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Minimization of waste from uranium purification, enrichment and fuel fabrication

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FOREWORD

As any industry, nuclear industry generates a diverse range of waste which has to be managed in a safe manner to be acceptable to the public and the environment. The cost of waste management, the risks to the public and employees, and the detriment to the environment are dependent on the quantity and radioactive content of the waste generated. Waste minimization is a necessary activity needed to reduce the impact from nuclear fuel cycle operations and it is included in the national policy of some countries.

In recognition of the importance of the subject, the IAEA has decided to review the current status of the work aimed at waste minimization in the nuclear fuel cycle. The waste minimization issues related to the back end of the nuclear fuel cycle are covered in Technical Reports Series No. 377 "Minimization of Radioactive Waste from Nuclear Power Plants and the Back End of the Nuclear Fuel Cycle" published in 1995. The present report deals with the front end of the nuclear fuel cycle, including existing options, approaches, developments and some specific considerations to be taken into account in decision making on waste minimization. It has been recognized that, in comparison with the back end of the nuclear fuel cycle, much less information is available, and this report should be considered as a first attempt to analyse waste minimization practices and opportunities in uranium purification, conversion, enrichment and fuel fabrication. Although mining and milling is an important part of the front end of the nuclear fuel cycle, these activities are excluded from consideration since relevant activities are covered in other IAEA publications.

A first draft of this report was prepared in April 1993 by consultants from Belgium, France, Germany, the Russian Federation and the United Kingdom. The draft was reviewed and revised at a Technical Committee meeting in November 1993 and at a consultants meetings held in April 1994, November 1996 and January 1998. The IAEA wishes to acknowledge the efforts made by a number of experts from Member States in drafting, revising and consolidating this publication. The officer responsible for this publication is V.M. Efremenkov of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION....................1
1.1. Background....................1
1.2. Objective and scope....................2
1.3. Structure....................2

2. WASTE MINIMIZATION STRATEGY....................3
2.1. Objectives of waste minimization....................3
2.2. Waste minimization options....................4
2.3. Source reduction....................4
2.3.1. Process selection....................4
2.3.2. Design....................4
2.3.3. Operation....................6
2.3.4. Decommissioning....................7
2.4. Recycle and reuse....................8
2.4.1. General considerations....................8
2.4.2. Principles of exemption and clearance applied to recycle and reuse....................9
2.5. Optimization of waste processing....................11
2.5.1. Waste segregation....................11
2.5.2. Waste processing....................11

3. PROCESS DESCRIPTIONS....................12
3.1. Refining....................12
3.1.1. Purification....................13
3.1.2. UO_3 and UO_2 production....................13
3.2. Conversion....................15
3.2.1. Reduction stage....................15
3.2.2. Hydrofluorination stage....................16
3.2.3. Fluorination stage....................16
3.3. Enrichment....................18
3.4. Fuel fabrication....................20
3.4.1. Uranium dioxide production....................20
3.4.2. Uranium dioxide fuel fabrication....................21
3.4.3. Metallic uranium fuel fabrication....................23

4. CURRENT WASTE MINIMIZATION PRACTICES....................24
4.1. Source reduction....................25
4.2. Recycle and reuse....................27
4.3. Waste management optimization....................30

5. FUTURE TRENDS....................31
5.1. Safety and environmental considerations....................31
5.1.1. Safety....................31
5.1.2. Environmental aspects....................32
5.2. Financial implications....................32
5.2.1. Costs estimation....................32
5.2.2. Potential benefits....................33
5.2.3. Costs of waste minimization....................33

5.3. Technical developments 34
5.4. Management initiatives...37

6. CONCLUSIONS...37

REFERENCES 39

CONTRIBUTORS TO DRAFTING AND REVIEW 42

1. INTRODUCTION

1.1. BACKGROUND

The front end of the nuclear fuel cycle which comprises facilities to purify, convert and enrich uranium from mining and milling and to manufacture fuel elements for nuclear reactors, gives rise to a variety of materials and products outputs. In addition to the products which the facilities were designed for, a wide range of other radioactively contaminated or suspect materials arise during their operational life. Not all these materials are considered waste. A lot of them have value and potentially can be recycled within the process or reused in other processes either directly or after treatment. The extent to which recycle and reuse are applied is mostly dependent on the economic factors. There are also other materials arise either directly from the main process or from the recovery operations which have no intrinsic value. These materials are classified as waste that has to be stored and ultimately disposed of. A general overview of the process material streams and routes in the nuclear fuel cycle is shown in Fig. 1.

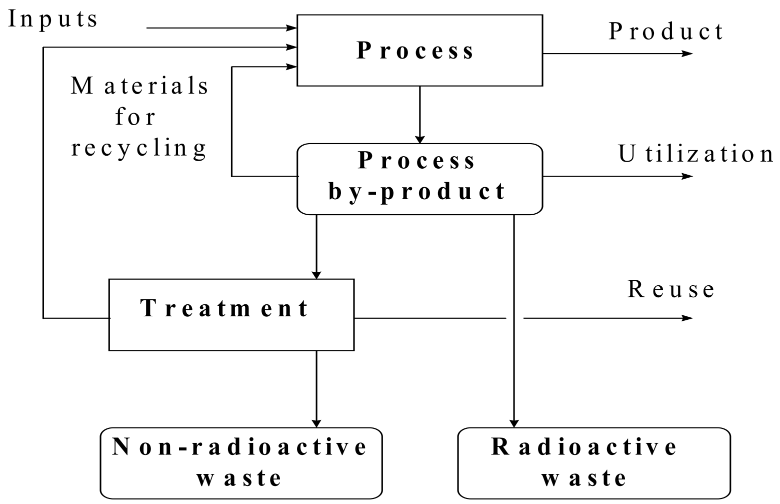

FIG. 1. Process materials streams and routes.

One of the fundamental principles of radioactive waste management is the control of waste generation. It is stated that “the generation of radioactive waste shall be kept to the minimum practicable, in terms of both its activity and volume, by appropriate design measures, and operating and decommissioning practices” [1]. In general terms, minimization includes both the reduction of generated waste and reduction of volumes of already generated waste since it is defined by the IAEA as “a concept which embodies the reduction of waste with regard to its quantity and activity to a level as low as reasonably achievable” [2]. An additional argument that is in favour of volume reduction associated with treatment of waste, is the possibility to change chemical composition of waste and make it more tolerant to the environment in case of disposal. The consequences of waste minimization is the reduction of the environmental impact and the increased efficiency of the nuclear fuel cycle owing to the decreased cost of waste disposal.

Like all innovative solutions to waste management problems, waste minimization requires careful planning, creative problem solving, changes in attitude, sometimes capital investment, and most important, a real commitment. The payoffs for this commitment, however, can be great. Waste minimization can save money — often substantial amounts — through more efficient use of valuable resources and reduced waste treatment and disposal costs. Waste minimization also can reduce a generator's radioactive waste related financial liabilities: the less waste generated, the lower the potential for negative environmental effects. Finally, taking the initiative to reduce radioactive waste is good policy. Waste minimization can pay off tangibly when local residents are confident that nuclear industry is making every effort to manage its waste responsibly.

It is recognized that the characteristics of waste from the front end facilities are significantly different from waste arising from the back end. They do not contain either activation or fission products, or actinides with the higher numbers than uranium. All of the radionuclides in waste are naturally occurring, albeit at much higher concentrations and usually in different chemical forms than in nature. They comprise uranium and thorium and the daughter products of their decay chains.

Another significant difference between the processes used at the front end as compared to the back end of the fuel cycle, is that the quantities of materials being handled, particularly in the early steps, are generally considerably greater and as a consequence, the physical size of the plants and the surface/volume exposed to potential contamination, albeit of low level, are substantially greater. However, because all these materials and equipment are only dealing with natural uranium the scope for decontamination of such facilities is not very high.

1.2. OBJECTIVE AND SCOPE

The purpose of this report is to review existing practices and experience gained in the minimization of waste from uranium purification and conversion, uranium enrichment and fuel fabrication in order to provide Member States with relevant information needed when making investment decisions and planning facility improvements. Both waste from operating facilities and from their decommissioning are included in the report.

Recycle and reuse of uranium and plutonium resulted from reprocessing operation (MOX fuel) and waste minimization aspects of uranium mining and milling are not included in the report because they are addressed in other IAEA publications [3, 4].

1.3. STRUCTURE

The report consists of six sections. A general strategy that may be used to minimize the amount or/and activity of waste generated (including non-specific approaches universally applicable to any generators) is discussed in Section 2. A brief description of the processes currently in use in the front end of the nuclear fuel cycle and corresponding waste arisings are given in Section 3. Section 4 presents the examples of waste minimization practices. Future trends and options are discussed in Section 5. Section 6 summarizes the main findings of the report.

2. WASTE MINIMIZATION STRATEGY

2.1. OBJECTIVES OF WASTE MINIMIZATION

The concept of waste minimization is capable of interpretation in various ways. It is often taken to mean minimization of the total quantity, usually volume but sometimes mass, or of the quantities of each individual waste stream. This may or may not involve reduction in the total activity in the waste streams. In practice, it leads to reduction of the total costs associated with waste processing which are of interest to the operator, while the regulators are primarily concerned with minimization of activity and sometimes the volume of waste for disposal and hence a potential environmental impact. The latter involves the nature and forms of wastes, as these affect their potential impact on the environment and hence on man and the biosphere. In practice, it is usually a trade-off between the benefits accruing from waste minimization and the costs to achieve these benefits.

Ideally, a waste minimization strategy should be considered at the planning and design stage of any process development. However, it is recognized that there are a significant number of installations already in existence and it is the challenging task from the feasibility and economic viewpoints to introduce technological innovations in the well established processes.

The development of a waste minimization strategy will always be dependent on many factors. These include the facility design features, the materials generated, the processing options and the costs to re-treat or recover, the quantities of waste generated, waste conditioning and the disposal routes available. For waste, there is also a balance to be made between the quantities of wastes generated in each category, e.g. short lived and long lived waste. For some of these categories, e.g. short lived, there may be existing disposal routes. For others, such as long lived waste, these routes may not exist and then there are major uncertainties over the duration and associated cost of interim storage and also over ultimate disposal costs.

In the implementation of a waste minimization strategy, it is very important to conduct a periodic review of effectiveness of the waste minimization programme. This review has to provide feedback and identify potential areas for improvements. Waste minimization assessments should be regularly made to evaluate material arisings including all measures to prevent their generation such as:

- Identification of opportunities at all points in the working areas and in the process where materials can be prevented from becoming radioactive waste, for example, by avoiding packaging material input into the controlled area, by using recycled materials in the process, or making equipment changes. Individual processes should be reviewed periodically.
- Determination of the true costs of recycling materials and of the waste management. The cost estimation of valuable materials found in the waste stream should be based on the purchase price. The cost estimation for recycling the valuable materials or managing these

materials as waste should include the costs for personnel, investments, treatment, accounting and tracking system, record keeping, intermediate storage, containers, transportation, liability insurance, and disposal.

2.2. WASTE MINIMIZATION OPTIONS

The most important elements of a waste minimization strategy can be summarized into three main areas [5]:

(a) Source reduction, or minimization of waste arising. The reduction or elimination of waste at the source, usually within a process is the first and the most important element of waste minimization.
(b) Recycle and reuse. Recycle and reuse are considered as the return of a valuable materials from potential waste streams into original process or other process for utilization (with or without treatment).
(c) Optimization of waste processing. Once waste is generated, its volume should be reduced by applying an adequate treatment technology. The objective of optimization in this content is to improve the quality and to minimize the volume of final waste forms (and assosiated cost) for storage and disposal.

These general principles are shown along with their main elements in Fig. 2.

2.3. SOURCE REDUCTION

Source reduction — the most prominent component of a waste minimization strategy — involves process selection, plant design and equipment choice, plant operation, process modifications, feed stock substitutions, improvements in feed stock specification, and increases in the efficiency of equipment.

2.3.1. Process selection

It is very important to select carefully the process for any new installation. For the operators who intend to build a new plant or to replace existing plant, it is important to examine the quantities and characteristics of materials arising from the various processes and degree of their complexity. Complicated processes or those which use larger quantities of materials should be avoided when selecting a technology for new installations. Compact, dry processes should be preferred over large wet processes. This can be further optimized in respect to waste minimization at the design stage.

2.3.2. Design

Waste minimization principles should be incorporated in the design phase for any new plant. Significant savings during the operational life of a plant can be achieved if sufficient attention is paid to waste minimization issues during the design stage. Cost savings accrued from the reduction in the waste treatment costs over the operation life of the plant usually significantly exceed this additional expenditure paid during design stage. The financial implications of any design proposals to minimize waste should be examined to confirm the cost-benefit of each proposal.

