The Challenge of Development of a Holistic Waste Management Approach to Support the Nuclear Renaissance -9177

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ABSTRACT

The recent growth of interest in atomic power, the “nuclear renaissance”, is undoubtedly driven by environmental concerns. Nevertheless, there are many opponents to such a move and, increasingly, their arguments focus on the backend of the nuclear cycle, with waste disposal claimed to be the “Achilles Heel” of nuclear power. It is clear that nuclear expansion - and introduction of advanced fuel cycles - will face intense scrutiny and a clear case must be made for its advantages, which will require an improved, integrated approach to waste management. Unlike the present, dispersed system that focuses only on disposal of individual waste streams, a holistic waste management approach needs to be developed for the entire backend. In this paper, the technical challenges associated with the development of such a holistic waste management approach will be discussed in the context of recent progress in relevant technical areas, especially introduction of optimized approaches for repository design and safety assessment.

INTRODUCTION

Radioactive waste management in the 21st century must be seen in the context of the major socio-political and environmental challenges which loom ahead. Probably the most critical challenge results from the rapidly growing world population. Population growth will clearly need to be balanced by increases in supplies of food, water and other essential services. However it will occur at a time of rising lifestyle expectations amongst those most disadvantaged, particularly when discrepancies are most evident in urban areas. This will expand pressure on many key natural resources, with associated threats on already strained environmental systems. Nevertheless, the most fundamental requirement is the availability of energy sources that are economic, convenient and cause minimal impact on the environment. Given enough energy, handling most of the other demands is possible - at least in principle. Without sufficient energy, a crisis is inevitable.

Given the desire to reduce use of fossil fuels, the inherent limitation in the number of locations in which new major hydro-power facilities can be developed (and environmental concerns about such developments) and in the absence of breakthrough in alternative energy sources, therefore, there seems little alternative to massive expansion of nuclear power - both for electricity generation and, possibly, other energy applications (e.g. hydrogen production). Indeed, this situation is becoming increasingly evident to politicians and the nuclear stagnation of the last couple of decades contrasts dramatically with ambitious plans for a nuclear renaissance. This situation is a critical boundary condition for planning nuclear waste management strategies for the 21st century and hence setting R&D priorities.

The "nuclear renaissance" is undoubtedly driven by environmental concerns - in particular the need to reduce risks of global warming. Nevertheless, there are many opponents to such a move and, increasingly, their arguments focus on the backend of the nuclear cycle, with waste disposal claimed to be the "Achilles Heel" of nuclear power.

It is clear that nuclear expansion - and introduction of advanced fuel cycles - will face intense scrutiny and a clear case must be made for its advantages, which will require an improved, integrated approach to waste management. Unlike the present, dispersed system that focuses only on disposal of individual waste streams, a holistic waste management approach needs to be developed for the entire backend that includes explicit emphasis on:

- Sustainability; minimizing waste production, recycling as much material as possible and integrating the management of all material needing disposal, so that it is done with minimum use of resources and as little impact on the environment as possible
- Safety; public concern about radiation is so great that required safety levels are much stricter than in any other industry. This must be accepted and a management approach must be developed to not only provide the desired safety, but also convincingly communicate this to all stakeholders
- Security; already an issue and will gain importance as nuclear technology spreads to more countries. Although past emphasis has been on misuse of enrichment, reactor and reprocessing technology, diversion of spent fuel or use of waste as the basis of a "dirty bomb" are probably more credible scenarios for terrorist organizations. Close integration of the management of all radioactive materials and placing waste materials in inaccessible locations as quickly as possible can help to minimize risks.

In this paper, the technical challenges associated with the development of such a holistic waste management approach, which are being tackled by JAEA[1], will be discussed in the context of recent progress in relevant technical areas[2]. Although this work is carried out from the perspective of the Japanese program, it is clear that the evolution of nuclear power displays strong international coupling and hence this is an area where collaboration with other leading national partners could be mutually beneficial.

A STRATEGY FOR DEVELOPING A HOLISTIC WASTE MANAGEMENT APPROACH

A critical starting point here is to identify credible scenarios for the evolution of worldwide power demand and the associated role of fission (and possible later fusion) in the production of electric power, hydrogen, desalination of water, etc. Such background must then be integrated with assessment of fuel supplies and the implementation of advanced fuel cycles to derive potential waste arisings profiles. Holistic treatment of future inventories allows the practicality of potential recycling options to be assessed and the disposal of unusable wastes to be planned on an optimal basis. To make the problem practical, a stepwise approach for optimization is discussed and applied. Objective functions, control variables and constraints to describe the optimization process are discussed at each step and lead to identification of R&D priorities to provide the tools for inventory manipulation, advanced repository design and realistic performance assessment required for its implementation.

