of fuel for commercial reactors. However, this opportunity for use of depleted uranium is not explored further in this report as recycle and reuse of fuel material is specifically excluded from its scope.

Recovery of fluorine and fluorine products, particularly HF is a well developed practice in conversion and reconversion, with both recycle in the process and reuse of HF outside the nuclear industry. In the IDR process the off-gas is filtered to remove particulates and scrubbed to remove the HF (as aqueous HF). The residual hydrogen gas is flamed off. The KOH scrub liquor is also routinely regenerated with lime.

Calcium and magnesium fluoride slags have little economic value or environmental input and are not exploited in terms of recycle and reuse.

Typical arising from the conversion, enrichment and reconversion process and possibilities for recycling and reuse are shown in Table II.

TABLE II. TYPICAL ARISINGS FROM THE CONVERSION-RECONVERSION PROCESS FOR 1000 t of U (natural)

Arisings	**Quantity (t)**	**Recycle & reuse**	**Comment**
Depleted uranium (<0.2% ^{235}U)	850	Has potential for recycle/reuse	Restricted release, used as a shielding material
Fluorine products (HF, etc.)	Not quantified	Recovered and recycled/reused	Commercial value of HF
Solid CaF_2	10	Not exploited	Low economic value
Sludges CaF_2 , $Ca(OH)_2$, H_2O	20–50	Not exploited	Low economic value
Sludges CaF_2, $Ca(OH)_2$, H_2O	30	Not exploited	Low economic value

5. FUEL FABRICATION

This sections describes the fabrication of the major fuel types (mainly oxide fuels) and also considers metal fuels such as ‘Magnox’ fuel. Continuous process improvement in the fabrication and utilization of fuel has minimized waste and has utilized recycle and reuse opportunities. The section dose not deal with advanced research or prototype reactors or their fuels, neither does it seek to discuss the production of military or naval reactor fuel. The fuel fabrication process covered are those of:

- Uranium oxide fuels for thermal and fast neutrons reactors;
- Mixed (uranium/plutonium) oxide fuels (MOX);
- Metal fuels (e.g. ‘Magnox’).

5.1. PROCESS DESCRIPTION

Oxide and mixed oxide fuels

The generic oxide fuel fabrication process consists of the following steps (Fig. 7).

- Preparation of material suitable for pellet formation (i.e. correct morphology, blend, purity, etc.). This is achieved, for example, by granulation and grinding, with blending of uranium and plutonium oxide powders where necessary (MOX fuels);
- Compaction to form a pellet either with or without a binder to sustain the integrity of the pellet;
- Sintering followed by grinding to produce pellets of the required dimensions;
- Pellets assembling in pins (zircalloy or stainless steel tubes) with the appropriate spacers and springs. These pins are assembled into fuel elements using the bracing, end fittings and caps appropriate to the fuel.

Metal fuels

Using ‘Magnox’ fuel, as an example, uranium metal in the form of rods is machined to produce a grooved rod around which is placed a magnesium alloy outer cladding (can). The can is then sealed under a helium atmosphere using end caps. The simplified flowchart of the process is presented in Fig. 8. Compared to oxide fuel, metal fuel fabrication is a small part of the total volume of fuel fabrication capacity [16].

5.2. MATERIALS USED

The materials used in the oxide fuel fabrication process are:

- UO_2 and PuO_2 (for mixed oxide fuel);
- Organic binders to give pellets integrity during processing; (e.g. polymethyl-methacrylate);
- Fuel element cladding and components; (zircalloy, stainless steel, Zr–Nb alloys);
- Cleaning and degreasing agents.

The materials used in metal fuel fabrication are:

- Uranium metal;
- Cladding (aluminum, magnesium alloys);
- Helium (purpose to keep inert atmosphere inside the fuel elements);
- Cleaning and degreasing agents.

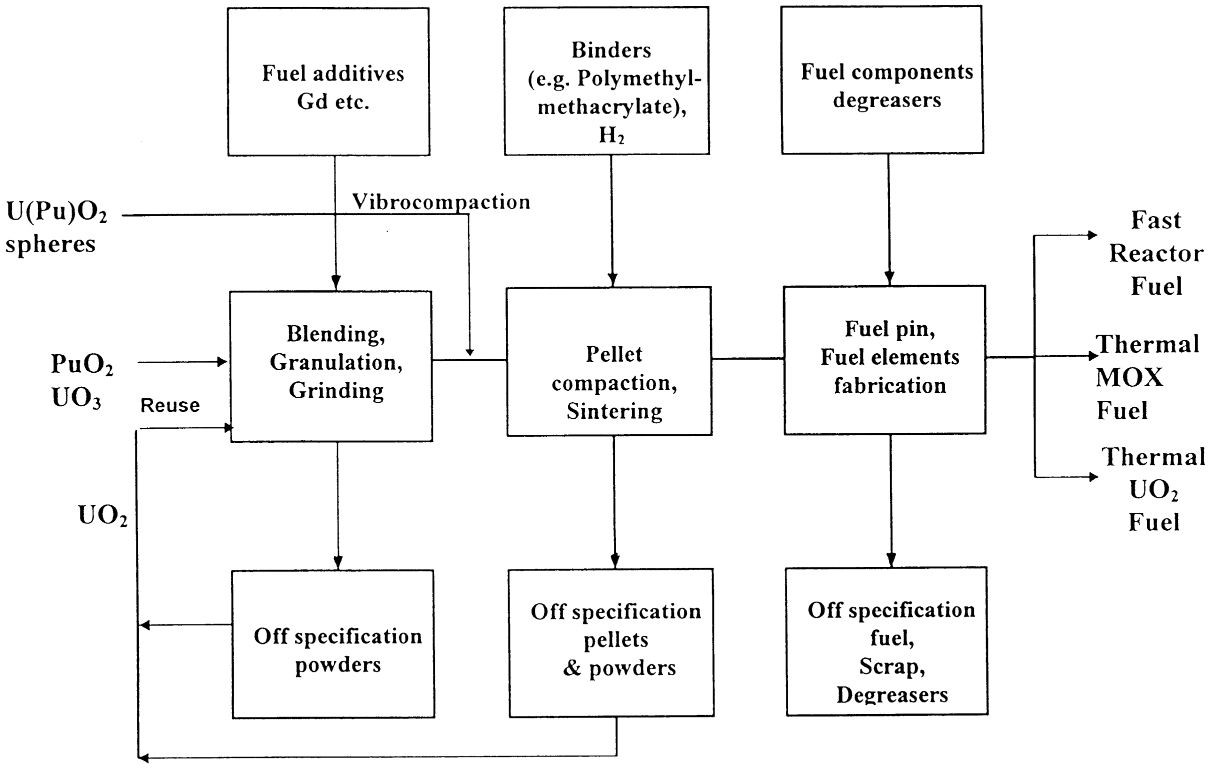

Fig. 7. Processes employed in oxide fuel fabrication.

5.3. OPTIONS FOR RECYCLE AND REUSE

Recycle and reuse in fuel fabrication is relatively limited. The main arisings in this process are UO_2 and PuO_2 powders from pellet production and metal swarf from the production of metal fuel, off-specification pellets, scrap fuel components, off-specification pins and mechanical items removed for maintenance or replacement, e.g. grinding mills, and materials arising from pre-production testing.

Recycle and reuse may include recovery of off-specification materials, or the recycling/reuse of materials consumed in pre-production testing. Avoidance of off-specification products is the main method of waste minimization. Off-specification materials may be recovered and returned to earlier stages of the process. Materials such as cladding and simulated (non-fuel) test core that are used in pre-production testing may undergo radiological characterization. This material may then be candidate for clearance to reuse.