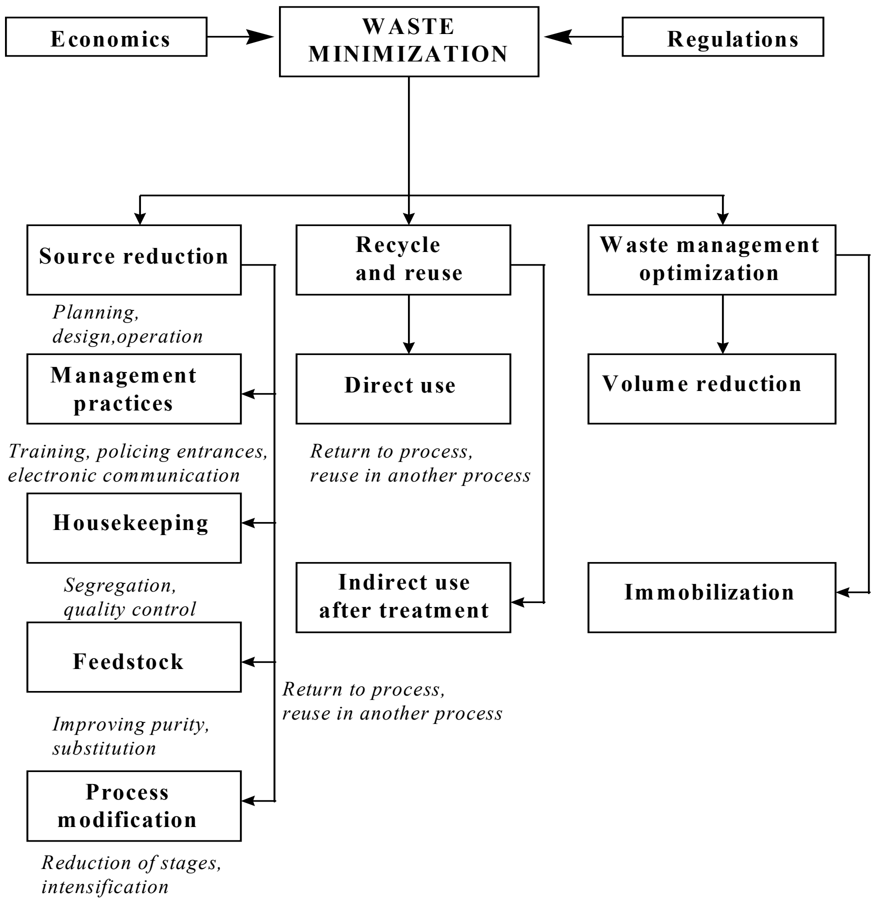

FIG. 2. Waste minimization options.

Design features can help to reduce both the level of radioactivity within the plant and the quantity of any non-product generation. Some of the design principles and features that can be used to aid waste minimization are the following:

– Careful selection of the materials used to construct the plant. This will minimize build up of contaminated materials and reduce decommissioning cost.
– Modular design. This again will aid decommissioning.
– Process intensification, that is to minimize the size and complexity of the plant.
– High integrity systems. These will reduce leaks and need for make up, and reduce process arisings, for example ventilation filters.
– Recycle and reuse of liquids and solid materials. Building these principles into the plant concept will reduce arisings and minimize treatment costs.
– Reliable equipment and proper arrangements for servicing. These measures will reduce the arisings from maintenance activities with subsequent savings from lower treatment costs.
– Appropriate plant layout to minimize contamination and assist in segregating materials. This will reduce arisings of contaminated waste for treatment and reduce the scale of decommissioning.

2.3.3. Operation

All operations should be reviewed on a regular basis and new techniques and practices adopted to ensure continuous improvement in the initiatives to minimize waste arisings.

Administration and management

One of the most important elements of a waste minimization programme is to raise the awareness of the need to minimize waste. This may be achieved in many ways, and each facility should use its own appropriate procedures for implementation of waste minimization. A rather effective action is education and training of employees in waste prevention and waste minimization practices. This education and training may be supplemented with bonus schemes for employees who identify ways to reduce the waste generation.

Another managerial approach to the implementation of a waste minimization programme is the explanation of the fact that the cost of waste management always will be deducted from the profit of the facility through the influence on the cost of the final product.

Contamination control

An efficient way to reduce waste generation at source is to apply strong management measures for the control of material flows into controlled areas. Specifically, the entrances to radiation and contaminated areas should be carefully controlled to prevent the introduction of unnecessary excess materials, equipment and paper. Electronic communication systems should be used to an extent practical instead of direct communication with the employees in controlled areas. In addition, when a number of tools and equipment entering controlled areas is declining, it reduces requirements for a frequent survey and decontamination. The reducing of the sources of contamination by such simple measures has a spiralling effect because the clean work areas do not require protective clothing for personnel and provide easier access for operation and maintenance.

Another focal area would be the substitution of PVC-based plastic as coating of concrete surfaces to prevent the spread of contamination and ease decontamination, by high quality epoxy coatings to surfaces. This coating could be mopped clean just as simple as plastic, but it does not need to be replaced, and, consequently, does not become a regular component of the problematic waste stream.

Attention could be also focused on laundry waste and launderables, including separation and separate treatment of contaminated and non-contaminated laundry, use of special washing process for PVC suits, so that over 95% of suits could be able to be recycled with the remainder being disposed of due to damage rather than contamination.

The bagless transfer system that can be used in conjunction with glovebox facilities (i.e. to handle radioactive metal oxides in reactor fuel fabrication plants) as well as for drum opening and closing allows to avoid secondary waste arising connected with PVC packages.

Materials quality control

Proper control over materials at all stages of the process from feed materials, through intermediates to final products is now recognized as an important waste reduction practice. In many cases non-products are just out of specification products such as contaminated, damaged or spillage materials. The costs of treating these materials include not only the treatment costs but also the loss of the product cost plus the additional fabrication costs to replace any shortfall.

The specification applied to the feed materials to a process can have an impact on the quantities of waste produced. For example, if a low specification material is accepted for the process, this means that there will be a significant amount of extraneous material supplied. These materials may have no any intrinsic value, and at the end of the process they become a waste and, therefore, have to be treated and disposed of. However, because they are generated within the front end of the nuclear fuel cycle, the treatment required to prepare such materials for disposal and disposal itself can be disproportionate to the value of the product.

It may be possible, within the confines of the final product specification to substitute certain process materials or process aids to reduce or even eliminate some non-product streams.

Product specification

A proper specification of the final product or product intermediates can also effect waste minimization similar to the impact on the feed materials. Relaxation of specification limits may increase the product efficiency with subsequent savings from the reduction in the rework required.

Process modification

A strategy for increasing the process efficiency is to reduce the number of processing stages either by combination of a few stages or the complete elimination of a certain process stage. This will increase the process efficiency with associated savings. In addition it may be possible to eliminate some by-products and waste generation.

Introduction of new equipment when replacement is required can result in a reduction of non-product streams. Generally, such an initiative will involve significant capital costs and therefore a detailed cost-benefit analysis should be carried out before such a decision is made.

2.3.4. Decommissioning

Decommissioning is the final phase in the life cycle of a facility. General information and guidance have been given in a specific IAEA publications on the decontamination and decommissioning of various nuclear fuel cycle facilities [6–9].

The general approach adopted for decommissioning of the front-end facilities is similar to that applied during maintenance of an operational plant. Before decommissioning commences, detailed planning with thorough initial decontamination should be undertaken. This is necessary to ensure that all operations are carried out in as safe and cost effective manner as possible, to minimize risks to workers and the public and to ensure that all operations giving rise to wastes are optimized to minimize such arisings.

Having established a management system for the decommissioning stage, the main principles should be identified. These should be in line with the normal practices during the operational life of the plant. That is, to decontaminate wherever possible to facilitate recycle of materials of value and to minimize the amount of waste to be disposed of, or facilitate disposal of non-radioactive waste with a minimum environmental impact. During decommissioning of the front end facilities, large quantities of materials and equipment, buildings and even sites will become available for recycle or reuse, or for disposal if economic and practical constraints prevent reuse.

2.4. RECYCLE AND REUSE

2.4.1. General considerations

For the purpose of this report, recycle can be defined as reutilisation of materials for the original purpose in their original form or after being treated or reworked. Reuse is utilization of valuable materials, tools and equipment for other than original purposes, also with or without treatment.

Although recycle of materials and reuse of facilities and equipment have traditionally been practiced in society, this trend has increased in recent decades. Part of the increased interest in recycle and reuse rests with the economic opportunities related to the savings in waste disposal and production of raw materials. In addition, there is an increased awareness in society of the desirability of conserving energy and other resources, making the best use of land and reducing environmental problems.

Recycle and reuse option seems to be very attractive during refurbishment and decommissioning of nuclear facilities, where large quantities of materials and equipment and some buildings and sites are released. Typical material categories arising from the above activities include:

- Radioactive waste which have no economic or practical value.
- Components whose activity levels can be reduced to levels acceptable for restricted reuse in a controlled area.
- Components which are inactive or have been decontaminated to bring their activity to levels below regulatory concern. These items can be released for unrestricted use if it is economic and practical, or sent for disposal as non-radioctive waste.
- For restricted release, the components remain under regulatory control. Examples include: the reuse of equipment within the controlled area, the fabrication from activated or contaminated metals of disposal containers for radioactive waste, and the use of a site for a new nuclear installation.

For unrestricted release, the components are no longer subject to regulatory control and can be used anywhere because they have been judged to represent negligible risk to the general public now and in the future. For example, contaminated metals can be cleaned, remelted and reused to make consumer goods. Also nuclear equipment, buildings and sites could be released for unrestricted use providing that they could be cleaned up so that activity levels are below the required regulatory standards for unrestricted release.

An option that may be considered in some situations is the controlled use of equipment, parts, tools, or basic metals. In this option, the material in question may not meet the exemption principles for unconditional release, but because of economic or other practical considerations, recycle or reuse may be prescribed for a limited (controlled) purpose. Such materials may be recycled within the nuclear industry if controls can assure that the accidental release of the material for public use will not occur, or that other means of potential public exposure can be prevented and that the radiation exposure to workers within the nuclear industry can be kept as low as reasonably achievable.

The decision whether or not to recycle or reuse components from nuclear facilities for restricted or unrestricted use depends on many factors some of which are specific to a facility or a country and others which are international in scope. Some of more important considerations are as follows:

- The availability of regulatory criteria giving activity levels for components which may be released for unrestricted use and those which may only be released for restricted use.
- The availability of the technology and facilities required to recycle the items.
- The availability of instrumentation to measure the regulatory activity levels and quality assurance programmes to assure compliance with criteria.
- The effect that recycling of materials will have on the extension of natural resources.
- The economic implications including the cost of decontamination, waste management, marketability of the recovered items, etc.
- The socio-political attitudes in the affected country or industry regarding the recycle/reuse of components from nuclear installations.

A possible decision process that could be followed when considering recycle or reuse is shown in Fig. 3.

Decontamination and reuse of tools and equipment for restricted use within the nuclear industry has been widely practiced and the techniques are well known. However, recycling/reuse of contaminated equipment for unrestricted use is not as widely practiced. One of the major problems is to confirm that inaccessible surfaces have been decontaminated to levels acceptable for unrestricted use. In addition, much of the equipment will be obsolete.

A wide variety of techniques are available and new or improved ones are continually being developed. The details of such techniques are fully described elsewhere [7 ,8]. They include a wide range of high and low concentration chemical and electrochemical decontamination processes, different mechanical processes, melting, etc. Thus, by removal of the contamination directly from the surface or in conjunction with a very thin layer of surface material, waste volumes can be minimized and the bulk of the material released as inactive for reuse. Considering the large volumes of metal from decommissioning reuse of this metal is a very important objective.

2.4.2. Principles of exemption and clearance applied to recycle and reuse

Some types of sources of ionizing radiation may not be a subject of regulatory control, either because they are not amenable to such control and are therefore excluded from the regulatory process, or because they present such a low risk that control by regulatory process would be a waste of resources [11–13]. In the latter case, two categories can be distinguished:

- Radiation sources which never enter the regulatory regime, i.e. control is not imposed (examption), and
- Radiation sources which are released from regulatory control, i.e. control is removed (clearance).

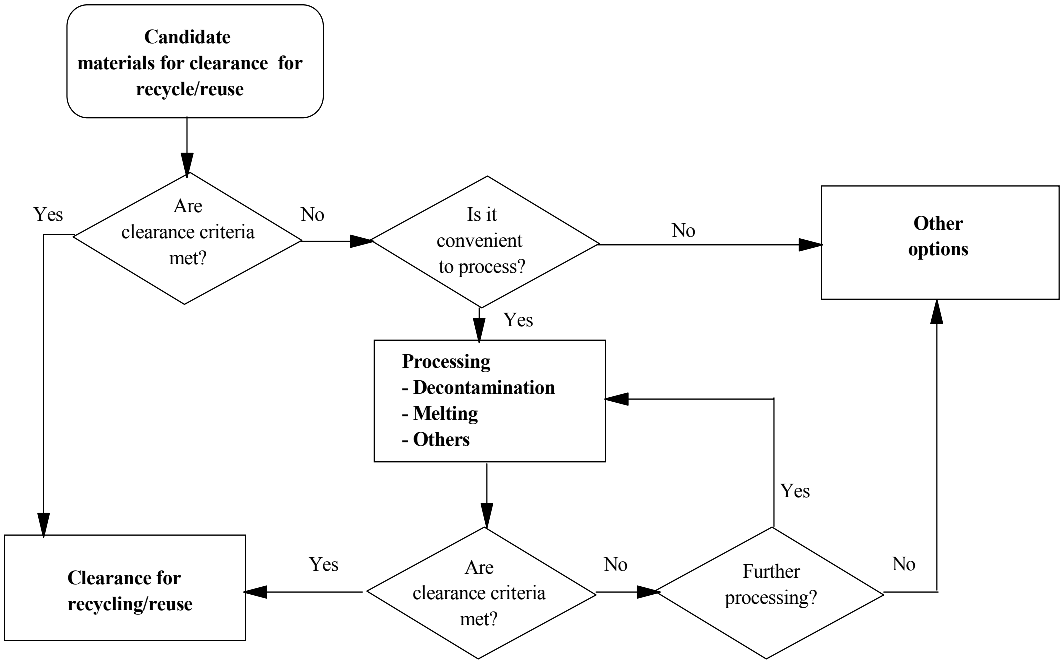

FIG. 3. Possible flowchart for considering clearance for recycle and reuse.