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[1] JAEA (Japan Atomic Energy Agency) has been assigned the responsibility for R&D to enhance disposal technology and safety assessment methodology together with associated databases; this should support both the implementer (NUMO: Nuclear Waste Management Organization of Japan) and the relevant regulatory organizations.

[2] This study was carried out under a contract with METI (Ministry of Economy, Trade and Industry) as part of its R&D supporting program for developing geological disposal technology.

Fig. 1 illustrates a schematic view of expected holistic waste management. It should be noted that boundary conditions will play an important role in this framework.

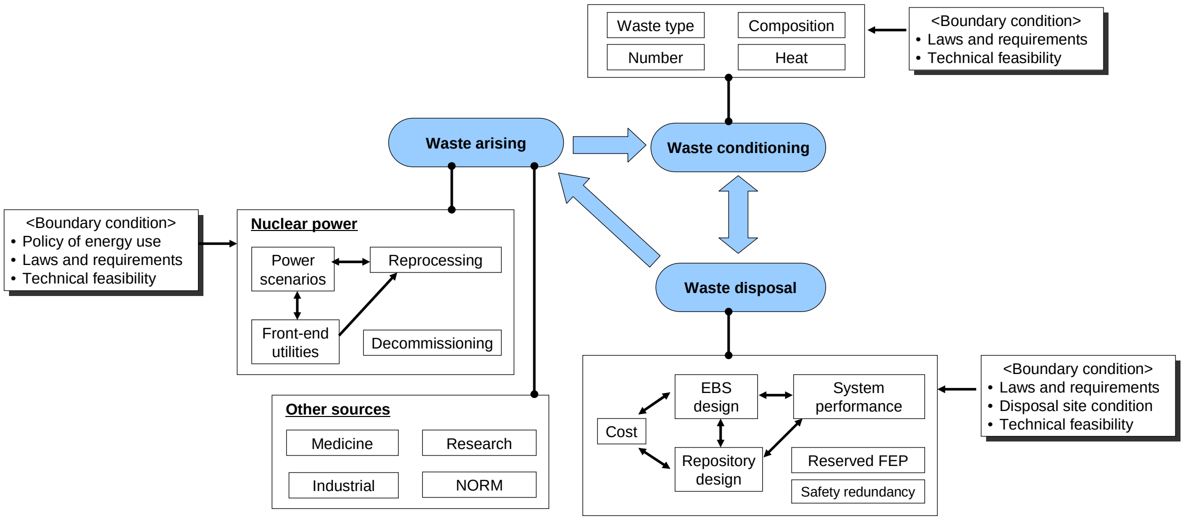

Fig. 1. Framework for holistic waste management

Expanding Role of Nuclear Power

As radioactive waste is generated predominantly by the nuclear power industry, developing scenarios for expected arisings (and hence repository requirements) involves consideration of:

- The evolution in total generation capacity;
- The extent of reprocessing;
- The development of advanced reactors/fuel cycles;
- The role of fusion.

The evolution in world nuclear capacity has an important bearing on national waste management strategies, as the global demand for uranium influences prices, which, in turn, affects the commercial viability of reprocessing. Reprocessing has already been successfully combined with use of resulting MOX fuels in many reactors. Repeated cycles of reprocessing, however, lead to U and Pu with isotopic compositions unsuitable for use in conventional light water reactors. If there is a desire to utilize resources of fissile fuels more efficiently, advanced fuel cycles need to be developed - e.g. using breeders and other types of fast reactors that can burn a much wider range of actinides. Such fast reactor fuel cycles produce a significantly different spectrum of wastes from those resulting from current nuclear programs, which may present novel management challenges. It should also be noted here that other possible future nuclear developments may need to be taken into consideration - e.g. small modular units for remote communities (islands), possibly based on a simple system like PBMR (Pebble Bed Modular Reactor).