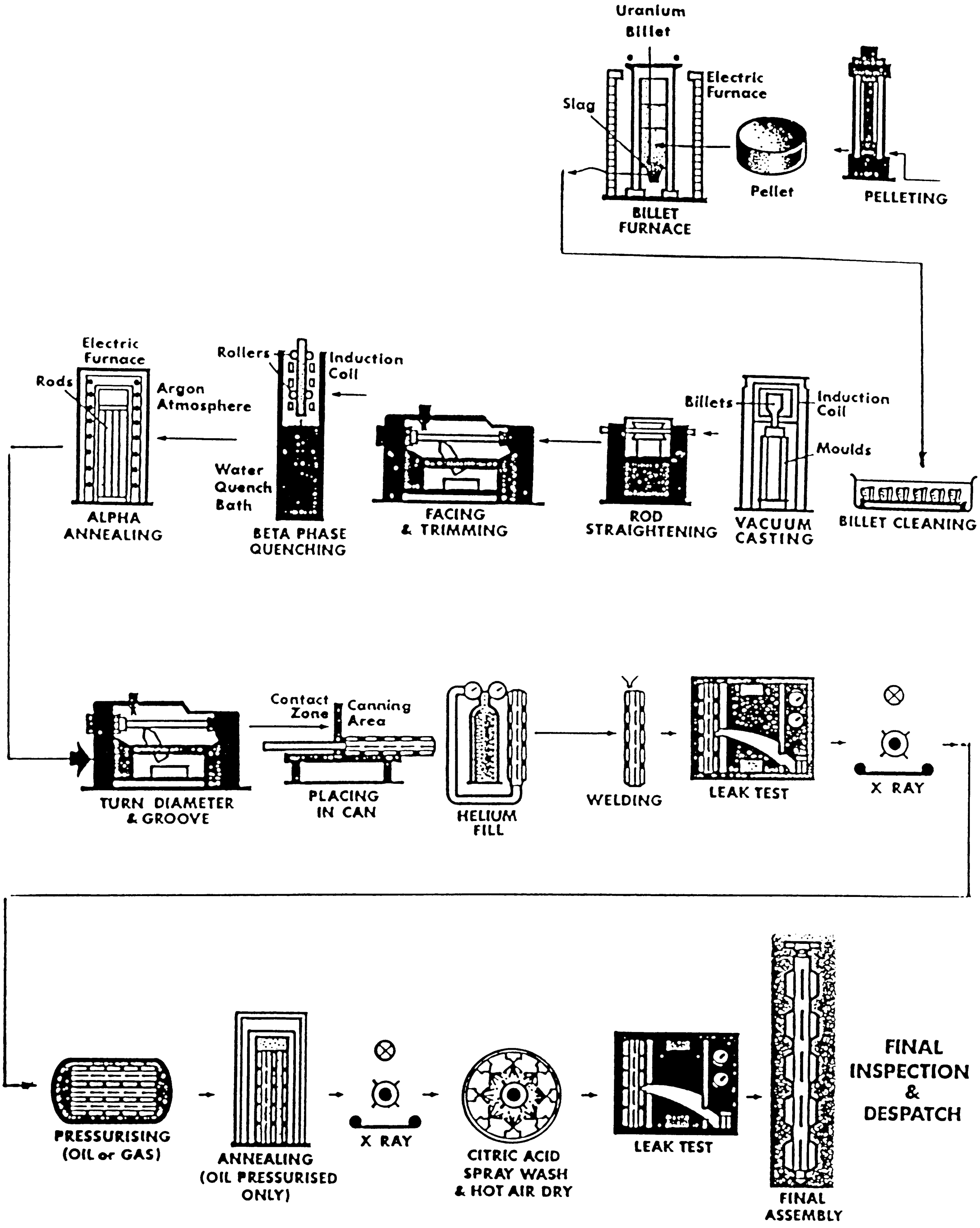

Fig. 8. Flow diagram of the production of uranium metal 'Magnox' fuel.

6. NUCLEAR POWER PLANTS

6.1. TYPES OF REACTORS

There are a range of reactor types, operation of which offer some opportunity for reuse or recycle of materials and components involved in operation and maintenance. These reactors are divided into two broad types:

Thermal neutron reactors. These types of reactors may be differentiated on the basis of used moderator and coolant, namely:

- Light water moderated and cooled reactors:
  - pressurized water reactors (PWRs and WWERs);
  - boiling water reactors (BWRs).

- Graphite moderated reactors:
  - magnox reactors, principally in the UK (CO_2 cooled);
  - advanced gas cooled reactors (CO_2, He cooled);
  - RBMK, channel type water cooled reactor, high capacity, design and constructed in the former Soviet Union.

- Heavy water moderated and cooled reactors:
  - CANDU reactors;
  - pressurized heavy water reactors.

Fast neutron reactors. Most of these reactors are at the stage of prototype or demonstration. A common coolant in this reactor type is sodium or its alloys.

Each reactor type is unique in its design and operation practices. Therefore, the level of recycle and reuse opportunities will be driven by the plant philosophy, existing regulatory requirements, specifics of the selected processes for reactivity and coolant/moderator chemistry control, and capability of operating and maintenance personnel to support established waste minimization strategy.

Opportunities for recycle and reuse of materials during operation of nuclear power plants may be considered during all stages of power plant life-cycle: design, operation, maintenance, upgrade and decommissioning.

The focus of waste minimization during design is waste source reduction. This is achieved through proper material selection for plant systems and structures, as well as through proper selection of processes for reactivity and chemistry control. Recycle and reuse are employed mainly through the recovery of coolant and moderator from plant systems or materials, tools and equipment that can be decontaminated and reused following operation or maintenance activities.

Plant maintenance, upgrade and modifications offer significant opportunities for recycle and reuse of materials. Plant maintenance manuals and procedures usually include:

- The plant guidelines for waste collection, segregation and characterization;
- Identification of requirements for waste minimization, estimation of waste generation and identification of its destination;

- Identification of responsibilities of personnel producing and processing waste;
- Identification of relevant national regulatory procedures and requirements.

6.2. MATERIALS INPUT

Reactor operation and maintenance require introduction of substantial amount of materials to support its safe and reliable exploitation. The materials input to power plants includes:

- Coolant (light and heavy water, CO_2 , sodium, sodium alloys, etc.);
- Moderator (light and heavy water, graphite);
- Process materials:
  - – Water preparation materials (filters, ion exchange resins);
  - – Additives to control water chemistry (LiOH , KOH, N_2H_4, NH_4OH);
  - – Reactivity control materials (H_3BO_4 – boric acid);
  - – Materials for cleaning of the coolant systems (additives, solvents, ion-exchangers, filters);
  - – Decontamination agents (solvents, complexants, water, abrasives, etc.);
  - – Analytical reagents.
- Waste containers;
- Consumables, tools and construction materials required to support maintenance and plant modification;
- Fuel flasks.

Theoretically, it is possible to envisage that almost all materials offer some recycle and reuse opportunity. Technologies to achieve that goal exist and could be applied even today. In the competitive world of power production application of these technologies are determined by the economic incentives, regulatory requirements regarding release levels for recycle and reuse, availability and cost of waste treatment and disposal options. These factors are discussed generically in Section 11.

6.3. OPTIONS FOR RECYCLE AND REUSE

Nuclear power generation is based on a relatively matured technology, and includes a variety of regulatory and voluntarily established waste minimization requirements. As a result, most western plant operators have achieved impressive results on the reduction of waste generation and minimization of waste disposal, with recycle and reuse playing its part in waste minimization. Availability of disposal sites and associated disposal cost represent strong additional motives to further intensify recycle and reuse efforts.

Nuclear power plant operators should accomplish waste minimization by good management practice. Substation reduction of operational waste generation are reported worldwide. Opportunities exist for recycle and reuse during plant operations and are mainly focused on recovery of reactor coolants, moderators and materials involved in maintenance and plant modification activities. The generic opportunities for recycle and reuse during operation of pressurized light and heavy water reactors are shown in Fig. 9.