The general principles for exemption and clearance provided by the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [14] are:

(a) the radiation risk to individuals caused by the exempted practice or source be sufficiently low as to be of no regulatory concern;

(b) the collective radiological impact of the exempted practice or source be sufficiently low as not to warrant regulatory control under the prevailing circumstances; and

(c) the exempted practices and sources be inherently safe with no appreciable likelihood of scenarios that could lead to a failure to meet the criteria (a) and (b).

Taking the concept of trivial risk into account, the BSS further state that ‘A practice or source within a practice may be exempted without further consideration provided that the following criteria are met in all feasible situations:

(a) the effective dose expected to be incurred by any member of the public due to the exempted practice or source is of the order of 10 μSv or less in a year; and

(b) either the collective effective dose committed by one year of performance of the practice is no more than about 1 man.Sv or an assessment for the optimization of protection shows that exemption is the optimum option.

References [12, 13] illustrate methodologies by which practical radiological criteria can be developed for release (clearance) of radiation sources and practices from regulatory control based upon the above radiological principles and provide some conservatively derived generic clearance levels which could be applied when regulating use of small quantities of radionuclides. This methodology is intended to demonstrate procedures that national authorities may use in setting appropriate clearance levels.

2.5. OPTIMIZATION OF WASTE PROCESSING

Optimization of the radioactive waste processing steps following the waste generation is a third major part of a waste minimization strategy. Impressive results in waste minimization can be achieved by the application of a systematic approach for waste segregation followed by waste treatment/conditioning, and optimization of all stages of the technological process taking into account waste characteristics, facility limitations, facility resources and waste processing alternatives [15]. This approach can be considered for reduction of waste volume at any nuclear facility dealing with waste generation or waste processing. Optimization should consider the total life cycle of the facility and technologies involved, and availability of existing or potential disposal routes [15, 16].

2.5.1. Waste segregation

Segregation refers to "an activity where waste or materials (radioactive or cleared) are separated or are kept separate according to radiological, chemical and/or physical properties which facilitate waste handling and/or processing" [2]. It may be possible to segregate radioactive from cleared material at the point where it is generated and thus reduce the waste volume. To accomplish that, appropriate instrumentation is needed to demonstrate that the activity or activity concentration is below clearance levels. Such materials could be released from regulatory control and be disposed of as non-radioactive waste in domestic landfill.

Segregation of waste into established categories (e.g. short lived and long lived, compactable and non-compactable, combustible or non-combustible) could contribute significantly to the reduction of the volume of radioactive waste.

2.5.2. Waste processing

By appropriate treatment of primary radioactive waste and its immobilization, a considerable reduction of waste volumes can be achieved. In order to realize this option, it is important to ensure the support and commitments of top management of the operating facilities. Some of the steps that can be taken are the following:

(a) Characterization by proper methods (the source of the waste, type, category and physico-chemical properties), accounting and tracking systems (the date of generation, amounts, location) of the waste generated.
(b) Selection of suitable technologies for waste treatment and conditioning.
(c) Determination of the life cycle costs of various waste management process stages to identify the true costs for the management of material arisings.
(d) Encouraging the exchange of technical information on waste management with emphasis on waste minimization from other companies and/or institutions to share best practices.

3. PROCESS DESCRIPTIONS

In this section a brief description of the typical processes used in the refining, conversion, enrichment and fuel fabrication stages is given. Details of the origin, types and quantities of waste generated during these processes are also presented. A general overview of the process material streams and routes in the front end nuclear fuel cycle facilities is shown in Fig. 4.

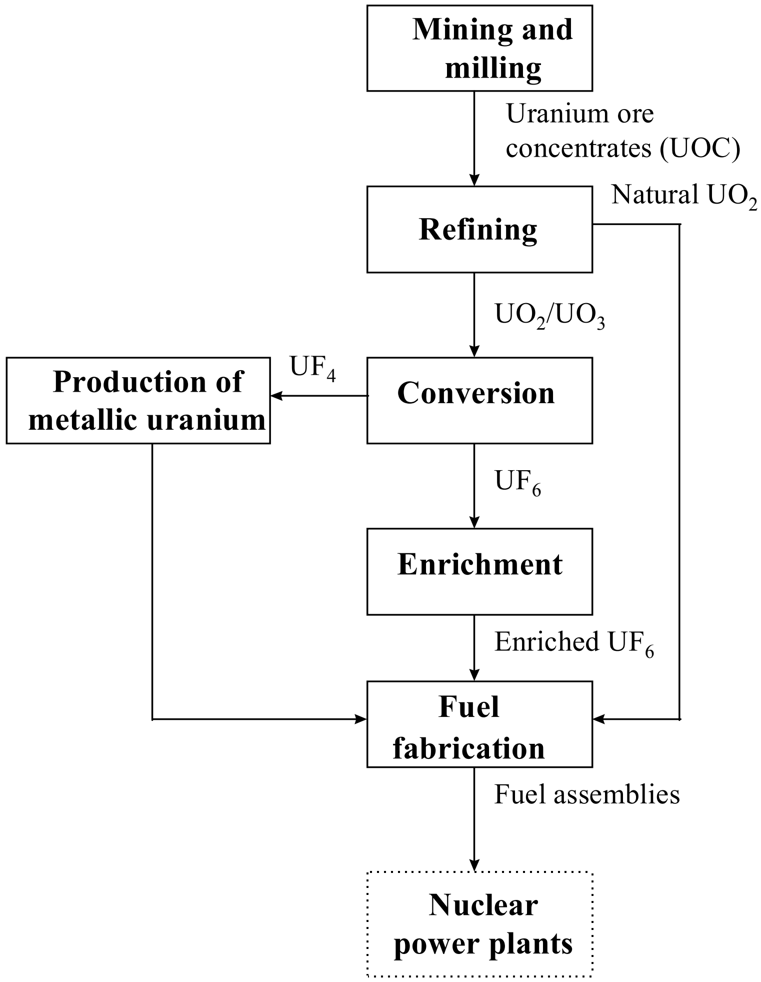

FIG. 4. Simplified scheme of the front end of the nuclear fuel cycle.

3.1. REFINING

Refining for the purpose of this report is defined as the processing of uranium ore concentrates (UOC) to produce uranium trioxide (UO_3) or uranium dioxide (UO_2). This process may be carried out on a single site or as part of an integrated process involving different sites.

A general sequence of different processes resulted in UO_3 and UO_2 production is presented in Fig. 5. These processes are briefly described below.

3.1.1. Purification

All refining processes have a common initial purification stage. Uranium ore concentrate is dissolved in nitric acid and then purified from a broad spectrum of impurities with a purification factors from 100 to 1000 by solvent extraction using, for example tributyl phosphate (TBP). Then the purified product is re-extracted from the organic phase to the aqueous phase forming so called uranyl nitrate liquor (UNL).

3.1.2. UO_3 and UO_2 production

Three basic processes are usually used to produce UO_3 and UO_2 from the purified UNL.

Thermal denitration (TDN) process

After the concentration of uranyl nitrate liquor, thermal dehydration and denitration are conducted in one single step. Uranium trioxide obtained is a fine powder with low reactivity.

Ammonium Diuranate (ADU) process

After the concentration of uranyl nitrate liquor, ammonium diuranate (ADU) is obtained by the precipitation of the uranium from the UNL using ammonia. ADU is separated from the liquid phase by filtration and then dried and calcinated to UO_3 at 250–350°C.

Ammonium uranyl carbonate (AUC) process

UNL is treated with ammonia bicarbonate to form ammonium uranyl carbonate (AUC) as a solid precipitate. This is separated from the solution, dried with methanol and then calcinated with hydrogen directly to UO_2.

The typical arisings/waste generation by the refining processes are given in Table I. A major part of the waste generated during the refining process is associated with the purification stage. The UNL after the purification stage is quite pure, and very low amount of waste is linked with the end of the process (purification of ADU, AUC, filtration and calcination steps)

Quantities of insolubles and sludges are strongly related with the type and quality of UOC. The waste arisings from TDN process are not directly comparable with those coming from ADU and AUC because the feeding UOC for these processes are different.

TABLE I. TYPICAL ARISINGS FROM THE REFINING PROCESSES (for 1000 t U)

Arisings	Quantity	Classification	Comments
Drums	70 t	Material for recycling or waste	All processes
Insolubles + filter aid	50 t	Waste	All processes, (depends on the nature of UOC)
Liquid effluent	3000–10,000 m^3	Waste	All processes
Sludges	300 t	Waste	(depends on the nature of UOC)
Liquid nitrates	200 t	By-product	ADU and AUC processes

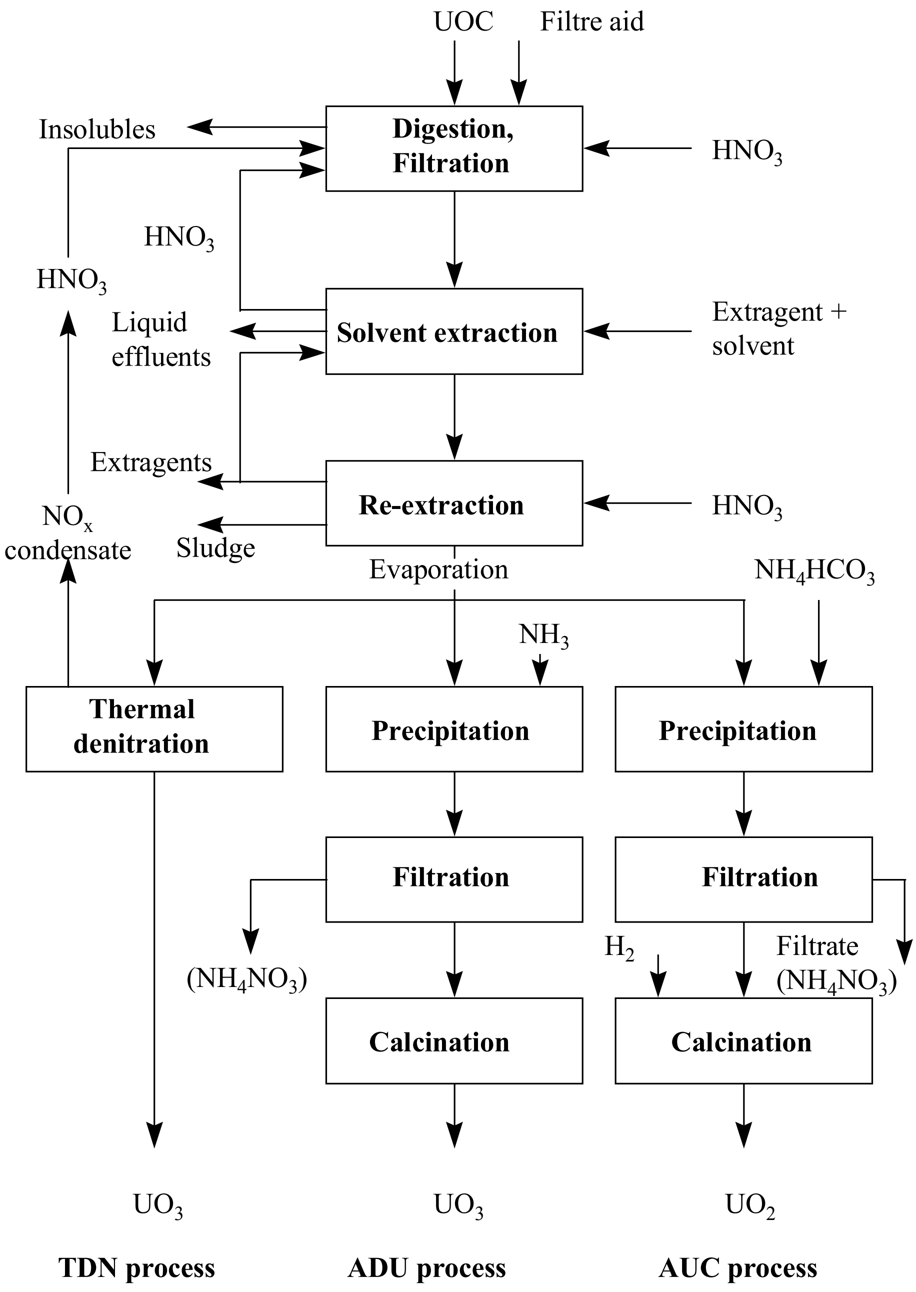

FIG. 5. Refining processes to produce UO_3/UO_2.

3.2. CONVERSION

Conversion, for the purpose of this report, is defined as the processing of UO_3 or UO_2 to produce uranium hexafluoride (UF_6)[1] . UF_6 is the only uranium compound that is suitable for performing enrichment because of its thermal stability and relatively high volatility. All current enrichment processes are based on the use of uranium hexafluoride. The flowchart of UF_6 production is presented in Fig. 6. This process has the following stages: reduction (if necessary), hydrofluorination and fluorination.