Japan's overall strategy for the nuclear fuel cycle currently envisages [1]:

- An expanding role for nuclear power; contributing to stable energy supply, reducing emissions of greenhouse gases and decreasing reliance on imports of fossil fuels;

- A commitment to reprocessing spent fuel (SF), recovered U and Pu being fabricated into MOX fuel which is burned in existing light water reactors (LWR) - the "Pluthermal" program;
- Commencing commercial use of fast reactors around the middle of the century, allowing burning of a wider spectrum of actinides in MOX fuel and also allowing breeding of fissile material from depleted uranium resulting from the enrichment process.

Nuclear power capacity development estimated in a reference scenario in Japan is shown in Fig. 2.

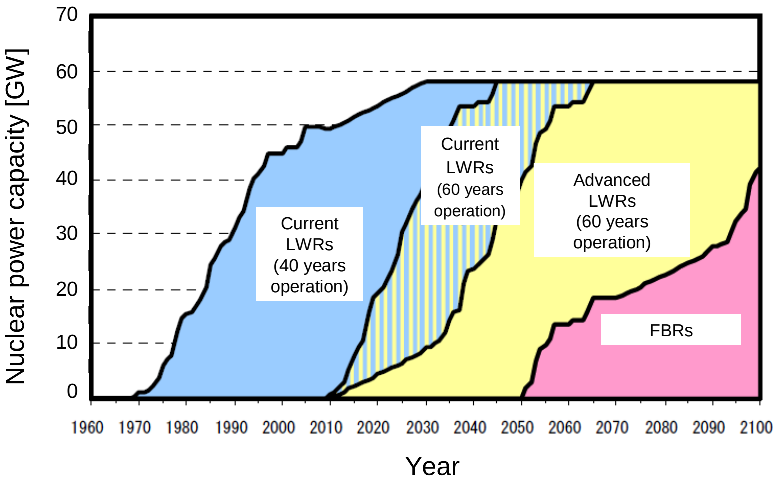

Fig. 2. Nuclear power development in a reference scenario in Japan (after [2])

When looking over timescales of decades, a further factor to be borne in mind is the potential role of fusion power [3]. Although progress towards commercial implementation (e.g. [3], [4]) has been painfully slow, there is huge potential for this power source to fill some (or all) of the energy gap developing during this century. Predictions about fusion are notorious for proving wrong, leading to the observation that "fusion is the power of the future - and always will be!" Nevertheless, commercial power plants might be expected to become operational by the middle of the century and this energy source might be a major component of the energy mix by the next century. Although the waste handling problem may be less for fusion than fission, the characteristics of resulting radioactive wastes will be very different and, in case of significant expansion of this power source, established management strategies should be in place in good time.

Waste Disposal

During the latter half of the 20th century, a range of HLW (high-level radioactive waste) repository concepts were developed to demonstrate the fundamental feasibility of deep geological disposal and support moves towards siting and licensing such facilities. At the start of the 21st century, however, the boundary conditions for this work are changing rapidly with increased concern about public acceptance and requirements for greater flexibility associated with a nuclear renaissance. There is also an acknowledged need for formally structured management of the requirements, quality and knowledge base supporting such complex projects, which extend over many decades from first planning until final closure of the facility.

While the future of nuclear power clearly influences the development of waste management strategies, the inverse is maybe more critical; the development and implementation of waste disposal projects will help determine the acceptability - and the extent of implementation - of future nuclear power programs.

The widespread concern about disposal of radioactive wastes contrasts dramatically with the consensus within the industry that such disposal is practically feasible, demonstrably safe and economic. It is true that, for higher activity wastes, repository implementation was not pressing due to their small volumes and the advantage of postponing disposal to allow radioactive decay to reduce thermal output. Nevertheless, most national programs have been significantly delayed due to public opposition, to the extent that some are effectively stalled. To support future nuclear power development, clear progress in repository implementation is needed.

This means that the traditional approach, in which waste disposal was discussed for individual waste types, should move forward to more comprehensive discussion of waste disposal, linked directly to waste generation through current and advanced fuel cycles. In order to initiate such a comprehensive approach, it is necessary to develop inventories and characteristics of potential wastes from various fuel cycle scenarios and assess disposal of all these wastes in an integrated and optimized manner.