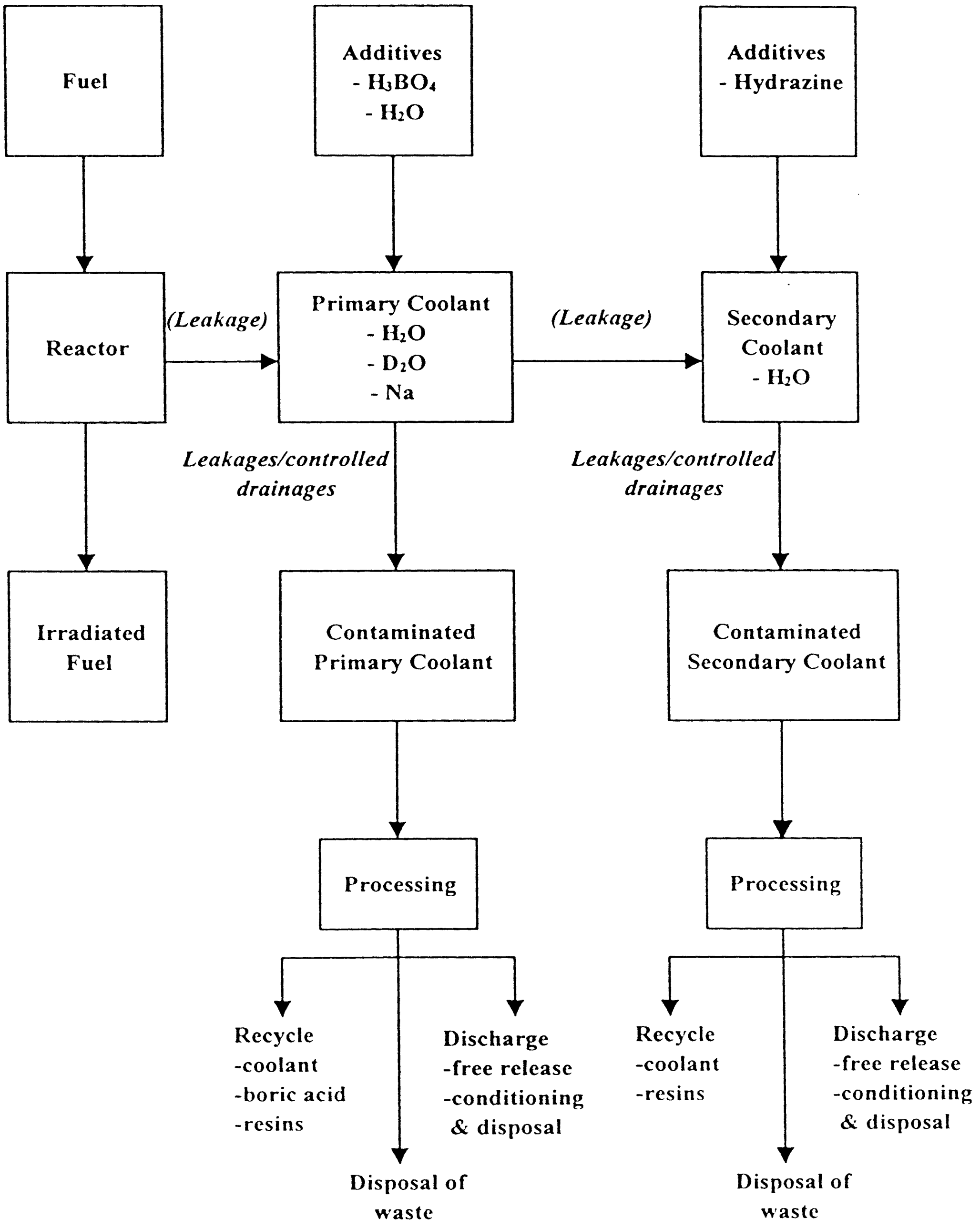

Fig. 9. Recycling opportunities at nuclear power plant.

Opportunities that do exist for recycle and reuse in nuclear power plants during the plant operations are:

- Recycle of coolant;
- Recycle of moderator;
- Recycle and reuse of additives and reactivity control materials (e.g. boric acid);
- Regeneration of cleanup and waste treatment materials (e.g. ion exchange resins);
- Recycle/reuse of waste and fuel containers or flasks;
- Decontamination and release of maintenance equipment and instrumentation for reuse.

The use of bulk but simple coolants such as water (light and heavy), or CO_2 offer opportunity for closed systems that are already exploited. Controlled and uncontrolled fluid leakages from plant systems are routinely collected and processed for recycle back to the systems or reuse for other purposes. The rest of effluents remaining after processing is treated as waste, if it is not meet plant technical specifications. A potentially hazardous primary coolant, such as sodium alloy has necessitated a recycle system that generates a waste stream of contaminated or suspect contaminated materials. These materials can be cleaned and reused within or outside the nuclear industry.

Many of the additives in cleanup systems and materials used during plant maintenance are routinely recycled in commercial nuclear power plants and associated waste management facilities.

Recycle (after regeneration) of spent ion exchange resins is widely practiced by WWER operators in Eastern and Central European countries on resins that have been used for polishing water condensate after evaporation (for recycling of cleaned water). However, regeneration of ion exchange resins is not routinely practiced in Western nuclear power plants. In this case the justification being that the cost of the regeneration process as well as the problems associated with the conditioning and immobilization of exhausted regenerant solution outweighs the benefit of regeneration and recycling of ion exchange resins.

Plant maintenance and upgrades use substantial amount of support materials (protective clothing, shielding materials, decontamination agents, papers, plastics, etc.) which after use become the waste. The power plants with good waste management practices use materials that offer easy recycle and reuse (i.e. decontamination friendly materials). In addition, operators should actively avoid the introduction of materials that offer either poor recycling opportunity or have a low volume reduction capacity for future waste treatment.

Consumable materials (e.g. plastic sheeting), may undergo segregation and radiological characterization to qualify them for clearance to appropriate recycle or reuse programs. Consideration must be paid to the risk of the presence of radionuclides that may be difficult to detect in these materials (i.e. tritium, alpha contamination, low energy beta contamination). Generally volume reduction techniques such as incineration or compaction are preferred based on the low economic value of the material.

Plant upgrades or replacement of major equipment present a substantial opportunity for material recovery and corresponding waste volume reduction. Numerous studies, investigations, development and technical documentation have been carried out by different national institutions and international organizations to evaluate and test waste volume reduction techniques, to develop more accurate activity measuring methods, to develop processes for further waste conditioning, and to analyze overall benefits associated with free or restricted release of materials involved with nuclear plant operations. Typically, replacement of heat exchangers offer opportunities to segregate materials or decontaminate vessels to levels of contamination that allow reuse of the metals in the heat exchangers.

7. REPROCESSING

Reprocessing of irradiated fuel represents the key part of the nuclear industry to achieve a closed fuel cycle. The objective of reprocessing is to recover fissile material from spent fuel so that it can be used for production of the new mixed oxide and uranium fuels. The fusion products and minor actinides are removed for appropriate treatment, conditioning, storage and ultimately safe disposal.

The most widely developed and operated reprocessing scheme used at an industrial scale is the PUREX process. Other processes with alternative extractants and non-aqueous processes such as molten salt processes or volatile fluorides have been developed and often demonstrated on small scale production. In view of the predominance of the PUREX process and its ancillary processes this section will concentrate on this process.

7.1. PROCESS DESCRIPTION

The aim of the PUREX process is to separate uranium and plutonium from the fission products and other fractions of irradiated fuel (e.g. cladding), and to separate uranium from plutonium. The basis of the separative process is solvent extraction between solution of nitric acid as the aqueous phase and tributylphosphate (TBP) in an inert diluent as organic phase.

The common steps in reprocessing are:

- Dismantling and/or shearing of fuel assemblies to allow access to the fuel;
- Dissolution of the fuel in hot nitric acid;
- Removal of undissolved solids if necessary by filtration or centrifugation;
- Extraction of uranium and plutonium from acidic solutions;
- Separation of uranium and plutonium;
- Purification of the separated uranium and plutonium;
- Finishing the uranium and plutonium nitrates for reuse/recycle or storage.

The PUREX process is specifically designed to recover and recycle the solvent phase [17]. The general scheme of this process is shown in Fig.10. Nitric acid, converted to oxides of nitrogen during dissolution and denitration, is routinely recovered and recycled to the process.

7.2. MATERIALS USED IN PROCESS

The main reagents and materials used in the PUREX process are:

- Nitric acid;
- Process water;
- Tributylphosphate (TBP);
- Diluent (dodecane or odorless kerosene (OK)).
- Redox reagents, hydrazine, hydroxylamine;
- Mechanical renewables (shear blades, dissolver baskets);
- Filters; caustic soda for off-gas cleanup.

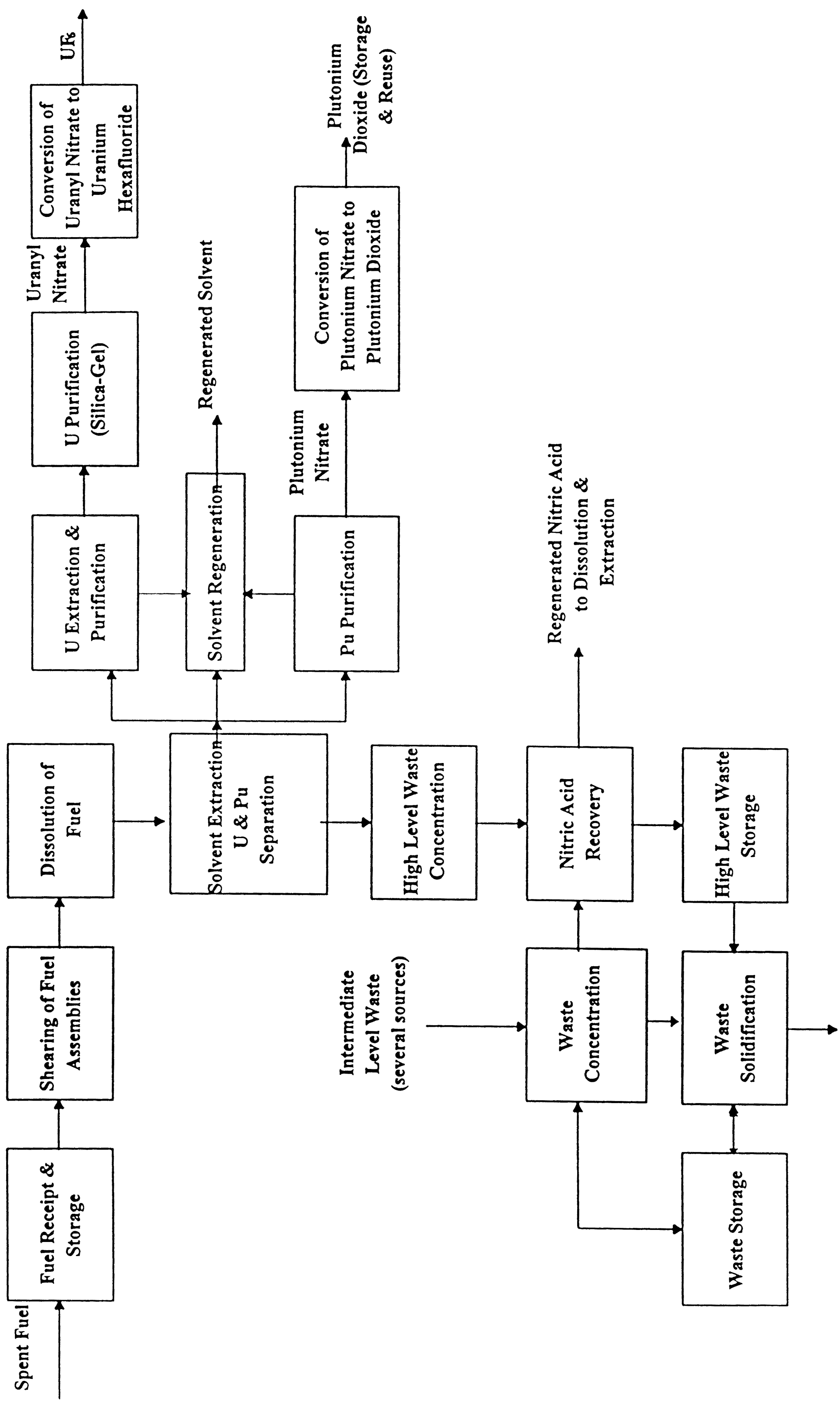

Fig. 10. Simplified flow diagram for a typical fuel reprocessing plant.