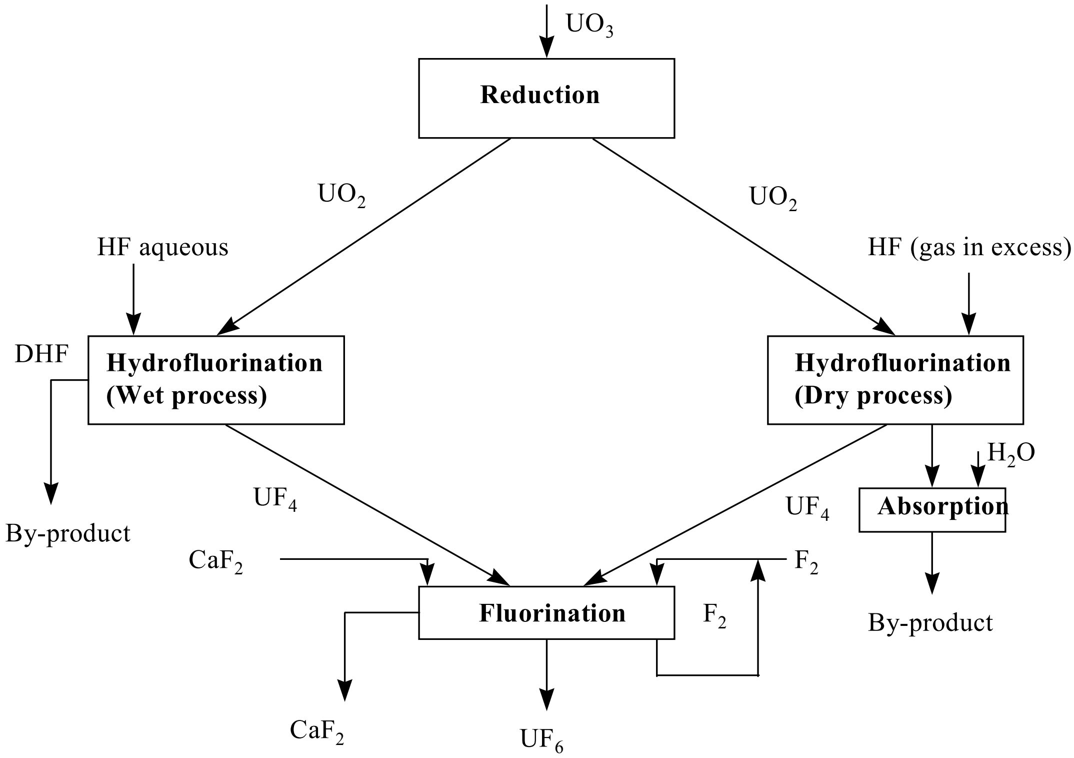

FIG. 6. Conversion of UO_3 to UF_6.

3.2.1. Reduction stage

The UO_3 is reduced to UO_2 by reaction with hydrogen or cracked ammonia in different kinds of reactors equipped with either moving bed, fluidized bed or rotary kiln. Reduction is carried out using hydrogen in a counter-current process.

[1]Although uranium tetrafluoride can also be used, e.g. for production of metallic uranium.

3.2.2. Hydrofluorination stage

Two different technologies are used for converting UO_2 to UF_4: wet process and dry process. In the wet process, UO_2 is converted to UF_4 by reaction with aqueous hydrofluoric acid. UF_4 is then precipitated from the solution. The only material arising from the wet process is some calcium fluoride from neutralization of unreacted HF by lime $Ca(OH)_2$.

In the dry process UO_2 reacts with gaseous HF. Any excess HF is recovered in the form of dilute hydrofluoride (DHF). This DHF has a very low uranium content and is reused in the chemical industry. Thus no significant waste is generated by dry process.

3.2.3. Fluorination stage

UF_4 reacts with fluorine to form UF_6 either in a flame reactor or a fluidized bed reactor which uses calcium fluoride as an inert bed. The tail gases from the flame reactor process contain residual UF_6, F_2 and HF. These substances are recovered by treating the gases with potassium hydroxide (KOH). The spent KOH is regenerated by reaction with lime. The fluorides are precipitated as CaF_2 which is stored as non-radioactive waste. Gaseous products from both processes are recycled within the plant.

The only waste arising in the fluidized bed process is the calcium fluoride. This material is stored to allow for the decay of the short lived daughter products of ^{238}U (^{234}Th- and ^{234m}Pa). The uranium is then recovered via nitric acid dissolution followed by solvent extraction to produce UNL which is recycled. The spent calcium fluoride, after drying, can either be consigned to a non-nuclear waste repository due to its low uranium content, or reused.

The general flowchart of uranium hexafluoride production at Springsfields (UK) comprising of purification, thermal denitration, reduction, hydrofluorination and fluorination steps is presented in Fig. 7.

The typical arisings from the conversion processes are given in Table II.

TABLE II. TYPICAL ARISINGS FROM THE CONVERSION PROCESS (for 1000 t U)

Arisings	Quantity (t)	Classification	Comments
Solid CaF_2	10	Material for treatment	Fluidized bed process
Sludges CaF_2, $Ca(OH)_2$, H_2O with small amounts of U	20–50	Material for treatment	Wet process
Sludges CaF_2, $Ca(OH)_2$, H_2O without U	30	Non-radioactive waste	Wet process

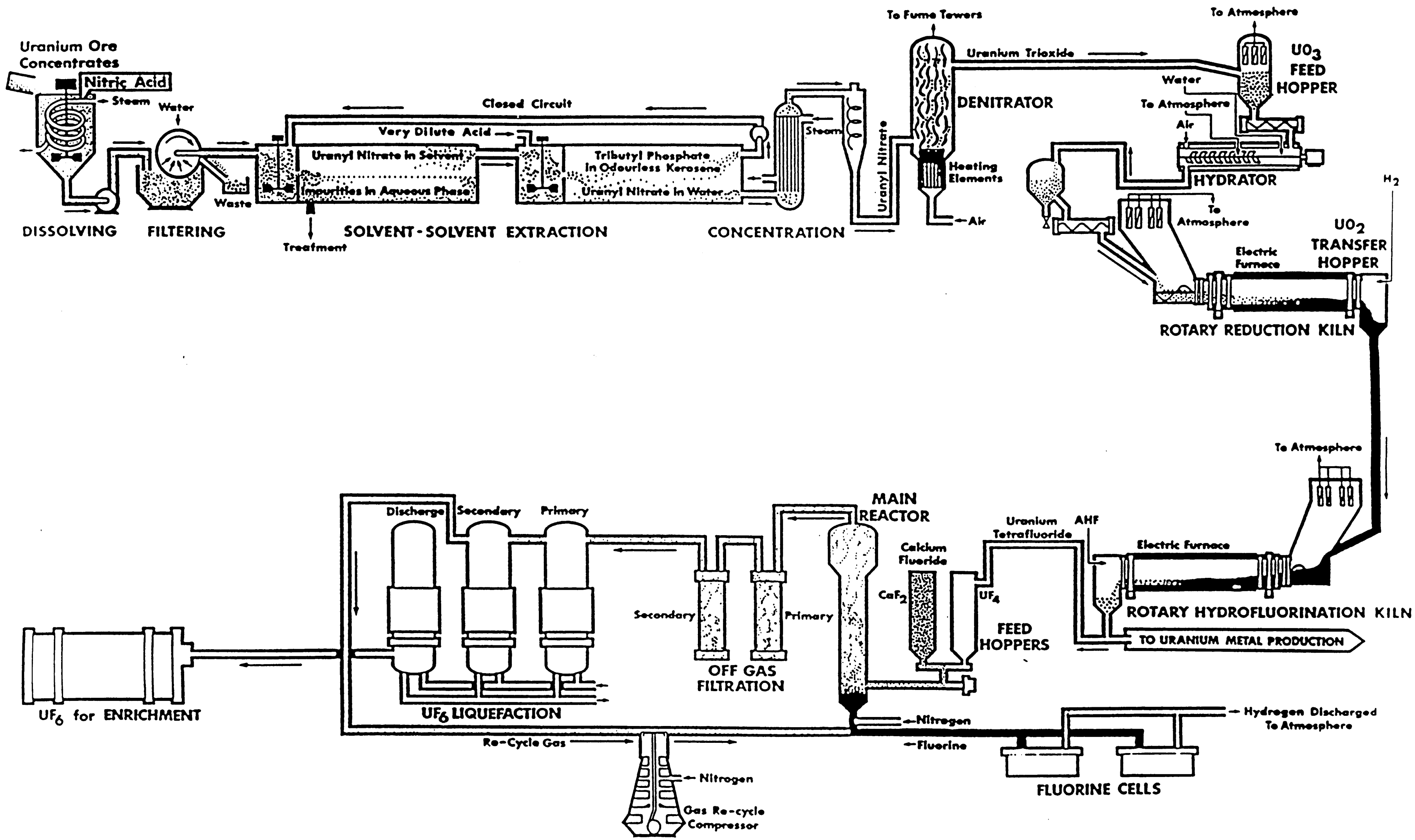

FIG. 7. Uranium hexafluoride (UF_6) production at Springsfields, BNFL.

3.3. ENRICHMENT

Enrichment involves increasing the proportion of ^{235}U, from the natural level of 0.7% to an average level of 3–5%, in UF_6. This can be done mainly by two different industrial methods: gaseous diffusion and centrifugation (Fig. 8).

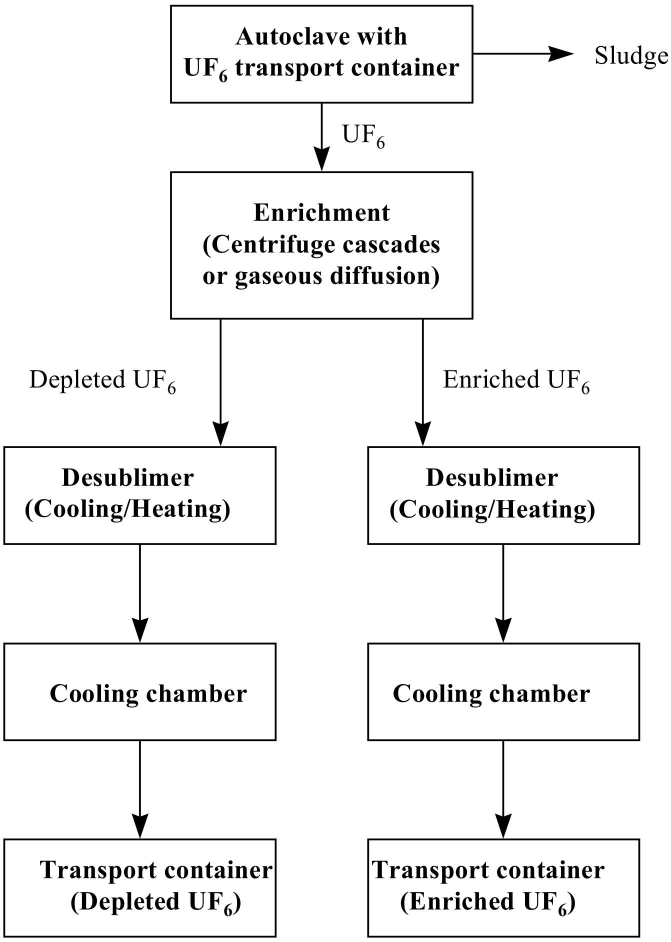

FIG. 8. Flowsheet of the enrichment processes.

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.

In the centrifuge process (Fig. 9) 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.

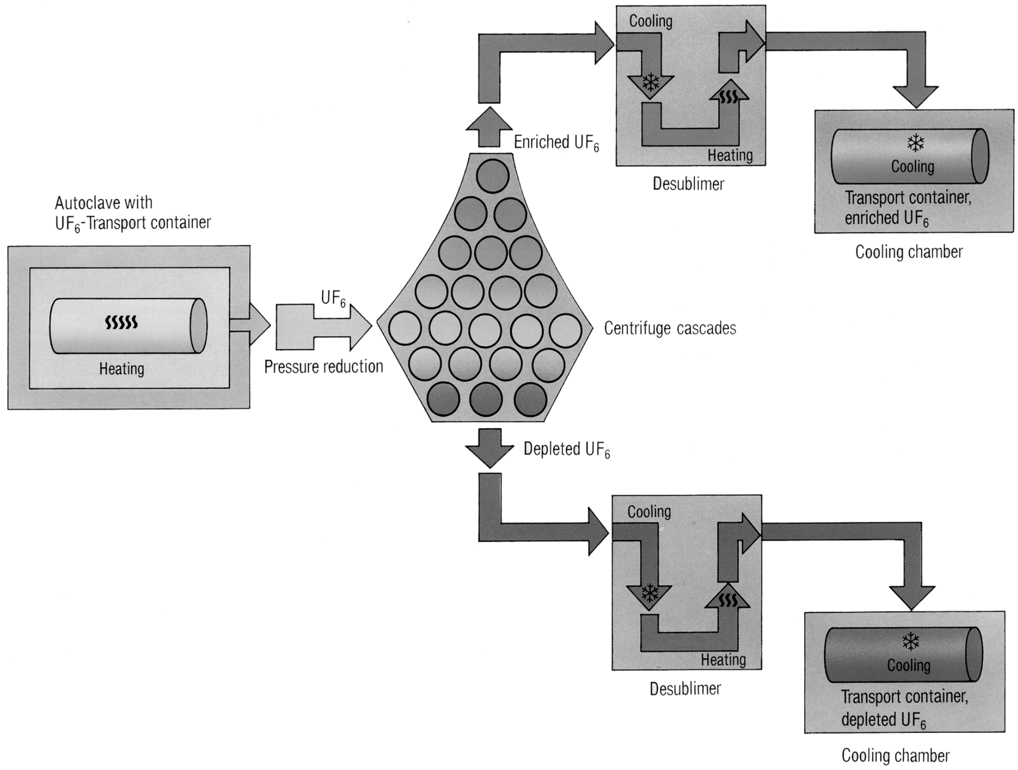

FIG. 9. The centrifuge process for uranium enrichment.