R&D Priorities

The R&D program required to provide the needed output at specific milestones, when the boundary conditions can be defined - at least to the level of credible scenarios - is an important consideration for any national program. However, rather than starting with what we have now and working forward, it is interesting to start from expected future needs and work backwards. Clearly, major advances in technology and system understanding will be needed but, when the appropriate R&D programs are initiated in good time, it should be feasible not only to develop all required tools and understanding, but also to ensure that these are well tested and validated. This last point is worth particular emphasis as the lead time for new technology is long; “first generation” concepts and assessment technology have developed over the last 3 decades and hence similar periods should be expected to bring a novel “second generation” to the same level of general understanding and acceptance.

DEVELOPMENT OF NATIONAL INVENTORIES

Inventory Scenario

The definition of waste sources and their classification is a key element of any waste disposal program. Without a proper inventory of radioactive waste arisings, including their chemical, physical and radiological properties, it is not possible to design or assess the safety of any proposed facility for the handling, storage or disposal of these materials. Especially in larger, longer established nuclear programs, even the former can be difficult due to the great diversity of sources of radioactive wastes. Indeed, for existing wastes, the extent to which they can be directly characterized is limited by practicality, cost and exposure to workers.

In general, existing HLW/SF inventory databases are reasonably complete. Major uncertainties are associated with possible future changes in waste (e.g. due to higher burn-up of fuel, use of MOX, introduction of fast reactors, changes in reprocessing technology, etc.). Inventories of lower activity wastes are generally less complete due to the much greater heterogeneity/chemical complexity of such wastes and the many variables influencing future arisings. At the present time, however, many types of waste may be grouped together and rather simplistic 'average' characteristics used. A combination of analyses of a small number of representative samples, assessment of operational procedures and material balances allows such characteristics to be defined.

Quantification Tools and Databases

From the specified waste arisings and a holistic assessment of their potential hazard, an optimized management strategy can be developed, including consideration of conditioning, disposal strategy and approach to developing a robust safety case. Some investigations to identify waste fluxes from an advanced fuel cycle have been carried out (e.g. [5]), but are focused on limited types of waste (e.g. Fig. 3). Fig. 3 shows a comparison of the volumes of vitrified HLW and TRU waste[3] per unit electricity generated for various reprocessing processes. This indicates that some options produce less vitrified HLW than the current PUREX, but more TRU waste. Analysis of such trade-off relationships between different waste types is important for characterizing and comparing fuel cycle variants. Understanding of such characteristics is important input for the optimization problem.

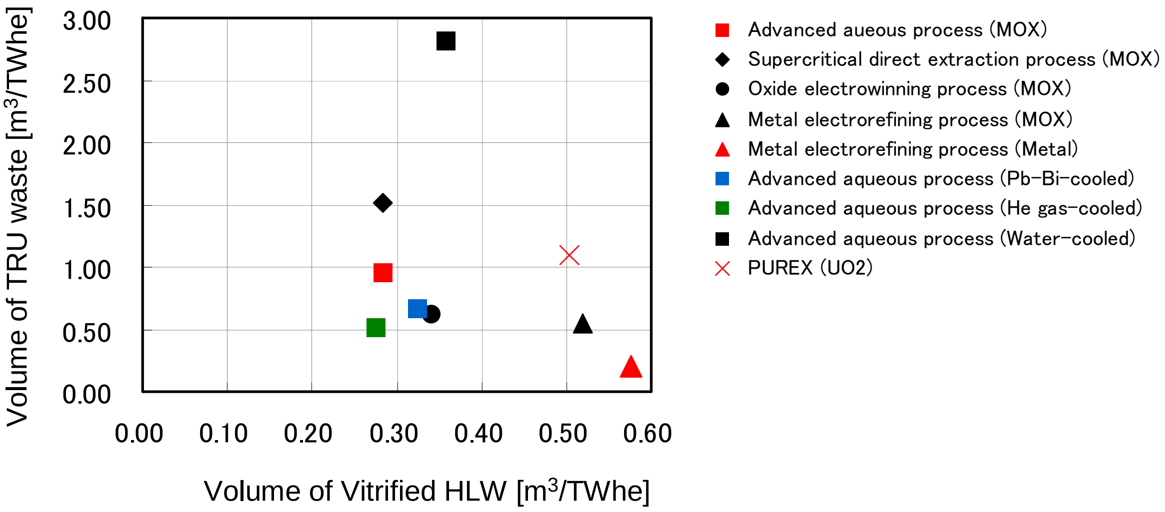

Fig. 3. Comparison of volumes of vitrified HLW and TRU waste

NB: Features of the "advanced aqueous process" in this figure are:

- U crystallization that can dramatically reduce the extraction process flow
- Single cycle co-extraction of U, Pu and Np with low decontamination
- MA recovery using extraction chromatography that allows the use of compact components and a lower amount of secondary waste

Individual measurements are combined with models of the generation of the waste or empirical correlation factors in order to develop inventories which, ideally, include all required radioisotope, chemical and physical characteristics of raw and conditioned waste. Such models are formalized in codes that can also determine property changes (e.g. isotope concentrations, thermal output, radiogenic gas production, etc.) as a function of time, accounting for

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[3] Low-level waste generated during the operation and dismantling of reprocessing facilities and MOX fuel fabrication facilities containing long-lived radionuclides such as C-14, I-129, Pu-239 and Np-237. This waste is defined as 'TRU waste' in Japan and broadly equates to long-lived intermediate-level waste (ILW) and low-level waste (LLW) with significant alpha content [6].

radionuclide decay/ingrowth.

The principles involved have been recently outlined [7], but technical developments are needed to ensure wider application of this approach. The challenges in developing improved inventory management tools can be summarized as:

- Integration and expansion of existing management codes and databases to provide a comprehensive overview of all existing and expected wastes;
- Setting such tools within a structure which allows feedback from repository design and performance assessment (PA) in order to optimize waste conditioning, packaging and, possibly disposal - assign benefits of co-disposal of particular waste streams (e.g. within an overarching Requirements Management System (RMS);
- Establishing a suitable Quality Management System (QMS) to ensure that all inventories will be rigorous enough for licensing purposes (NB future licensing may be set within an environmental impact assessment structure, which could additionally require demonstration of optimization).

All measured and modeled inventories would be combined in an integrated inventory database that can be used to respond to changes in the fuel cycle and requests from safety assessors, regulators, etc., in a timely fashion.

INTEGRATED REPOSITORY DESIGN SYSTEMS AND NEXT GENERATION OF PA

The separation of disposal projects by waste type reflects the different hazards associated with different wastes - those that are more toxic and longer-lived requiring greater robustness of the engineered and / or natural barriers. In previous studies, such an approach has been applied in a rather simplistic manner and ignored opportunities for optimization by, for example, combining different wastes within a particular disposal facility (e.g. [8]) or, indeed, co-disposing of different wastes within a single package (e.g. [9]). Further potential for optimization becomes evident if an integrated design procedure is used - the design engineers working closely with fuel cycle teams, PA teams, site characterization teams and public communication teams to ensure that the concepts developed are not only safe, but also practical, acceptable and cost-effective [7]. In this regard, there is a grey area with considerable overlap between inventory development and optimization of repository design (e.g. [10, 11]).

Such inventories have, however, been rather limited in their use to form an effective interface with the repository designers and safety assessors. Information flow has tended to pass in only one direction - the inventory effectively defining a boundary condition for repository concept development. A two-way flow is planned that could lead to significant optimization. For example, feedback from PA can help identify areas where increased characterization provides maximum benefit (e.g. definition of C-14 in certain waste types) or where improved conditioning could be valuable (e.g. improved immobilization of I-129).

The challenge in this field will be to analyze existing conceptual ideas, examining their advantages and disadvantages for a variety of boundary conditions given for repository system development, e.g. different waste characteristics, different repository settings. Such analysis will not only have to consider long-term safety, but also other factors [12] such as operational safety, engineering feasibility and QA, engineering reliability, site characterization and monitoring requirements, retrievability, environmental impact and socio-economic aspects. Potentially, novel concepts could be developed using formal methods for solution generation such as TRIZ (Theory of Inventive Problem Solving) [13], allowing greater flexibility for possible new requirements in the future.

The fundamental challenge involves not only the range of widely differing factors that need to be considered when selecting between alternative design options (or when refining selected designs), but also the uncertainties that exist in most (or all) of the factors that need to be considered and the fact that some of these uncertainties will decrease with time, as the characteristics of the site become better defined. An important part of justifying any particular design (or justifying the selection of a particular disposal site) is a demonstration that a wide range of potentially suitable alternatives have been considered and that the selected option represents, in some sense, "an optimum choice" or "better solution", taking into account a range of relevant factors (e.g. [14]).