The main products of reprocessing are recovered uranium and plutonium that are destined for utilization in the next step of fuel cycle (production of new fuel). In addition, the PUREX process plant generates a wide range of other products and maintenance materials often destined for disposal or discharge as wastes. These products may include:

- Spent solvent;
- Nitrogen oxides;
- Fuel element components such as sheared fuel pins (hulls) and appendages;
- Soluble fission products in liquid high level waste;
- Volatiles, e.g. iodine (^{131}I and ^{124}I), krypton (^{85}Kr), carbon ^{14}C as $^{14}CO_2$ and tritium ^{3}H as ^{3}HHO (tritiated water);
- Contaminated nitric acid containing tritiated water.

7.3. OPTIONS FOR RECYCLE AND REUSE

7.3.1. Solvent recovery

A key component of the industrial PUREX process is the recovery of solvent. This is driven by the value of the TBP and the need to eliminate a waste stream that is difficult to dispose of. The solvent becomes contaminated with radiolysis and degradation products (e.g. dibutylphosphate) and other small organic molecules. These modify the properties of the solvent and form emulsions that inhibit effective extraction. The solvent is cleaned by a succession of alkaline, carbonate and water [18] washes to remove the degradation products. The cleaned solvent is recycled to the process.

Solvent wastes are estimated to be in the range of 0.01 m^3 to 0.10 m^3 per ton of fuel [19]. The waste contains up to 10 mg/L uranium, up to 0.5 mg/L plutonium, total α activity 37 MBq/L and β activity 37 GBq/L. During reprocessing at WAK, Germany [20] more than 100 m^3 of solvent was treated and the residual activity reduced to about 0.37 MBq/m^3 to allow recycle of the solvent.

7.3.2. Nitric acid

Nitrogen oxides are produced by dissolution of fuel and denitration of metal nitrates (uranium and plutonium). Nitric acid is recovered from the off-gases by scrubbing with water to reform nitric acid. This nitric acid, together with dilute acid streams can be evaporated to return the acid to the fuel dissolution stage of the process. The nitric acid recovery process at La Hague in France is described in reference [21]. This process also functions as a tritium control step. The tritium which appears in the distillate as tritiated water is discharged to sea. A similar process is utilized at the Industrial Association “Mayak” in the Russian Federation [22–23].

7.3.3. Other recycle opportunities

There are a number of opportunities for recycle and reuse that have been investigated at the pilot scale. All are likely to be technically feasible but are usually defeated by a clear environmental or economic considerations. Possible opportunities include:

- Use of hulls or end appendage materials (zircalloy, zirconium alloys or ferrous metals) either as a matrix for waste or as new cladding material;

- The fission products are a rich source of materials with potential uses e.g. recovered technetium as a corrosion inhibitor, the noble metals as catalysts, etc. [24]. However, the cost and complexity of the recovery has prevented so fare a commercially viable process from being devised;
- Fission products such as ^{99}Tc, ^{131}I and a multitude of other isotopes could be recovered for commercial application. Again, the complexity of the process and availability of alternative sources militates against this opportunity;
- Isotopes such as ^{137}Cs have been recovered in the past for use in sealed radiation sources. This has largely been discontinued as demand for these sources has declined;
- Imaginative suggestions are to use of ^{85}Kr as an energy source in luminous devices (e.g. airfield lights). To date these options have not justified removal of ^{85}Kr from off-gas streams either as economic or environmental grounds.

A number of other schemes have been proposed for separation and recovery of fission products [18, 25–26]. These have yet to be demonstrated at a commercial scale.

8. CENTRALIZED WASTE TREATMENT FACILITIES

There are a number of large centralized waste treatment facilities for radioactive waste that are either co-located with production plant within nuclear licensed sites or are located at sites dedicated to receipt and treatment of waste from a number of sources or from other sites. Examples of these include the Sellafield Waste Treatment Complex for treating transuranic wastes, the Site Ion Exchange Plant (SIXEP), at Sellafield, Vitrification Facilities at Sellafield, the Marcoule and La Hague facilities in France, the Grouting Plant in the UK, the Waste Receipt and Packaging Plant (WRAP) at Hanford, USA. Other facilities that provide a central service to many waste produces include the Waste Acceptance Monitoring and Compaction Plant (WAMAC) at Sellafield, Manufacturing Sciences Corporation (MSC) and GTS 'Duratek' both located at Oak Ridge, Tennessee, USA, ECN Petten in the Netherlands and 'Belgoprocess' in Belgium.

8.1. PROCESS DESCRIPTION

In general the processes used in central facilities for treatment and conditioning of waste are similar to those employed for single waste streams or in conjunction with other production facilities. Typically these large scale or centralized facilities are designed with some flexibility to accommodate a range of wastes and frequently group a number of process steps together. Some of the generic treatment and conditioning processes found in central facilities include:

- Liquid effluent treatment such as ion exchange [27], precipitation [28] and evaporation [29];
- Immobilization of solids, sludges and liquid waste, for example cementation [30], vitrification [31], bituminization [32] and polymer encapsulation [33];
- Solid waste treatment such as compaction [34] decontamination [35], incineration [34–36] and metal melting [37].

8.2. OPTIONS FOR RECYCLE AND REUSE

Centralized facilities do not automatically offer recycle and reuse opportunities not available at dedicated facilities. However, the high throughput of material consigned to central facilities does offer economic incentives that would not otherwise be justified at smaller or dedicated facilities by exploiting larger volume of waste, justifying sophisticated treatment options and utilizing enhanced flexibility afforded by centralized facilities.

The collection of large waste volumes in centralized facilities encourages recycle and reuse practices such as the segregation and recovery of valuable items (scrap, tools, safety clothing) that could not be justified at the various locations where the waste was generated. This has been practiced, for example, by GTS 'Duratek' at Oak Ridge on bulk waste from utilities and other waste producers.

The central location of sophisticated processes is illustrated by MSC (Oak Ridge) where, in conjunction with size reduction, segregation and decontamination capabilities, metal working facilities are provided to convert contaminated metal scrap to useful articles such as flasks and containers for radioactive materials and waste (see Fig. 11) [38]. A similar opportunity is the reuse of depleted uranium oxide as a high density and shielding aggregate to produce concrete containers for storage/disposal of radioactive waste [39].

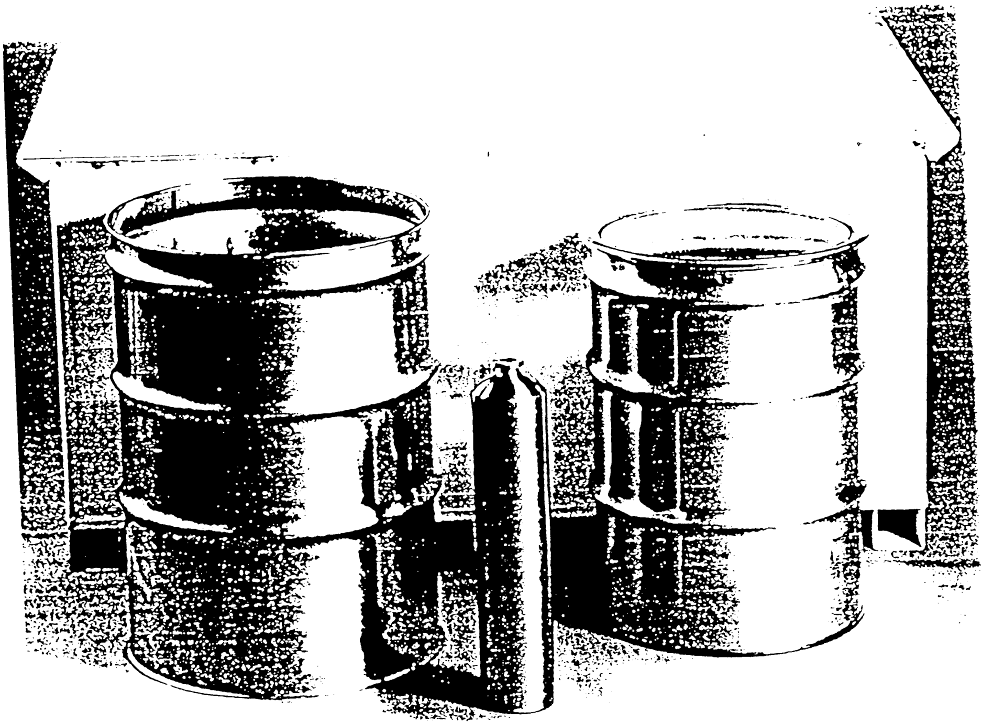

FIG. 11. Container for radioactive waste produced from recovered metal scrap.