Centrifuge and gaseous diffusion processes produce only very minor quantities of waste. This is because the plant handles a single process medium (UF_6) which is completely contained in a high integrity system throughout the operation. Since the processes are physical, not chemical, there are no auxiliary inflows of material and no rejects of intermediate or waste products in the accepted sense. The minor quantities of waste which do arise result from the light gas which is passed through a small scrubbing system to ensure that only clean exhaust is released to the atmosphere, and from maintenance activities, which are infrequent and incidental to the main operations of the plant.

It should be noted that enrichment of 1000 t of uranium in the form of UF_6 leads to generation of around 850 t of depleted uranium with a ^{235}U- content of approximately 0.2%. This material may be classified as a by-product or as a waste.

Laser technology (e.g. AVLIS process, Fig.10), which is now under development on the laboratory or pilot scale level, potentially provides opportunity to reduce the content of ^{235}U in depleted uranium at least by factor 5, and to exclude highly toxic fluoride from the enrichment process [17].

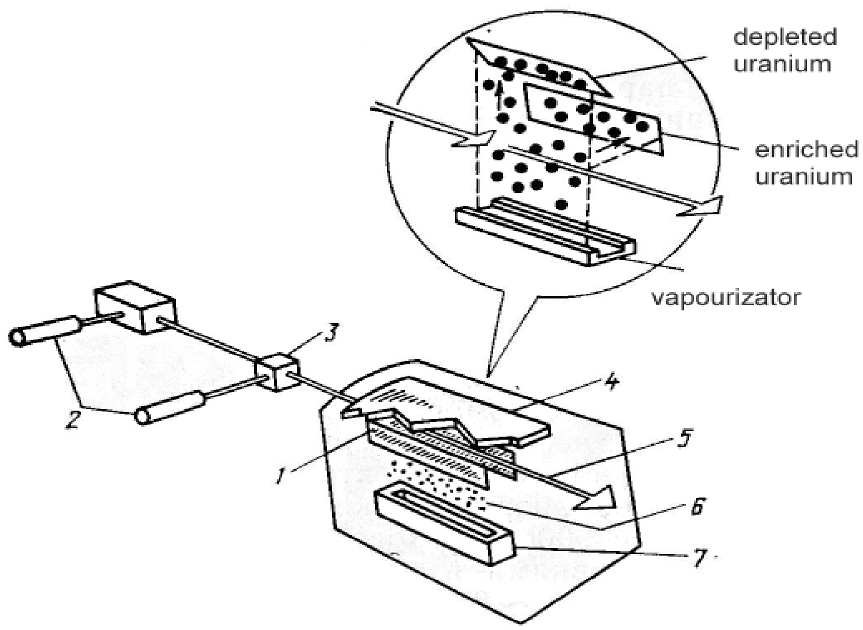

FIG. 10. Principles of laser induced isotopes separation in atomic vapours (AVLIS process): 1,4 — collectors of enriched and depleted products; 2 — exiting lasers; 3 — laser amplifier; 5 — laser beam; 6 — uranium vapours; 7 — electron beam vapourizator of metallic uranium.

3.4. FUEL FABRICATION

In the context of this report, fuel fabrication is the production of the finished fuel for loading into the nuclear reactor. For fuel fabrication, two products, uranium dioxide and metallic uranium are used as starting materials. Only natural uranium is used for production of metallic uranium fuel. When uranium dioxide is used for fuel fabrication it can be both natural or enriched.

3.4.1. Uranium dioxide production

There are three basic processes for the production of UO_2 powder for fuel fabrication: ammonium uranyl carbonate (AUC) process, ammonium diuranate (ADU) process and integrated dry route (IDR) process. These processes are schematically shown in Fig. 11.

The AUC process may be used to produce natural or enriched UO_2. The starting material to produce natural uranium may be uranium ore concentrate, or uranyl nitrate liquor as described in Section 3.1. For enriched UO_2 the starting material is UF_6.

The ADU process is primarily used to prepare natural UO_2 powder used for CANDU type reactors. The starting material for the ADU process is uranyl nitrate liquor. This may be prepared directly from the refining process or by the dissolution of UO_3 or other uranic compounds.

The IDR process is used to produce enriched UO_2, via a single stage starting with enriched UF_6.

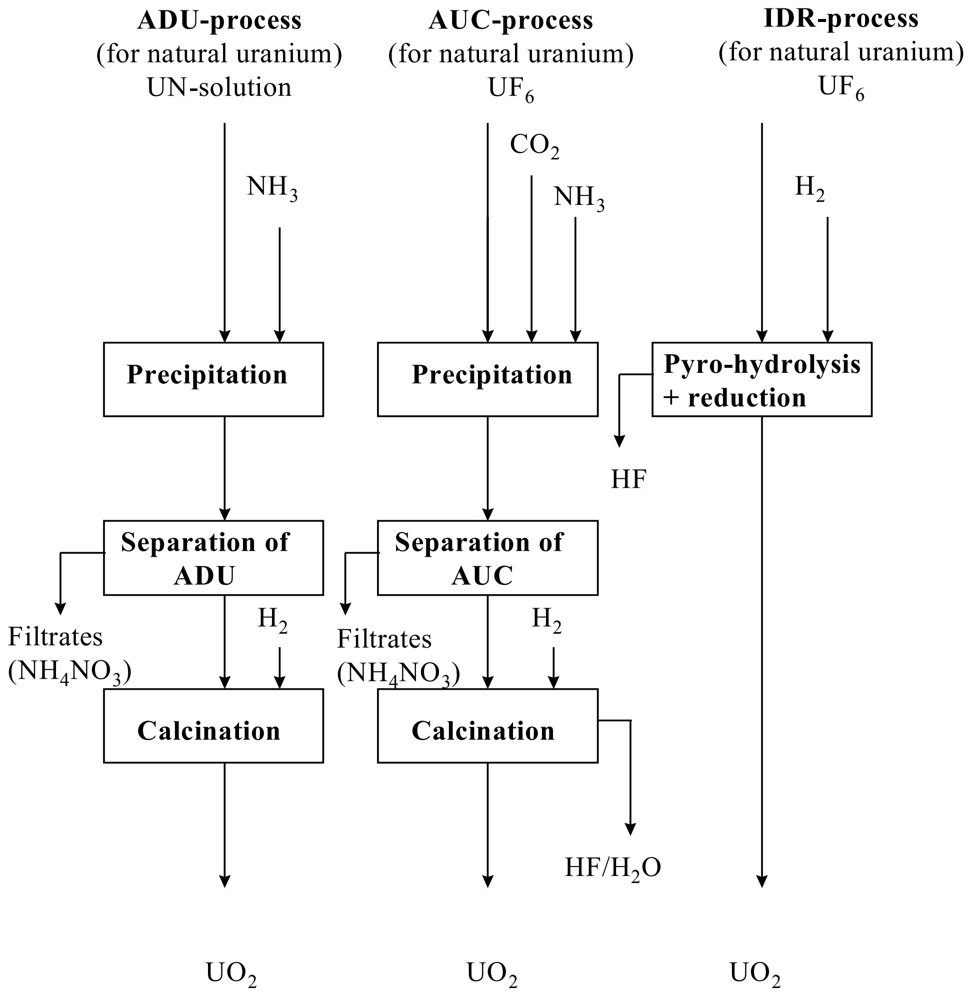

Fig. 11. Processes to produce UO_2.

3.4.2. Uranium dioxide fuel fabrication

Most of power reactors use uranium dioxide fuel in form of pellets sealed inside a metal cladding. Both natural and enriched uranium are used. The major reactor systems are light water reactors (LWRs) which utilize enriched UO_2 as the fuel, and zirconium alloys as a cladding material.

While there are variations in both the uranium enrichment in the fuel and the cladding materials, the main manufacturing process from the UO_2 powder to the finished fuel is basically the same. Therefore, only one process description is provided which identifies the major stages involved.

The UO_2 powder is first blended to provide an homogenized powder batch. U_3O_8 or other additives may be added if necessary. In specific cases, for fuel containing a neutron poison (e.g. gadolinium) the gadolinium/UO_2 mixture is prepared at this stage. All operations involving neutron poisons are carried out in a special separated facility. The blended powder is pre-compacted and granulated (some facilities do not use these steps). The granulated powder is compacted in a press into a cylindrical form ("green pellet"). The green pellets are sintered in a high temperature furnace in a hydrogen (reduction) atmosphere. After the sintering the pellets are grounded and loaded into zirconium alloy tubes. The tubes are filled with helium and then welded. The last production step is the assembling of the fuel elements to fuel assemblies. The whole fabrication process and the material arisings is shown in Fig. 12.

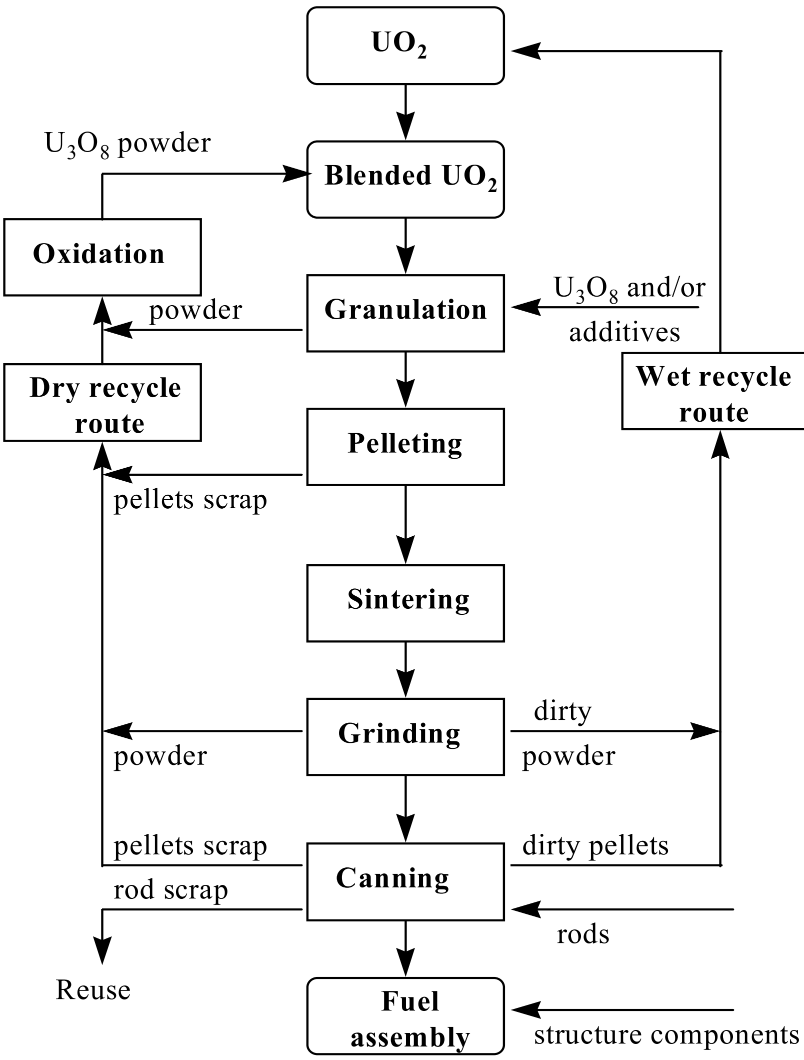

FIG. 12. UO_2 fuel fabrication process.

3.4.3. Metallic uranium fuel fabrication

Natural metallic uranium is used as a fuel in a certain cases, for example, to the Magnox reactors in the United Kingdom. The term “Magnox fuel” refers to the cladding material that is an alloy, on magnesium base. The starting material for this fuel is natural UF_4, and the production route is shown in Fig. 13.