At the stages of siting and repository concept development, PA models and process models need to be as realistic as possible, to allow comparison and determination of key differences among waste forms, waste inventories, repository system options, repository conditions, etc. For the Japanese case, complex and heterogeneous geology may increase the relative weighting of EBS performance within the safety case. There are certainly strong indications that optimized EBS designs can greatly increase post-closure performance (e.g. [9]), but tools are needed to quantify this more rigorously and develop the supporting arguments needed to develop an associated, robust safety case.

To increase flexibility of PA for different waste forms, waste inventories, repository system options, repository conditions etc., two aspects should be focused on:

- Integration of available models and knowledge for the performance assessment required;
- Better understanding of processes and features, with special emphasis on identified open questions.

CHALLENGES IN THE MANAGEMENT AND COORDINATION OF R&D

Challenges from an Exponentially Expanding Knowledge Base

The safety case for a radioactive waste repository involves many complex, multi-disciplinary issues; these must be summarized in a comprehensive and concise manner, with links to all supporting information. The safety case can thus be considered an edifice built on structured knowledge. Knowledge is defined here in the very widest sense, including all of the information underpinning a repository project. Knowledge management covers all aspects of the development, integration, quality assurance, communication and maintenance/archiving of such knowledge. When seen from this perspective, the exponential expansion of the knowledge base represents a little-discussed challenge to safety case development [15]. Indeed, knowledge production rates in this area are rapidly reaching, if not already surpassing, the limits of traditional management methods.

This problem has been recognized in Japan and a project to develop a "next generation" knowledge management system (KMS) has recently been initiated [16]. This will utilize advanced electronic information management technology to handle the vast quantity of information involved. Autonomic systems will perform many of the information processing functions, helping to ensure that required knowledge is accessible to all stakeholders and that gaps can be identified and supporting R&D prioritized. In a departure from conventional structuring by technical discipline, the prototype KMS utilizes a safety case structure. This should facilitate use of the core of "neutral" scientific and technical knowledge by both the implementer and the regulator. Flexibility is built into the system, to allow it to be restructured to match the user's needs or even interfaced directly to a formal requirements management system.

The development of a conceptual KMS is challenging in itself. Based on the considerations above, however, to be of real use this should not simply be a passive tool to archive and disseminate information. It requires internal analytical facilities to synthesize and integrate material from a diversity of sources, identify trends and inconsistencies and, ideally, even produce feedback to the data producers. In effect, it should replace many of the functions of the network of peer reviewers and expert advisors who currently carry out such work.

A further problem lies with establishing a strategy to produce a functioning system which has the capacity to respond to a rapidly growing knowledge base. It must also have the flexibility to respond to changing requirements of end-users and the user-friendliness to ensure that it is adopted by both knowledge-producers and knowledge-users.

In principle, the situation looks feasible based on the observations that:

- Already, most key information for repository projects is available electronically and accessible via internet/intranet systems. It is reasonable to expect that this will very soon provide effectively 100% coverage.
- Increasingly sophisticated content-recognition and cross-referencing systems allow relationships between documents and any form of datasets to be defined in much more detail than traditional document labeling / keyword approaches.
- The development of autonomic data mining techniques involving network agents, bots, etc. is currently an area of very rapid progress, which allows much of the information gathering, sorting and compilation processes to be automated.
- The combination of expert systems with autonomic learning approaches (e.g. based on neural networks) allows, at least in principle, many of the key processes involved in knowledge management - collation, synthesis, review, etc. - to be completely automated.

The preliminary concept for the Japanese KMS is shown in Fig. 4. Although such a system is still at the early stages of development, it can be seen that the emphasis is on interaction - with two-way flows between the knowledge base and the central guiding knowledge office, the R&D sectors which produce focused new knowledge, the World Knowledge Base which is the interface to the wider international community, the think tank which attempts to anticipate the inherently unpredictable future and, most importantly, the end-users - the sine qua non of the entire exercise!

Given the generic nature of this problem, KMS development certainly seems to be an area where cooperation in tool development could be mutually beneficial and, indeed, establishing collaboration with other advanced programs is a goal of this project.