Other examples of recycle/reuse in centralized facilities are:

- The use of the liquid effluent as a process feed to the formation of cement grout for waste immobilization;
- The use of recovered concrete dust from decontamination/decommissioning process as a filler in preparation of cement grout;
- Accepted energy saving process such as, utilization of heat generated during incineration of combustible waste.

Centralized decontamination facilities also offer a benefit to nuclear sites as they are able to accept a wide range of maintenance materials for decontamination and recovery for reuse and recycle. A typical facility is found at Sellafield where, for example, master slave manipulators (MSM) components are decontaminated to a level where they can be maintained rather than disposed of as waste.

9. HISTORIC WASTES

Historic wastes include those that were stored at temporary facilities (e.g. silos), or were disposed of in ways that are no longer acceptable, thus necessitating recovery of the waste and further treatment. The historic wastes generated by the nuclear industry represent a large fraction of the total inventory of waste (historic, current and future), that must be dealt with. Historic wastes cover a wide range of waste types, some of which are not well characterized. Typical examples of the historic wastes include:

- High level liquid wastes from spent fuel reprocessing stored in tanks;
- Mixed waste, that is waste contaminated with both radionuclides and chemically toxic elements or compounds;
- Material contaminated with transuranic elements (TRU wastes);
- Fuel cladding and other wastes stored in silos;
- Contaminated oils and sludges;
- Depleted UF_6;
- Low level solid wastes stored in concrete bunkers/silos at NPPs;
- Contaminated soil, etc.

In some cases there are strong immediate pressures to treat these wastes. For example in the UK, the Licensing Authorities have encouraged BNFL to empty silos of stored ‘Magnox’ cladding from spent fuel and treat the recovered waste prior to disposal. In the USA also there are strong drivers to achieve significant progress in the next decade on treatment of these kind of wastes.

The worldwide holdings of historic waste are large. As an example the inventory of these wastes in the USA are shown in Table III [40].

9.1. HISTORIC WASTE PROCESSING

Since waste characteristics of historic waste are varied, there is no single process that may be applied to treat such waste. There are, however, generic techniques that are used to minimize volume of this waste. These may include characterization, decontamination, treatment/conditioning and certification of recovered materials.

The National Conversion Pilot Plant at Rocky Flats in the USA is a good example of utilizing recycle and reuse practice. Here residual metal from process plant equipment is decontaminated to a level where it can be reused as contaminated scrap into manufacture products such as drums and shielding [41]. In addition old facilities can be cleaned up to allow reuse.

An area where there are strong drivers to recycle is the mixed waste area, in particular mercury contaminated radioactive waste. Thermal treatment and distillation methods have been proposed under the auspices of the US DOE for recovery of mercury. The estimated volume of mercury contaminated mixed low level waste identified as requiring this treatment is 1.260 m^3. Here the mercury must be encapsulated in a suitable matrix or recovered and returned to commercial use [42].

A similar philosophy has been adopted for surface contaminated lead shielding blocks. These have been decontaminated using conventional wet techniques in the UK and have either been returned to service or sold as scrap lead.

TABLE III. QUANTITIES OF RADIOACTIVE WASTE AND SPENT FUEL IN THE USA (1994)

Types of Waste	**Volume of Waste (10^3 m^3) Commercial Sites**	**Volume of Waste (10^3 m^3) DOE Sites**
High Level Waste (HLW)	2.18	378.4
Transuranic (TRU)	0	216.4
Spent Fuel	29,812	>2,643
Low Level Waste (LLW)	1,519	2,963
Mixed LLW	*	162.4
Uranium Mill Tailings	118,600	0

* Information is not available.

9.2. OPTIONS FOR RECYCLE AND REUSE

The viability of recycle and reuse of some components from historic wastes depends on the comparison between the value of the recovered articles and the savings in the processing and disposal costs. The total environmental impact and cost benefit of saving valuable resources (e.g. steel), so fare has not been factored into the justification. The disposal costs for the significant volumes of historic waste may provide a strong driver to the use of every waste minimization and volume reduction opportunities available to optimize cost savings and reduce environmental impacts.

10. DECOMMISSIONING

For nuclear facilities, decommissioning is the final phase in their life-cycle. It is a complex process involving operations such as decontamination, dismantling of plant equipment and facilities, demolition of buildings and structures and management of resulting materials. Decommissioning should offer the most spectacular reuse opportunities, particularly for reuse of metals. There are currently numerous studies worldwide to take advantage of recovery and reuse of materials as part of a significant reactor decommissioning programme.

General information and guidance for the decommissioning of fuel cycle facilities has been given in a specific IAEA publications [43–50]. In addition, many elements of nuclear power plant and research reactor decommissioning are also applicable to non-reactor facilities and have been published in other IAEA reports [51–55].

10.1. PROCESS DESCRIPTION

As indicated in most of the referenced publications, the decommissioning of a nuclear facility can be carried out to:

- establish a safe enclosure with surveillance;
- carry out plant decontamination, partial dismantling and removal of plant systems against limited or conditional release;
- decontamination and dismantling of the plant for unconditional release of the site.

The strategy choice depends on a number of factors such as national policy, availability of technical and financial resources, etc. The generic activities that are involved in the implementation of the chosen strategy are:

- Characterization of the facility to be decommissioned;
- Post operational clean out of the facility;
- Planning and evaluation of the decontamination and dismantling work;
- Decontamination to facilitate dismantling;
- Dismantling of equipment and facilities;
- Treatment or conditioning of resulting waste and materials;
- Recycle, reuse or disposal of materials and waste;
- Final site cleanup.

Different techniques and equipment used during decommissioning are described in many national and international publications [56–57].

10.2. ARISINGS FROM DECOMMISSIONING ACTIVITIES

The wide spectrum of fuel cycle facilities includes some plants, materials and processes which have similarities to those found on other plants as reactors sites. These are mainly irradiated fuel stores (wet or dry), waste handling, treatment and storage facilities, and supporting ancillaries such as secondary circuits, ventilation systems, laboratories, maintenance, etc. The nature of the fuel cycle facilities and radioactive materials involved in many cases pose similar problems for decontamination and decommissioning, and similar possibilities for recycle and reuse.

In general, the decommissioning of nuclear facilities results in large amounts of materials such as:

- Constructional concrete, brick and other constructional materials;
- Mild steel, found in plant structures;
- Stainless steel, more commonly encountered in the construction of reprocessing plant;
- Aluminum, used in bulk in some processes such as enrichment.

There are a wealth of minor wastes such as exotic alloys and components of equipment e.g. copper from motor windings, together with shielding materials such as lead. In addition there are the usual challenges common to all civil demolishing activities such as removing insulation (asbestos and materials such as wood or plastics).

The most common secondary wastes produced during decommissioning include contaminated equipment and effluents from decontamination activities. The volume and type of these wastes have been extensively documented elsewhere [35, 44–54].

10.3. OPTIONS FOR RECYCLE AND REUSE

Substantial quantities of materials (mainly metal and concrete substances) to be generated during decommissioning of nuclear fuel cycle facilities create large opportunities for recycle and reuse options. Minimization of radioactive waste management cost and recycle and reuse of equipment and materials are important considerations during decommissioning. In this area of recycle and reuse, a major impact on waste treatment and disposal costs can be effectuated. Technologies for preparing these materials for recycle and reuse are mostly available. The main challenge however remains the ability to characterize the material and to establish a coherent dialogue with legislators and authorities to gain acceptance for free release practices and to promote options to recycle and reuse materials. Additionally, there is a need to ensure public understanding and acceptance of the concept of exemption/clearance and more efforts are needed in this area.

The main thrust of decommissioning activities and waste minimization include careful planning, avoiding the spread of contamination by using, for example, tie down coatings, adequate ventilation, etc. In addition processes and equipment can be used that minimize the formation of secondary wastes, for example, the use of dry decontamination techniques such as abrasive blasting [56].