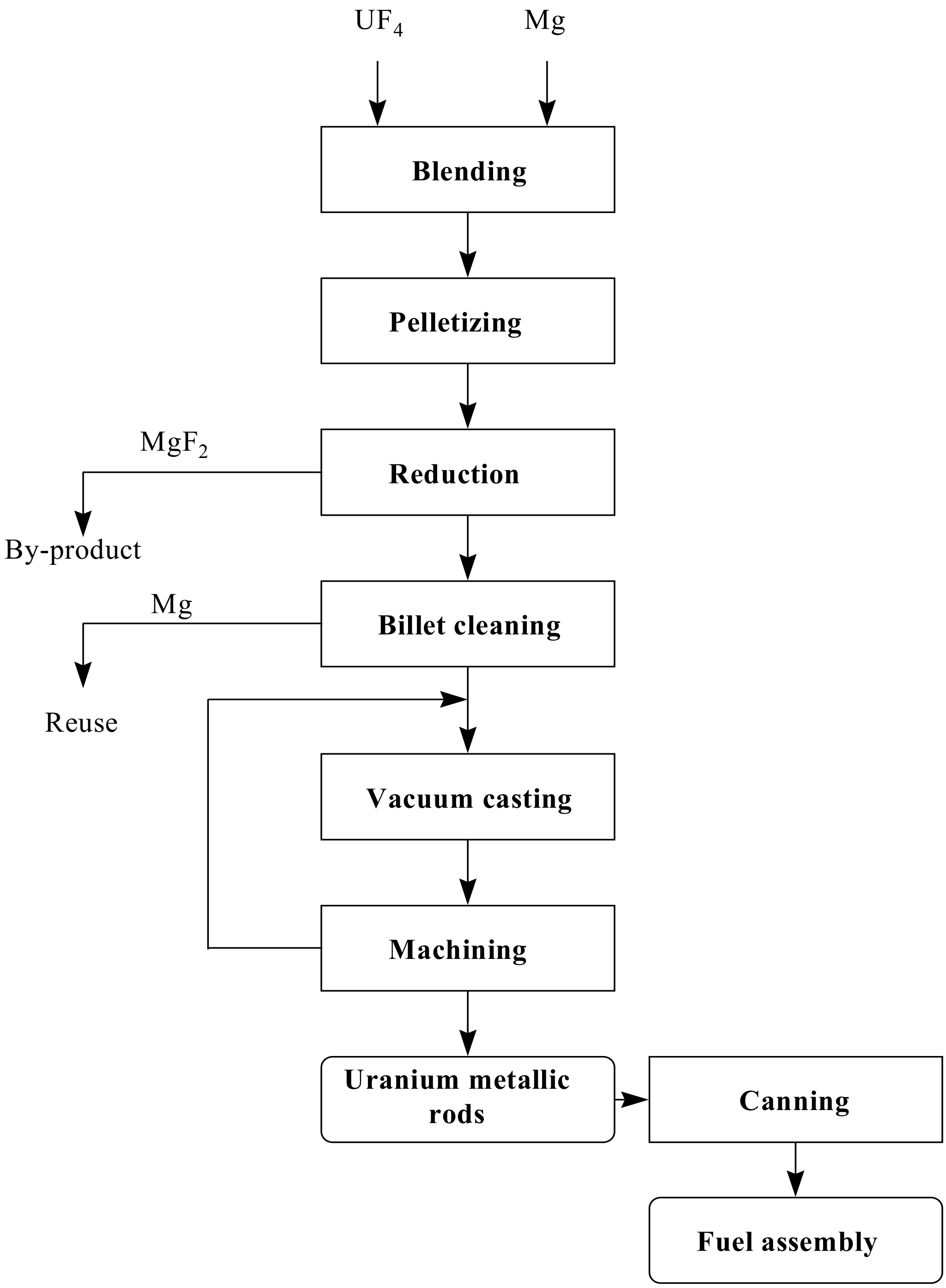

FIG. 13. Metal uranium fuel fabrication process.

The fuel canning stage follows the production of the metallic uranium rods. These rods are first machined to turn grooves along the length of the rod. The rod is then inserted into a Magnox can, the can is filled with helium and an end cap welded in place.

The fuel fabrication stage has the potential to produce a significant number of material scrap. Most of this scrap are not considered as waste because of significant value, and the majority of the materials can be recycled within the process. Some other materials, for example combustible materials or spent ventilation filters, may contain uranium that can be recovered for reuse. The objective here is to reduce the true waste component to a minimum.

The typical arisings from different fuel fabrication processes are shown in Table III.

TABLE III. TYPICAL ARISINGS FROM THE FUEL FABRICATION ROUTES FOR 1000 t U THROUGHPUT

Arisings	Quantity	Classification	Process/origin
Ammonium fluoride solution	4000 m^3	By-product	AUC
Ammonium nitrate solution	5000 m^3	By-product	AUC + ADU
Extraction residues	10 m^3	Material for treatment	AUC + ADU
Sludges	1 m^3	Material for treatment	AUC + ADU
Hydrogen fluoride	1000 t	By product	IDR
Magnesium fluoride	450 t	By-product	Magnox
Graphite	300 t	Material for treatment	Magnox
Zircaloy	1 t	Material for treatment	Water reactor fuel
Stainless steel	1 t	Material for treatment	Gas cooled reactor
Miscellaneous metal scrap	40 t	Material for treatment	All
Ventilation filters	100–200 m^3	Material for treatment	All
Mixed combustible material	300 m^3	Material for treatment	All

4. CURRENT WASTE MINIMIZATION PRACTICES

An extensive range of approaches to waste minimization, from management actions and technological solutions to innovative R&D programmes, has been developed and implemented all over the world in the recent years. One of the most important elements of a waste minimization program is to raise the awareness of the need to minimize wastes. This may be achieved in many ways, and each organization should use its own appropriate procedures for implementation of waste minimization and for dissemination of information on positive achievements in waste minimization practice. Rather effective action is training and appropriate courses should be made available to all employees, to educate them that all materials are valuable and should not be considered as "wastes". This education may be supplemented with bonus schemes for employees who identify ways to reduce waste generation.

As discussed in Section 2, the main options of waste minimization include source reduction, recycle and reuse of valuable materials and optimization of waste treatment and conditioning processes. The waste minimization options which can be applied for the materials arising from the various stages of the front end of the nuclear fuel cycle as detailed in Section 3 are shown in Table IV. The following text illustrates how these main options have been applied in practice in some Member States. (see also [18–21]).

4.1. SOURCE REDUCTION

The principles of waste minimization are now being widely applied in nuclear industry, both in front end and back end of the nuclear fuel cycle. Figure 14 demonstrates the application of this strategy in Germany, where the strategy has been incorporated into basic law and is to be applied to all material arisings. Similar strategies are also employed in other countries where nuclear industry is well established.

TABLE IV. WASTE MINIMIZATION OPTIONS

Process	Arisings	Source reduction	Recycle and reuse	Waste management optimization
Refining	Drums		√	
	Insolubles	√		√
	Liquid effluents	√	√	
	Sludges	√		√
	Liquid nitrates		√	
	Solvent		√	
Conversion	Solid calcium fluoride	√		√
	Radioactive sludges			√
	Non Radioactive sludges	√	√	
	Hydrogen fluoride		√	
Enrichment	Uranium contaminated solids		√	√
	Depleted uranium		√	
Fuel fabrication	Ammonium fluoride solution		√	
	Ammonium nitrate solution		√	
	Magnesium fluoride		√	√
	Graphite		√	
	Hydrogen fluoride	√	√	
	Extraction residues	√	√	
	Sludges	√		
	Zircaloy	√	√	
	Stainless steel	√	√	
	Miscellaneous metal scrap	√	√	
	Ventilation filters	√		√
	Mixed combustible materials	√		√

Employment of the concept "surveillance of materials rather than direct disposal" in the US nuclear power industry has resulted in conclusion that up to 80% of the material is not contaminated above established threshold radiation levels and need not enter the radioactive waste stream [22–24].

The waste arisings at BNFL Sellafield site fell by 35% between 1988 and 1994 despite the introduction of many new facilities [22].

Source reduction efforts should be reflected in the Quality Engineering of a process that normally defines all the process steps and operating limits to ensure that it is operated at maximum efficiency. In this way, the product output is maximized and the other non-product material arisings are minimized. For example the amount of uranium contaminated calcium fluoride from the conversion process using a fluidized bed reactor will be reduced if the conversion of $UF_4 \rightarrow UF_6$ is maximized. This will have two benefits:

- Reduction in the amount of calcium fluoride required a special treatment with consequential savings in the treatment costs.
- Diminishing of the quantity of calcium fluoride for disposal.

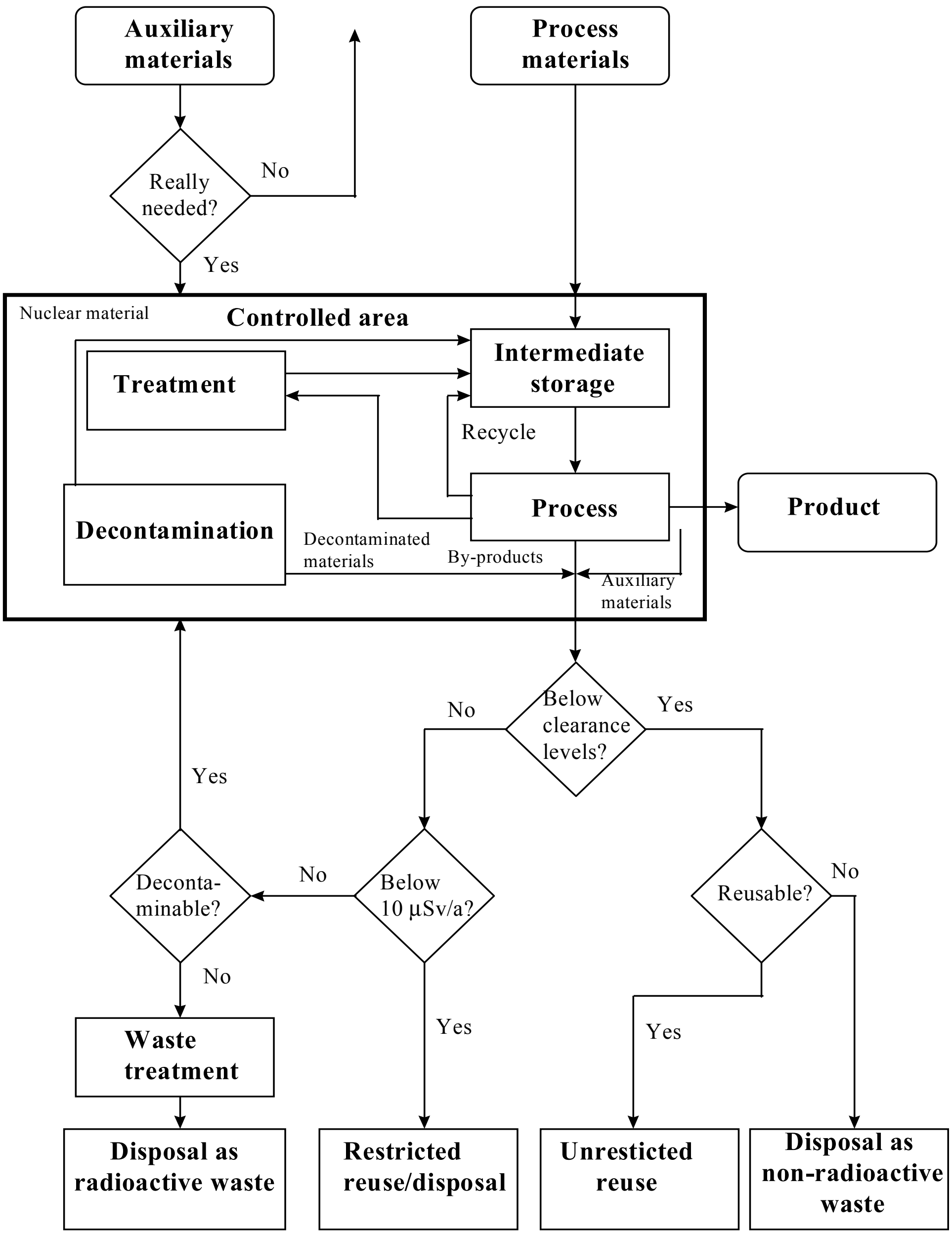

FIG. 14. Waste minimization strategy in Germany.

4.2. RECYCLE AND REUSE

The principles of recycle and reuse of process by-products is a significant element in any waste minimization programme. Typical example is the recycle and reuse of rejected pellets from fuel fabrication. Another examples of materials recycle and reuse in the front end of nuclear fuel cycle are presented below.

Nitric acid recovery

Nitrogen oxide gases (referred to as NO_X) are released when the uranium concentrates are mixed with the nitric acid at the digestion or dissolution stage. These are drawn off the digestion vessel by a water-jet vacuum scrubber. The dilute nitric acid solution produced by the scrubber is recycled into the digestion process. The residual air stream is released to the atmosphere. Additionally, the NO_X gases produced in the thermal denitration process are drawn-off the reactor by a water-jet vacuum scrubber or an exhaust turbine and sent to an absorber tower where they are re-captured to produce dilute nitric acid. The acid is concentrated in a distillation tower for recycling to the digestion stage.

Nitric acid and ammonia can also be effectively recovered from the waste water discharged from the nuclear fuel fabrication plants by the electrochemical processes: electrolysis and electrodialysis (Fig. 15). The target values of the processing system are the nitrogen concentration in a treated water < 0.4 mM; the ammonium concentration > 8 M, and the nitric acid concentration > 6 M [22].

The ammonium nitrate (NH_4NO_3) produced in ADU precipitation normally contains less radioactive components (uranium and ^{226}Ra) than normal ammonium nitrate, and may be used as fertilizer depending on the national regulations.

HF recycling

Conversion of UO_3 to UF_6 is carried out in three steps as described in Section 3.2. The arisings from the second step, the hydrofluorination of the UO_2 with HF, to produce UF_4, comprise water vapour plus excess hydrofluoric acid. This mixture can be condensed to produce dilute hydrofluoric acid for recycle or reuse. Alternatively, the mixture is scrubbed with an alkaline solution, e.g., potassium hydroxide, to remove the HF and any uranium particulates carried over.

In the dry-volatile process, impurities not removed prior to the UF_4 to UF_6 reaction are separated during UF_6 distillation, treated for uranium recovery and the residue goes to disposal.