Materials arising during decommissioning are particularly amenable to recycle and especially reuse since they are either lightly contaminated, contaminated with a relatively small range of well characterized contaminants, or indeed only suspect to be contaminated. The large volumes of materials provide an economically attractive source of material for reuse but it should be noted that, although reuse avoids disposal costs for materials that would otherwise be wastes, there are no instances so fare where the value of recovered material fully covers the cost of recovery. Nonetheless, recovery of valuable materials forms a key part of decommissioning strategies. The ultimate aim is to release materials for unrestricted use and free the material for any form of institutional control. Whilst this is an entirely laudable aim there remains a debate as to the levels of residual activity that are acceptable for unconditional release, a debate that is fueled by some well publicized incidents in which radioactive material has found its way into products due to poor control of, for example, radioactive sources.

During decommissioning there are a lot of options for restricted release or reuse of different materials in the nuclear industry. This includes a layering technique for molten metal where comparatively heavily contaminated materials is encased in lightly contaminated material to provide both shielding and containment [57]. The material recovered from decommissioning may also be used as shielding [58–59] and for fabrication of waste containers [38, 60–61]. Some imaginative options are being considered such as use of recovered steel to form an oxide aggregate to replace up to 100% of the sand in the concrete, or use this steel as reinforcing bars in concrete structures [62–66].

One of the largest volumes of material is concrete and rubble from decommissioning. This offers opportunities for processing to produce hardcore for use in the construction industry in general or construction on nuclear sites in particular.

These options imply selection effective characterization and decontamination techniques. The latter have been extensively reviewed [56–57] and selection can be made on factors such as cost, ease of use, secondary wastes generation, availability of practical experience, etc.

10.4. CURRENT ACTIVITIES

Recycle and reuse of materials during decommissioning have been applied in different projects at:

- the Capenhurst diffusion plant decommissioning (UK) with aluminum and copper returned to the scrap market;
- the National Conversion Pilot Project (Rocky Flats, USA) with decontamination of active facilities to process slightly contaminated scrap and convert it into wastes casks;
- a metal melting project in Sweden to treat and recover metal from reactor components for free release.

A comprehensive overview of applied and planned recycle and reuse applications is given in Table IV [67]. The key to a successful recycle and reuse strategy is its cost saving compared to conventional disposal. A number of studies have been carried out in which estimated savings accrued from recycle and reuse are projected to values as high as 47% of the disposal costs [67]. However, it must be noted that the value of material in recycle and reuse cannot fully defray the decommissioning costs, nor therefore can the recovered material compete on a per ton basis with raw materials or scrap from a non-nuclear origin.

11. FACTORS INFLUENCING RECYCLE AND REUSE ACTIVITIES

11.1. GENERAL CONSIDERATIONS

Economic considerations are a major driving force when considering the practice of recycle and reuse over alternative disposal options for radioactive and non-radioactive materials arising from operation, maintenance, upgrade and decommissioning of nuclear fuel cycle facilities. It should be clear, however, that recycle and reuse practices are a typical example of industrial activities that are governed by multiple factors, some of which may be mutually exclusive. Consequently, some level of optimization is an inherent part of determining whether recycle and reuse practices could be applied on a larger scale in particular case or at particular facility in the nuclear industry. An overview of some major influencing factors is given in the following paragraphs.

TABLE IV. CASE HISTORIES OF APPLIED AND PLANNED RECYCLE/REUSE APPLICATIONS IN DECOMMISSIONING [67]

Country	**Project**	**Category**	**Technology**	**Status**
Sweden	BWR preheater	Free release/recycling	Melting	Completed
Sweden	PHWR steam generator	Free release/recycling	Decontamination/ melting	Completed (ingots stored for decay)
Sweden	PHWR steam generator	Free release/recycling	Decontamination/ melting	Study
United Kingdom	Fuel racks SGHWR	Free release/recycling	Decontamination/ measurement	Study
Belgium	Fuel racks Belgoprocess	Free release/recycling	Melting	Completed (ingots stored for decay)
Belgium	Aluminum heat exchangers	Free release/recycling	Melting	In progress
Belgium	Drip tray of reprocessing plant	Free release/recycling	Decontamination/ measurement	Completed
Belgium	Reprocessing plant components	Free release/recycling	Decontamination/ measurement	In progress
Belgium	Concrete from Eurochemic pilot project	Free release/unrestricted disposal	Measurement	Completed
France	Concrete from G3	Free release/unrestricted disposal	Measurement/ crushing	Completed
France	Heads of prestressing cables-G3	Free release/unrestricted disposal	Measurement	Completed
France	G1 scrap air circuit	Restricted release/authorized recycling	Decontamination/ measurement	In progress
France	Siloe reactor heat exchangers	Restricted release/controlled recycling	Decontamination/ melting	Completed (cast into shield blocks)
France	Scrap Iron of PEGASE rector loops	Restricted release/controlled recycling	Decontamination/ melting	Completed
France	G2/G3 scrap	Restricted release/controlled recycling	Decontamination/ melting	Completed (ingots stored for reuse)
France	Rapsodie stainless steel primary circuit	Restricted release/controlled recycling	Decontamination/ measurement	Completed (ingots stored for reuse)

11.2. INFLUENCING FACTORS

11.2.1. Quantities of materials

As indicated in the previous sections, substantial quantities of materials, that are routinely generated during the operation of different nuclear fuel cycle facilities, can be recycled or reused. Further quantities of materials (predominantly metal and concrete substances) are likely to be generated in the near future from decommissioning and dismantling of nuclear fuel cycle facilities. A significant portion of this material will be only slightly contaminated with radioactivity, if at all. Based on practical experience in current operational and decommissioning programs [64–66], for large amounts of materials, the implementation of recycle and reuse options is more likely to be justified than for smaller quantities.

11.2.2. Technical feasibility

The availability of technically and economically proven methods to aid recovery, recycle and reuse of materials from nuclear fuel cycle facilities is essential. This is mainly concerns decontamination and characterization techniques. Technically feasible treatment methods should not give rise to large quantities of secondary waste generation, further processing and disposal of which would involve substantial additional cost, impact on workers, the public and environment. There are numerous technologies to support recycle and reuse options that are at laboratory or pilot scale but these will require additional time, resource and efforts for further development to prove applicability at industrial scale. That should only be considered if they demonstrate a clear advantage over the current methods.

Whether to proceed with recycle and reuse options, however, also largely depends on the characteristics and economic value of the material, type and level of contamination (alpha, beta-gamma, loose or fixed, depth of penetration, absence or degree of activation), nature and duration of storage, accessibility of surfaces for decontamination and measurement, and compatibility of materials with processes (potential for explosion, combustion, etc).

In addition, appropriate methodologies and monitoring techniques (procedures and instrumentation) for the radiological characterization of materials to the clearance/release levels are essential to the implementation of recycle and reuse options. Typically the monitoring and sampling regime could be expected to provide information on the following:

- the type and composition of material to be characterized, its physical properties, geometrical form and the quantities to be measured;
- the degree of surface survey required;
- the natural (ambient) background level (limit of detection), and the natural radionuclide content in the material;
- the radioactivity distribution on and/or within the material;
- the types of radionuclide to be measured, and the presence and significance of difficult to measure radionuclides;
- the required confidence level;
- the costs and performance levels of available detection devices.

All these factors are important in selection and implementation of different recycle and reuse options.

11.2.3. Release from regulatory control

International surveys indicated that the criteria, actually applied for release (exemption and/or clearance) practices, vary widely among Member States [5, 68]. Sometimes these criteria are based on established and available national regulations, while in other practices, they are based on a case-by-case evaluation. Historical examples of clearance criteria from specific projects in various countries are indicated in Tables V and VI [68]. The limits for alpha emitters generally are one-tenth of the limits indicated. In some cases (USA and Sweden) limits are three to ten times higher for smaller contaminated areas (spot contamination or ‘hot spots’). Additionally, some countries (Finland, Belgium) specify separate limits for alpha and beta-gamma emitters, whilst others (USA, United Kingdom) maintain nuclide specific limits. Some of the regulations specifically indicate that decontamination prior to clearance is considered acceptable (Belgium, Germany and the USA).

Additionally, nuclide specific limits have been applied in some countries as in France, Germany, Sweden, United Kingdom and the USA. In Germany, also, a specific formula has been applied to set limit values in some projects/plants for those nuclides that can be handled without regulatory control. In addition, further restrictions in terms of total activity, total mass and total volume in some of the projects/plants have been applied in countries as in Belgium, Germany and Sweden. Examples of conditional release levels applied on a case-by-case basis depending on the end-use of the materials can be found in several publications [65, 69–72].

The variability in criteria applied in projects/plants in various countries, have also shown that release criteria are a significant factor in determining whether recycle and reuse practices can be applied on a large scale. In several publications, it has been stated that it is vitally important to arrive at internationally accepted criteria for the release and reuse of material from nuclear installations [13, 73]. Clearance criteria must be based on reasonable assumptions with respect to dose, other hazards and associated risks, in the context of global optimization thereby saving the non-renewable resources of the world. If clearance criteria were excessively restrictive, large quantities of material would require disposal as ‘radioactive waste’, resulting in greatly enhanced costs, and additional environmental impact.

In addition, many derived clearance levels are close to, or below, current limits of detection for practicable field instrumentation. Consequently expensive instrumentation (in both time and cost) must be utilized, or where this is not feasible, materials must be deemed to be above the clearance level and treated accordingly (again with significant cost and environmental implications).