TBP recovery

The TBP solution used in the solvent-extraction process gradually degrades due to oxidation and polymerization by the acid in the aqueous phase. To maintain the quality of the TBP solvent, a small stream is withdrawn from the process and treated with a sodium carbonate solution to neutralize the stream and precipitate the heavy molecular weight organic impurities. These are removed from TBP solution and either incinerated or drummed and sent to storage or disposal.

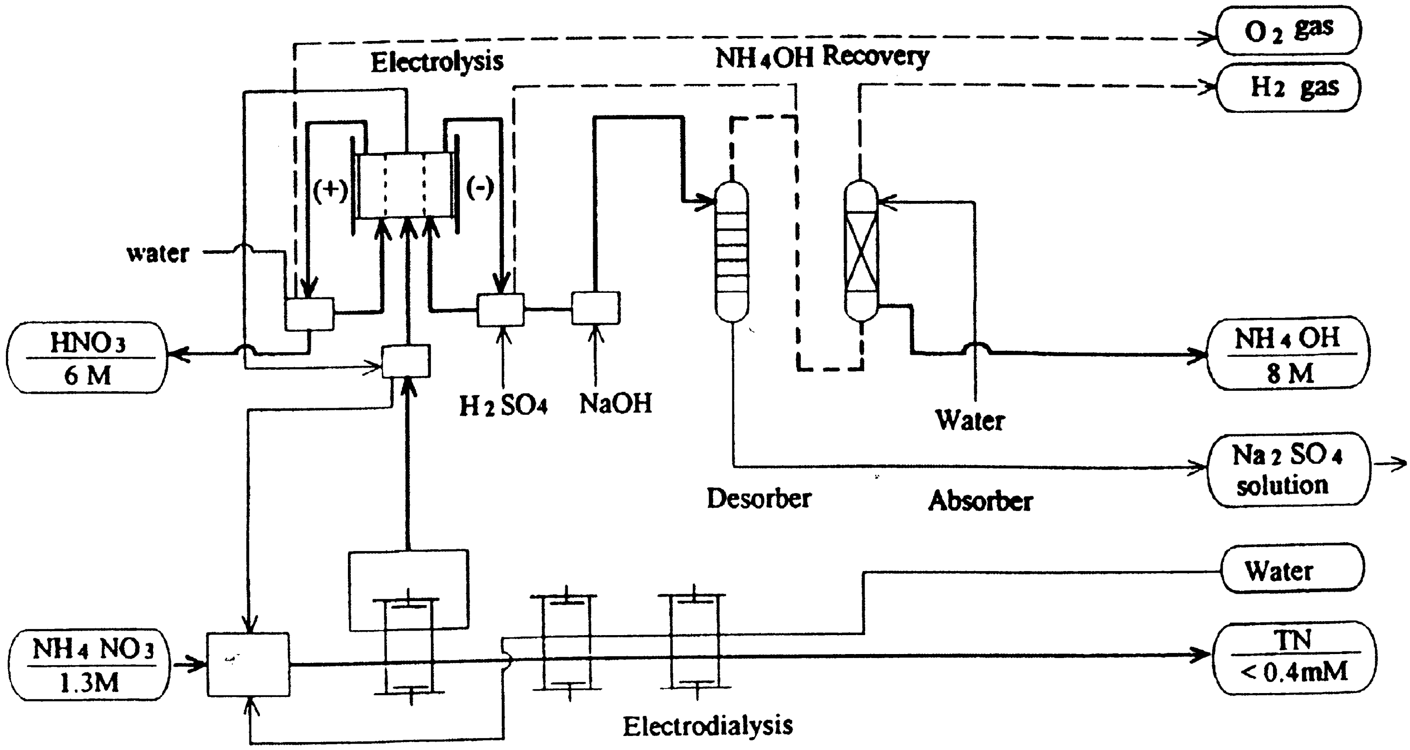

FIG. 15. Conceptual design of NH_4NO_3 contained waste water treatment system.

Other in-process streams

Sump and other liquors are normally recycled in-process, and do not present a significant requirement for waste treatment/disposal.

Decontamination of drums

UOC produced at the mine is usually transported to the refining plant in 210 litre steel drums. Drums found to be in good condition after emptying may be returned to a mine for reuse where this is economically feasible. Drums which cannot be reused, either because of their condition or because the cost of returning them to a mine is prohibitive, are washed and then crushed, to reduce their volume. The uranium removed from the drums is recovered by a process similar to that shown in Fig. 5. The crushed drums may either be sent to a steel mill for reuse or they may have to be stored or disposed of as non-radioactive or low active waste.

Decontamination during decommissioning

An example of how effective surface decontamination can lead to a very significant reduction in waste volume is given by the decommissioning of the original gaseous diffusion enrichment plant at Capenhurst in the United Kingdom. This plant was operated from the early 1950s until 1982, when diffusion technology was replaced by the centrifuge enrichment process. The project involved dismantling of eleven cooling towers, the plant's stage units (motors, membrane packs, valves etc), connecting pipework and other equipment. Post-operational clean up of the plant by washing ensured that little residual contamination remained. The bulk of the materials, totaling several thousands of tonnes of aluminium and steel, were chemically decontaminated and disposed of as clean scrap metal for general use.

Figure 16 shows some details of the plant constructed for a large scale chemical decontamination operation. Figure 17 gives some an indication of the scale of the decontaminated diffusion equipment awaiting disposal as scrap. Large pieces of equipment such as the stage units had to be cut up into smaller pieces of single shapes and smaller sizes before decontamination.

The process used in the decontamination facility was specially tailored to achieve high decontamination factors, whilst not exceeding the very strict discharge authorizations within which the site operates.

FIG. 16. Plant for large scale chemical decontamination operation.

FIG. 17. Decontaminated diffusion equipment.

The volumes and characteristics of the waste from these operations should be considered in terms of their minimization and further processing to meet the acceptance criteria for disposal. Thus, the liquid decontamination waste is usually filtered and/or chemically treated to concentrate the activity into a very small volume and to allow recycle of the liquor or its discharge to the environment. The solid waste is usually disposed of as low level waste, sometimes after compaction or immobilization into a matrix such as cement.

4.3. WASTE MANAGEMENT OPTIMIZATION

Strictly speaking, the management (segregation, treatment, immobilization) is not waste minimization, however application of waste processing methods leads to the reduction of storage or disposal costs owing to the reduction of waste volumes. Typical volume reduction methods applied are mechanical compaction, incineration, evaporation and melting [24]. More advanced methods are also applied: micro-chemical engineering, biodecontamination, supercritical fluid extraction with subsequent free release of waste to the scrap market, etc. Typical immobilization methods are the conversion of a waste by solidification, embedding or encapsulation into a form which reduces the potential for release or dispersion of radionuclides [25–27].

Incineration of combustible low level radioactive waste (plastic, cellulose, etc.) results in a spectacularly volume reduction. Incineration radioactive ash and residues are chemically inert, and in significantly more homogenous form than the original waste. Conditioning of ash from incinerators by cementation, supercompaction or sintering and melting processes provides waste packages for final disposal [28–30].

The advanced technology for environmentally clean treatment of organics contaminated with radionuclides (lubricating and hydraulic fluids, solvents, filters, ion-exchange resins, plastic containers, protective clothing, etc.) is flameless combustion of waste in a fluidized catalyst bed [31]. The unique feature of this technology is the possibility of the total oxidation of organic compounds at nearly stoichiometric ratio with oxygen at low temperature (600–750°C) what provides, in addition to the volume reduction, elimination of secondary pollutants, such as NO_x, CO, and polyaromatic hydrocarbons, dioxins.

Biotechnological processes, that are based upon the use of biologically produced compounds for the concentration of radionuclides and/or the degradation of organics, can be effectively applied for the waste minimization purposes in many branches of nuclear industry, and in medical, research and industrial applications of radioisotopes. These processes normally may involve three basic systems:

- Biodegradation of organics accomplished by cellular catabolism which utilizes the organics as a carbon source in the presence of nitrogen and phosphorus.
- Biosorption, which is the passive uptake of metals and radionuclides based on the chemical composition of the cell or its components (biosorption normally denotes the use of a dead biomass).
- Bioaccumulation as an active uptake and concentration by living microbial cells of radionuclide species.

In one or another way, these processes, that require minimal operator intervention, are actively used for decontamination and reducing secondary waste significantly.

Supercritical fluid extraction using solvents such as CO_2 offers the opportunity to extract contaminants without generating aqueous streams that need subsequent treatment. The contaminant can be recovered simply by backing off the CO_2 pressure from the supercritical regime. This technology can be productively applied for decontamination of steel and alloys from inorganic contaminant such as uranium what, in turn, leads to further waste minimization by the free release of non radioactive materials to the metal scrap market [32].

5. FUTURE TRENDS

When discussing future trends in waste minimization in the front end of the nuclear fuel cycle it is necessary to consider all aspects relating to the nuclear fuel cycle as a whole. As an example the widespread adoption of MOX fuel and the availability of large quantities of highly enriched uranium from military programmes could significantly affect the timing and even needs for new enrichment capacity. In addition, improvements in the utilization of fuel through enhanced reactor load factors and increased fuel burn up will increase the amount of power obtainable from a given quantity of fuel and hence will indirectly reduce the quantities of fuel needed and hence waste produced per unit of electricity generated.

The nuclear industry like other industries will have to recognize future trends and provide solutions to meet these demands. These developments will have to meet both environmental and economic needs. The main pressures which will affect the industry can be categorized as safety and environmental, financial, technical and managerial/educational.

5.1. SAFETY AND ENVIRONMENTAL CONSIDERATIONS

5.1.1. Safety

Since a waste minimization strategy may introduce new hazards or modify those associated with a facility, all future activities must aim to reduce this impact. Thus, prior to implementing the strategy, whether at the conception of a new facility or when modifying the existing plant, processes or procedures, it is most important to examine the potential implications to ensure that the strategy does not somehow increase risks to the health of workers or the public and to the environment. Appropriate, systematic assessments need to be undertaken to identify hazards and the impacts resulting from the normal operations and potential accidents due to internal and external causes. This may be accomplished by such techniques as **HAZOP** analysis (i.e., Hazard and Operability [33–35]), **FMEA** (i.e., failure mode and effects analysis [36]), **fault tree and event tree** studies and probabilistic risk assessment.

A type of the assessment which needs to be undertaken and the level of detail to which the assessment is taken and also the thoroughness of reviews carried out by internal bodies and/or regulatory authorities should be related to the characteristics of the strategy and the significance of the changes involved. Thus minor changes in operating procedures which do not have impacts beyond the workers immediately involved in the operation will require less analysis and review than, for example, process changes which could have potential impacts on the public and the environment.

5.1.2. Environmental aspects

Environmental aspects mean:

- need to minimize the environmental impact of discharges/waste,
- acceptability of disposal routes, and
- availability of disposal facilities.

Environmental aspects also include regulatory requirements:

- requirements to reduce operator doses to even lower levels,
- requirements to reduce discharges to the environment,
- the move to risk-based assessments health impact, and
- uniform release requirements.

Regulatory requirements to seek continuously ways to minimize waste arising and hence reduce emissions to the environment is now reflected in the national legislation of many countries. Limits on waste arising and discharges to the environment are just the first part of most site or process authorizations, which are then augmented by other conditions which require continuous improvement. The applications of the **ALARA** ("as low as reasonably achievable") [37] and **ALARP** ("as low as reasonably practicable") [38] principles, as well as recent supplements, such as the use of "best available techniques not entailing excessive cost" **(BATNEEC)** [39], and "best practicable environmental option" **(BPEO)** [40] all require the waste producer to regularly review his processes and practices to see whether changes cannot be reasonably made to further reduce environmental impacts.

5.2. FINANCIAL IMPLICATIONS

The minimization of waste in the front end of the nuclear fuel cycle inevitably has financial implications, both negative and positive. It may be thought that the costs of waste minimization would be greater than any savings, but in actuality, the opposite may result. Experience from non-nuclear operations has shown in many cases that waste minimization efforts can produce significant profits.

5.2.1. Costs estimation

In the analysis of the economics of waste minimization, it is not unusual for certain expenses to be overlooked and thus, the overall cost (and the potential for savings) to be underestimated [41, 42]. The real cost arising from the generation of "non-products" and in particular, waste, includes the following:

- Expenses associated with inefficiencies in the production process.
- Direct and indirect expenses associated with handling and controlling waste prior to disposal or storage.
- Actual and potential expenses associated with disposal or storage.

The expenses arising from inefficiencies in production include the capital inputs and operating costs associated with having to process additional feed materials, to off-set the losses, to non-product outputs, the costs of separating and recycling the unconverted raw materials from the outputs and poor quality products and the loss of value of input materials which are contained in waste.

In regard to the second element, the direct expenses which should be taken into account include costs associated with treating and packaging the waste for storage (whether for temporary or long term storage); labour and capital inputs to move and temporarily store waste; labour (and possibly capital) inputs to monitor waste during temporary storage (including keeping track of records); and labour and consumable inputs to clean up any leaks or spills during temporary storage. The indirect expenses include costs of administrative inputs to achieve and maintain compliance with regulatory requirements during temporary storage. Where such requirements are complex and demanding and are imposed by more than one regulatory authority, such indirect expenses may be quite significant.