11.2.4. Cost

The choice of recycle and reuse options is usually justified on the basis of cost-benefit analyses. Some aspects to be considered in the preparation of such analyses include:

- the cost for retrieval and processing of materials from the nuclear fuel cycle, including removal, characterization, decontamination, transport, licensing, etc.;
- contingency funding required to offset financial risk due to unforeseen events (legislative aspects, technical constraints, public relation requirements);
- marketability of the material determined by the availability of new resources , and the specific cost of new (basic) material (for various reasons these costs may be lower or higher);
- an evaluation of the available waste management option, as low waste management cost including cost of storage and/or disposal represent negative influencing factors for recycle and reuse activities;
- credits/benefits based on national policies promoting recycle and reuse practices, i.e. tax incentives.

TABLE V. EXAMPLES OF SURFACE CONTAMINATION LIMITS FOR BETA-GAMMA EMITTERS APPLIED IN SPECIFIC PROJECTS FOR UNRESTRICTED REUSE OR UNRESTRICTED DISPOSAL

Contamination limit	Country	Additional information
0.37 Bq/cm^2 0.50 Bq/cm^2	Germany	Averaged over 100 cm^2 for fixed and removable contamination and for each single item. Applied to scrap metal and concrete originating from nuclear installations.
0.37 Bq/cm^2	Slovakia	Case-by-case decision on materials from decommissioning, 100% direct surface measurements.
0.40 Bq/cm^2	Finland	Removable surface contamination over 0.1 m^2 for accessible surfaces. Applied to radioactive substances originating from use in the production of nuclear energy.
0.40 Bq/cm^2	Belgium	Mean value for removable surface contamination over 300 m^2, for beta-gamma emitters and alpha emitters with low radiotoxicity.
0.83 Bq/cm^2	USA	Surface contamination above background over no more than 1 m^2 with a maximum of 2.5 Bq/cm^2 above background if the contaminated area does not exceed 100 cm^2. Generally applicable regulation.
1.00 Bq/cm^2	Italy	Case-by-case decision for a limited amount of materials from decommissioning.
1.00 Bq/cm^2	Canada	Averaged over 100 cm^2 for total contamination, 100% survey of all surfaces [69].
3.70 Bq/cm^2	France	Materials from decommissioning, 100% direct surface measurements.
4.00 Bq/cm^2	Sweden	Mean value for removable surface contamination over 100 cm^2, with a maximum of 40 Bq/cm^2 if the contaminated area does not exceed 10 cm^2. Applied to radioactive substances originating from use in the production of nuclear energy.
4.00 Bq/cm^2	India	Averaged over 100 cm^2 for fixed uranium contamination. Applied to scrap metal originating from refining facilities. The material is considered for free release if the concentration of uranium in the slag is less than 4 ppm.

TABLE VI. EXAMPLES OF SPECIFIC ACTIVITY LIMITS APPLIED IN SPECIFIC PROJECTS FOR UNRESTRICTED REUSE OR UNRESTRICTED DISPOSAL

Contamination limit	Country	Additional information
0.10 Bq/g 1.00 Bq/g 0.1–2.0 Bq/g	Germany	Specific activity limit regardless of type of emission. Applied to scrap metal originating from nuclear installations. Specific activity limits regardless of type of emission. Reuse of metal in a general melting facility. Specific activity limit for beta-gamma emitters.
0.10 Bq/g	Slovakia	Specific activity limit for beta-gamma emitters.
0.10 Bq/g	Sweden	Specific activity limits regardless of type of emission. Over and above the content of natural activity that occurs in corresponding goods outside the nuclear installation (primarily for limiting the activity in materials that, having been melted down, can be reuse in new products). Applied to radioactive substances originating from use in the production of nuclear energy.
0.40 Bq/cm^3	United Kingdom	Specific activity limits regardless of type of emission. Total activity for solids, other than closed sources, that are substantially insoluble in waste. Generally applicable regulation.
1.00 Bq/g	Belgium	Specific activity limit for beta-gamma emitters.
1.00 Bq/cm^3	Italy	Specific activity limit for beta-gamma emitters.
5.00 Bq/g	Sweden	Specific activity limit for beta-gamma emitters (artificial activity).

11.2.5. Availability of disposal facilities

The availability of, or access to fully developed treatment and disposal routes for large volumes of waste on a national or international basis, which must be paid for whether they are used or not, will not normally provide good incentives for recycle and reuse options. However, if disposal acceptance criteria could be amended to exclude material with potential for recycle and reuse, then recycle and reuse practices would be promoted. If disposal is not available, there will be more incentive to develop reuse and recycle options.

11.2.6. National policy

The availability of national policies and long-term strategies in support of recycle and reuse principles may have a profound impact on the efficiency and extent of recycle and reuse practices [72, 74]. These practices must be supported by a coherent dialogue among legislators, other competent authorities and the public to gain acceptance for release practices and to promote options to recycle or reuse of materials, rather than to restrict this practice. In the absence of a national policy promoting recycle and reuse, practitioners and operators should optimize opportunities for input in policy development, i.e. using results of real demonstration projects.

11.2.7. Public acceptance

Public acceptance of different options for the disposition of materials arising from operation, maintenance and decommissioning of nuclear fuel cycle facilities will play a role in the successful implementation of that options. Establishing a successful recycle and reuse policy is highly dependent on public information, communication and involvement.

Recycle/reuse and disposal/replacements each present different public acceptance issues [67]. Public acceptance of the practice of recycling materials with traces of radioactivity may be problematic because of the stigma associated with the nuclear industry in most industrialized countries. However, products containing low levels of added or naturally occurring radioactivity are widely used, and substantial quantities of scrap metal with very low residual radioactivity have been successfully recycled in a number of countries. Public perceptions of risk related to products containing radioactive materials (like smoke alarms) are influenced by product familiarity, its particular benefit, and the extent to which the radioactive aspects of the product are publicized.

Perceptions of repositories for disposal of radioactive waste are subject to similar public scrutiny and heightened sensitivity. Replacement/disposal options will present requirements for increased disposal capacity in excess of the capacity of currently operating facilities. Moreover, siting and licensing of radioactive waste disposal facilities have been the subject of intense political opposition.

Ultimately, public perceptions of the acceptability of both radioactive material management alternatives (recycle/reuse versus disposal/replacement) will influence significantly the implementation of either alternative. Consequently, additional information on the relative risks of both management alternatives could be a determining factor in the formation of public opinion and in the decision making process.

Other factors include inequitable social or geographic shifts in the impacts of dispositioning radioactive materials. The distribution of impacts among world regions differs between recycle/reuse and disposal/replacement options. Radioactive materials would probably be recycled or disposed of in facilities located in their country of origin. Radioactive material inventory is greatest in relatively industrialized countries, so the impacts of waste disposal would most likely occur in these regions. The increased mining and processing of raw materials required for material replacement is likely to take place in less developed countries and equally influence these countries. Consequently, the disposal/replacement option is likely to result in more substantial risk and impact both in developing and developed countries, in contrast with recycle/reuse option.

11.2.8. Hazards and risks

The disposition of nuclear fuel cycle materials inevitably entails some level of risk to workers, the public and the environment, including radiological and non-radiological risks. The radiological consequences for workers, the public and the environment of technically feasible methods for recycle and reuse should be comparable (not higher) to existing options for management of these materials as waste.

Although the radiological health risks from either recycle/reuse or disposal/replacement are relatively low, this is not often to be the case for non radiological risks, such as health risks for workplace and transportation accidents, as well as from exposures to chemicals that are carcinogenic or toxic. Of these two types of risks, the accidental fatality and injury risks to the public and workers are higher and much more immediate than radiological health risk [67].

Many aspects of replacement processes are conducted within environments that are less stringently regulated than the environment in which recycle/reuse alternatives would operate. Replacement necessarily involves mining of coal, iron, coke production, the occupations that have relatively high accident rates. Consequently, risk to workers from replacement/disposal alternatives may exceed those for recycle/reuse alternatives.

Moreover, because of the multiple stages involved in replacement/disposal practices, transportation requirements usually exceed those associated with recycle/reuse practices. Replacement must consider not only shipment of wastes, but also transportation of the coal and ores necessary for steel production. Accordingly, risk attributable to potential transportation accidents is often an order of magnitude higher for disposal/replacement option.

Similarly, the potential for adverse environmental impacts is higher for replacement/disposal alternatives. Although recycle and reuse alternatives will impact the environment by utilizing relatively small disposal capacity, replacement/disposal presents more severe adverse impacts to the environment from land use, disruption, and damage that results from mining and related processes [67].

Other environmental impacts attributable to replacement/disposal practices also include increased leaching of heavy metals from soils and mining wastes into surface and ground water, increased sedimentation of streams and rivers, emissions of toxic chemicals from mining operations, waste piles, and coke production, and increased energy requirements. Energy requirements for radioactive scrap metal replacement likely to be twice higher that for recycling and reuse of this metal.