The expenses arising in the third element are more difficult to determine because most of them hinge on unpredictable and thus uncertain future events. They include the definite costs of preparing the waste for disposal or indeterminate storage, and constructing, maintaining and servicing the disposal or storage facilities required. They also include indefinite liabilities arising from the failure of those facilities, to pay for remediation work on them or for the provision of new facilities, and fines or other legal penalties, cleanup expenses and compensation related to the leakage and dispersion of hazardous materials. Such expenditures may arise long after the placement of the waste in the disposal or storage facility, as, for instance, in the case of the Love Canal Chemical Waste Facility in the USA. where Hooker Chemical had to remove toxic materials from a landfill many years after they had been buried there in accordance with the methods acceptable at that time [43].

5.2.2. Potential benefits

The principal benefits which may be achieved through implementation of the strategy of source reduction and recycle are, of course, the tangible savings obtained through reductions in the direct expenses associated with one or more of the cost elements.

Improving the efficiency of production process steps reduces the feedstock and energy needed per unit of product and reduces the level of process arisings with a consequent reduction in treatment costs.

Reducing the quantities of waste which must be disposed of or stored will reduce potential risks to people and the environment and thus future expenses and potential liabilities. While such savings are not tangible, they do, nevertheless, constitute a substantial benefit.

In addition, the more efficient use of raw materials and the minimization of waste reduces demands on the environment, which provides benefits for future generations.

5.2.3. Costs of waste minimization

The costs of implementing a waste minimization strategy can vary over a wide range, depending on the economic and technical factors applicable in each specific case. At one end of the scale, upgrading or replacing equipment or installing a new process would typically involve large capital expenditures, while at the other end, developing new procedures and training staff to operate or maintain the facility more effectively and efficiently would generally cost relatively little. In the former case and possibly in the latter one too, there would also be ancillary costs to provide information to regulatory authorities to demonstrate that planned changes do not increase risks and environmental impacts.

5.3. TECHNICAL DEVELOPMENTS

Further waste minimization or elimination of waste streams will be an important aspect of technical developments. Some advanced concepts, approaches and technologies (being introduced into practice on industrial scale and potentially able to improve the existing situation in the front end of the nuclear fuel cycle) are briefly summarized below.

Dry processes reduce the environmental impact by eliminating liquid waste streams. For example, an alternative method for uranyl nitrate conversion which does not lead to a liquid by-product is being developed in Russian Federation [44, 45]. This process avoids the ammonia treatment. It consists of the plasma treatment of the uranyl nitrate solution. This process converts the nitrate solution into commercial products: disperse uranium oxide and solution of nitric acid. During this process no chemical reagents are added, and no liquid wastes are generated. The schematic flowsheet of the process is presented in Fig. 19. The technique proposed is efficient, easy controlled and does not produce any harmful by-products.

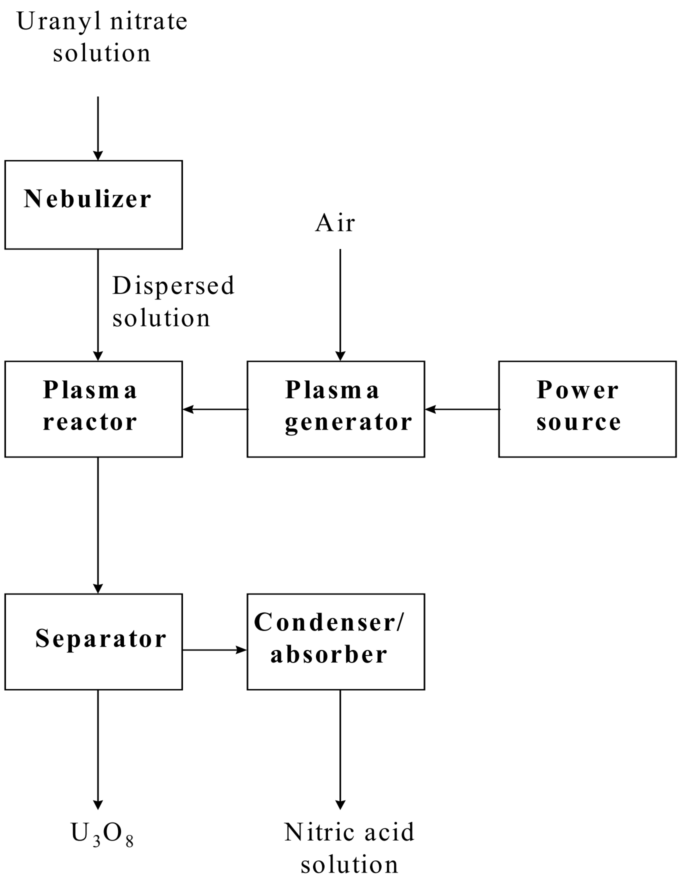

FIG. 19. Schematic diagram of uranium oxide production by plasma decomposition of uranyl nitrate solutions.

The commercial application of the laser enrichment technology (for example AVLIS) could lead to much smaller enrichment plants for a given separation efficiency. It also has the potential to lead to significantly lower arisings of both operational and ultimately decommissioning waste in the enrichment phase. True, to assess its full impact, it will be necessary to consider the changes in waste arisings elsewhere in the front end associated with its use of a metal feedstock rather than UF_6. Thus, technical developments are likely to concentrate on the development of more environmentally acceptable process for the production of uranium metal or alloys. Such work will have to consider the feedstock for such processes and the overall cost and safety implication relative to current operations.

Another example of waste minimization by application of dry process is the MIMAS technology of MOX fuel production [46]. The MIMAS plutonium fuel is a "UO_2-like" fuel. This means that not only the MOX rod is identical to the UO_2 rod, but also that the MOX pellets present as much similarities as possible to the UO_2 pellets. Basically, a solid solution of UO_2 - PuO_2 is dispersed in UO_2 matrix (Fig. 20). It is expected that more than 1000 t of MOX fuel will be produced by this way by the year 2000. Thus, this is rather matured technology which could be considered as an inseparable stage of the front end of the nuclear fuel cycle of LWRs.

The MIMAS process allows direct dry scrap recycling both at the level of primary and secondary blending. The main streams of waste produced are solid: they are separated in so called contaminated waste and suspect ones. Waste such as gloves, paper or used tools coming from inside the glove boxes are considered contaminated, that is containing some plutonium oxide. Those coming from outside the process boxes are nevertheless suspect unless proven non-active. Some 20 m^3 of each category of solid waste are generated each year. The contaminated waste contains less than 0,1% of the plutonium processed (about 2 kg); and there is practically no plutonium in the suspect waste.

In general, the future development of MOX fuel may radically influence situation in the front end of the nuclear fuel cycle with respect to the types, volumes and activities of the waste generated. If the use of MOX fuel expands, what is driven by a number of objective reasons, this could affect the economics of enrichment, because of a lower demand for enriched uranium. This could restrict or halt the introduction of the laser enrichment process. Additionally, because the need for ^{235}U will reduce, some of the older enrichment plants may be closed. And finally, expanded utilization of plutonium and recycled uranium, including military highly enriched uranium [47], in the front end of the nuclear fuel cycle could significantly reduce generation of uranium mining and milling waste simply because of a lower demand for natural uranium.

Even more dramatic reduction of waste in the front end of the nuclear fuel cycle could be achieved in the framework of so called "transmutational" fuel cycle (TFC) concept [48]. An important step in TFC is recovery of long lived ^{226}Ra and ^{230}Th together with U, with their subsequent transmutation in fission products.

The activity of natural uranium, including 14 members of the radioactive family of ^{238}U, is 4.7 Ci/t when ^{226}Ra and ^{230}Th are co-extracted with uranium, or 1.36 Ci/t without Ra and Th co-extraction when only four attendant disintegrations are allowed for. Co-extraction of Ra and Th with uranium is technically feasible and is being considered both in Russia and other countries with the aim to reduce the long lived activity of uranium spoils.

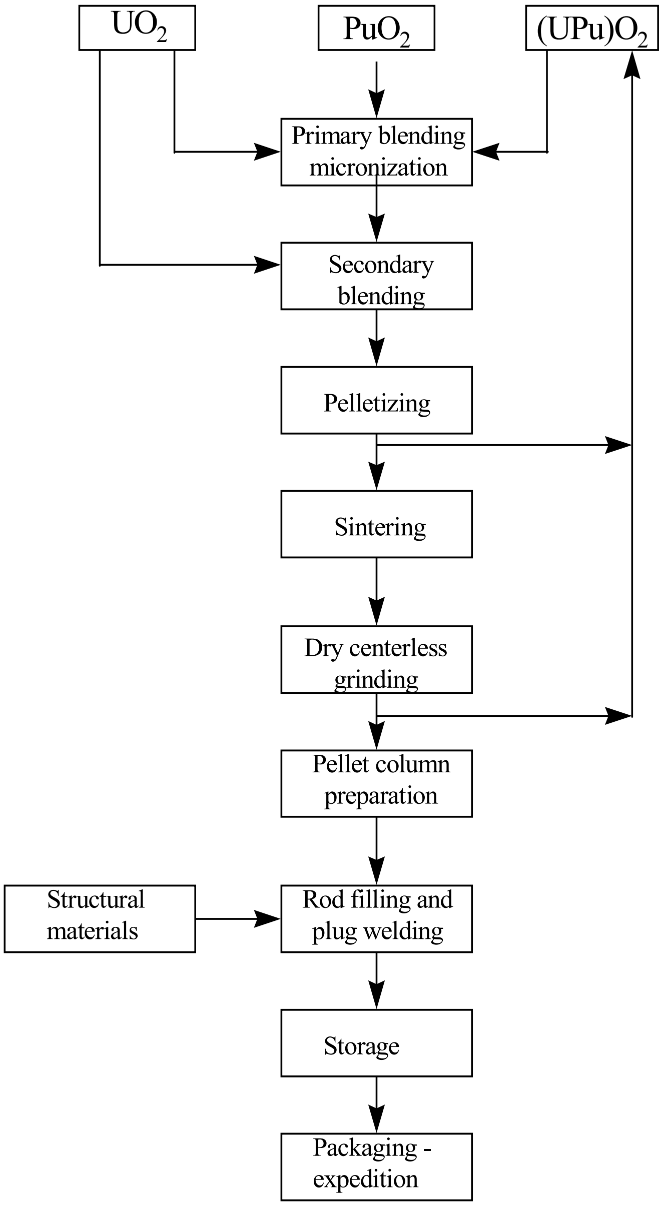

FIG. 20. The MIMAS process.

In principle, it is possible to transmutate ^{226}Ra and ^{230}Th in the neutron field of existing reactors at a rate of 3–6% per year. The immediate result of this operation will be the reduction of the activity removed from the earth to 72% (3.34 Ci/t). The remaining part of the activity withdrawn from the earth (1.36 Ci/t) can be utilized at a later stage when the whole mass of depleted uranium is going to be burnt in fast neutron reactors [48–50].

5.4. MANAGEMENT INITIATIVES

These initiatives are related to the training and education of the staff to raise the awareness for waste minimization.

Education and training of the staff to understand the economics of waste management is an important element in any waste minimization initiative. Future trends will develop this theme via co-ordinated programmes to increase the awareness of workers to the problem. This awareness will need to be conveyed to all workers, not just those involved in the manufacturing processes. It should be a fundamental element in the research and development stage and subsequently in the design of any new plants. The concept of clean technology, i.e. the development and design of plants to eliminate wastes is seen as a fundamental need for the future.

To ensure consistency of approach and to maintain waste minimization practices the use of effective quality assurance programmes are essential for future initiatives. Such systems are a necessary requirement for any nuclear manufacturer and operator. Their extended use in defining the control and procedural systems for the process areas will be an important element in any coordinated waste minimization program. The extension of this approach via quality circles and total quality management is seen as an important future trend. Their adoption and continuous improvement will help to prevent unnecessary materials entering the process environment.

6. CONCLUSIONS

The aim of this publication has been first to identify the outputs from some of the front end processes and then to define the principles and components of a waste minimization strategy. Examples of waste minimization practices have been given by reference to current practices employed by various facility operators.

During uranium purification, enrichment and fuel fabrication only naturally occurring radionuclides are present, albeit at significantly higher concentrations than occur in nature. As a consequence there are real prospects for cleaning up many of the waste materials to below clearance levels. Such procedures must be safe, economic and environmentally acceptable. It should be pointed out, that in case of waste from the identified front end processes this is much easier to achieve than with back end wastes.

The following general principles are applicable to any waste minimization strategy development and implementation, and fully acceptable for the majority of front end processes of the nuclear fuel cycle. In order of priority, these principles could be summarized as follows:

- Strict control should be exercized to prevent all unnecessary contact between inactive and active materials.
- Wherever possible, materials with potential value should be recovered from waste streams for recycle and/or reuse.
- Segregation should be employed to ensure that waste is always in the lowest possible category as this facilitate opportunities for decontamination and disposal.
- Decontamination should be used wherever possible to allow recycle, reuse, sale as by-products or disposal as inactive waste.

In respect of clearance levels there are significant differences in values used between countries. Work is being performed to generate internationally agreed guidelines for release of materials from regulatory control. The uniform international approach to this subject could foster consensus and facilitate recycle and reuse of different materials and equipment from nuclear fuel cycle activities and provide for further waste minimization, especially during decommissioning.

Future trends, and first of all expanded involvement of recycled uranium, plutonium and surplus weapon-grade fissile materials for nuclear fuel production, could drastically change the situation in the front end of the nuclear fuel cycle with respect to the types, volumes and activities of the waste generated at the stages of uranium mining and milling, refining, conversion and enrichment.

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