Finally, recycle and reuse of radioactive material would conserve valuable natural resources. For example, an analysis has been performed which concluded that the reuse of radioactive scrap metal would reduce related raw material consumption (mainly coal) by 90% and mining wastes by 97% [75].

11.2.9. Legal/liability

Entities engaging in reuse and recycle practices carry full legal consequences of product responsibility for all arisings from those activities, which should be taken into consideration when analyzing disposition options for these materials.

11.2.10. Global optimization — full cycle impact

In general, a recycle and reuse strategy should present a net benefit when considering the health and safety of workers, the public and the environment, regardless of local or national boundaries. In addition, reducing the quantities of wastes which must be disposed of or stored, will reduce potential risks to people and the environment and thus potential future expenses and liabilities.

The overall objective of recycle and reuse practices, as part of the waste minimization concept, should be to reduce the environmental impact of the wastes, as well as the total costs involved. When considering global optimization, it is important to consider the costs of the individual contributions to obtain a net benefit status for recycle and reuse. In practice, it is usually a trade-off between the benefits accruing from the program and the costs to achieve these benefits. A full life cycle analysis should not only include radiological impact, but also the risk and environmental impact associated with material generation and energy consumption. To improve the effectiveness of choice between various material management and waste management alternatives, in addition to radiation protection, a global optimization should be considered, including a broad range of issues, such as:

- non-radiological detriments, e.g. health risks from chemical exposures, industrial accidents and transport activities;
- non-radiological environmental impacts on land, air, water, energy and other resources; and
- social and economic impacts, e.g. public acceptance, market factors, and equity issues.

11.3. METHODOLOGY FOR DECISION MAKING BASED ON FACTORS INFLUENCING RECYCLE AND REUSE

In the previous section, it was indicated that recycle and reuse practices may be influenced by multiple factors. When considering these influencing factors in the context of recycle and reuse, it should be clear that some level of optimization is required, and that, on a case-by-case basis, the ranking and relevance of these factors will differ.

When evaluating the various influencing factors for a specific recycle and reuse option, a simple ‘decision-tree’ approach could be adopted as indicated in Fig. 12, in which the various factors are evaluated. The limitations of a linear approach are that influencing factors may only be considered one at a time, and in descending order of priority. In addition, factors which are mutually influential cannot be considered in combination.

A more sophisticated approach to a multi-variant system is to use a decision matrix such as the Kepner–Tragoe decision analysis. This provides a method of ascribing a numerical weighting to different criteria. These can be defined as essential criteria, often those relating to safety at cost, and desirable criteria. A simple scoring of the criteria in a given option allows options to be discarded or considered further. Regardless of the approach it is necessary to produce a justifiable and auditable solution to options.

12. CONCLUSIONS

This report provides a summary of recycle and reuse opportunities at different stages of the nuclear fuel cycle, supported by selected examples indicating how these opportunities were implemented. The major issues related to recycle and reuse are described in order to promote discussion and feasibility assessment in particular Member States.

In the past, recycle and reuse of materials arising from activities related to the nuclear fuel cycle has not been a priority, with the exception of the long-standing practice of recovery and recycle of materials relating to some processes (i.e. fuel reprocessing and some aspects of power plant operations). A shift in emphasis in the last decade towards waste minimization in all parts of the nuclear fuel cycle has resulted in the development of technologies for recycle and reuse practices. Factors supporting this shift in emphasis include corporate responsibility and the ever-increasing cost of radioactive waste disposal. However, for a number of Member States, ongoing issues concerning clearance of materials for restricted and unrestricted release have presented challenges that have retarded full implementation.

A number of reuse and recycle approaches have been successfully considered in facility design, construction, operation, maintenance and modification. Substantial quantities of materials (mainly metal and concrete) are likely to be generated in the near future from decommissioning of nuclear fuel cycle facilities, and will create considerable opportunity for the implementation of recycle and reuse options. The report indicates and discusses major factors influencing decision making process and methodologies to optimize waste minimization through recycle and reuse at the facility and national level. The methodologies are broad enough to allow customization of the decision making process for various technical and regulatory environments. New generation nuclear fuel cycle facilities, that are in various stages of design and construction, employ appropriate technology to facilitate reuse and recycle activities in all facets of the facility life-cycle.

A number of issues have been identified in this report affecting the successful implementation of reuse and recycle of valuable materials from potential waste streams. These issues can be summarized as follows:

- There is a need for national policy and national strategy considering and favoring recycle and reuse.

- There is a need to have adequate and internationally acceptable release standard (both for restricted and unrestricted release), allowing potentially valuable materials to be systematically recovered through reuse or recycle practices. Disposition of very low radioactive materials currently relies on disposal at licensed low level radioactive waste disposal facilities or, less commonly, release on the basis of a detailed evaluation.

- There is a need to ensure public understanding and acceptance of the concept of release/clearance and the need for more efforts in the area of public consultation. More efficient use of raw materials and minimization of waste to be disposed of, reduces demands on the environment, providing benefits to future generations.

- There is a need for "global optimization" in order to improve the effectiveness of choice between various material management alternatives, including in addition to radiation protection a broad range of non-radiological detriments such as health risks from chemical exposure, industrial accidents and transport activities, non-radiological environmental impacts on land, air, water, energy and other resources.

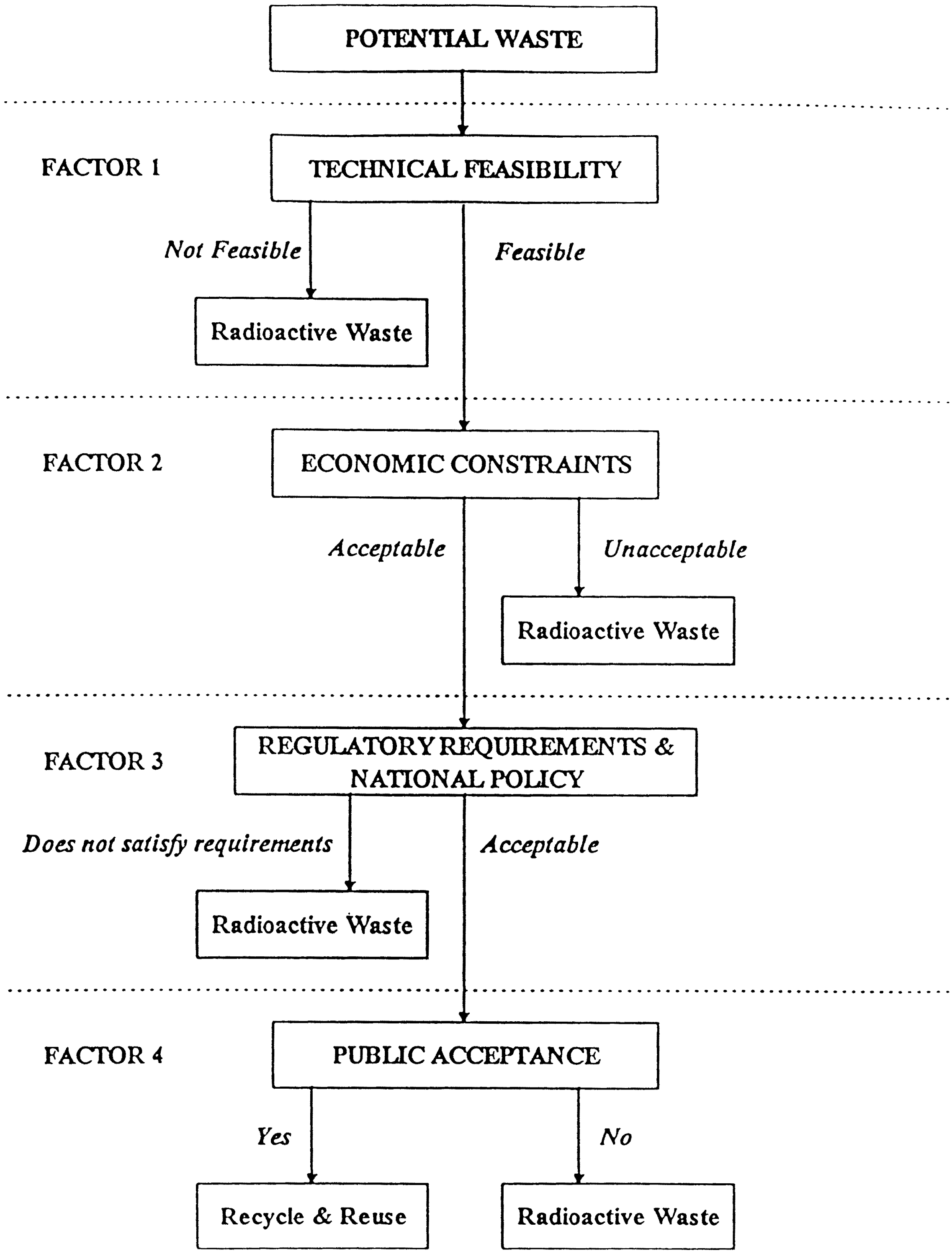

Fig. 12. Linear decision-tree approach.

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