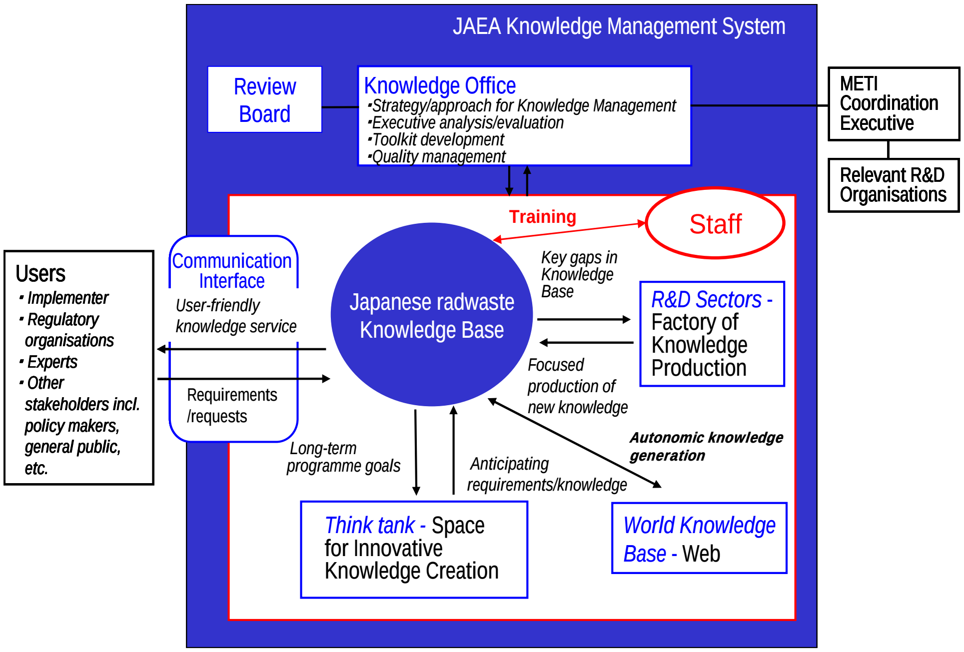


Fig. 4. Preliminary KMS concept: structure and key elements [16]

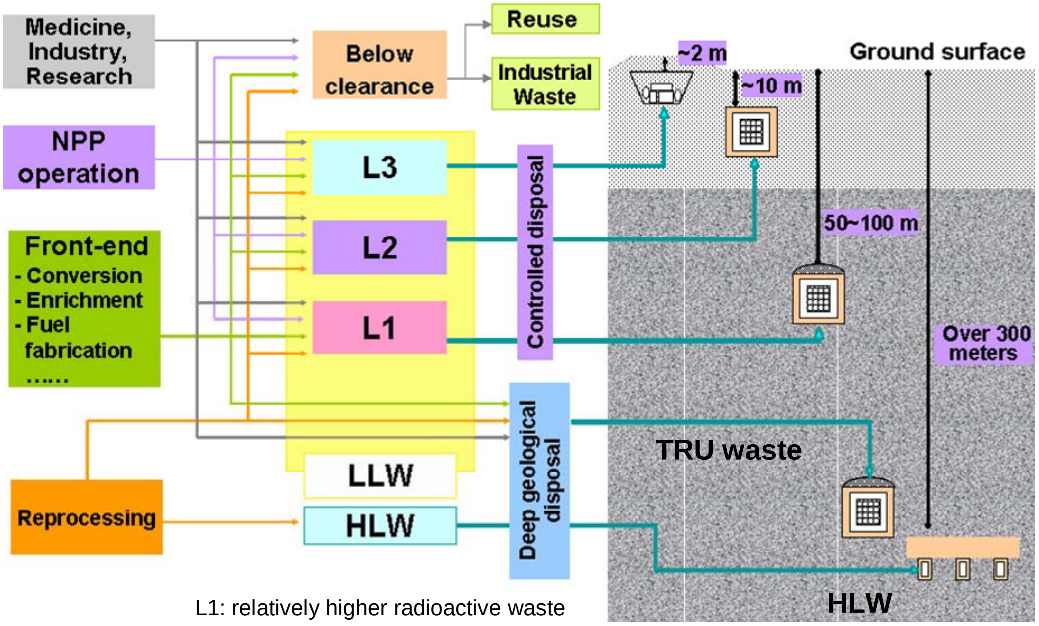
An Optimization Process for the Entire Backend

The most important initial activities in this optimization would be clarification of goals and definition of appropriate indicators to describe optimization problems in order to answer the questions, for example:

- What disposal systems are most appropriate for different scenarios of nuclear energy use?
- How much capacity of what kind of repositories will be needed for each scenario?
- Which nuclear scenario/fuel cycle options are most favorable in terms of reducing the requirements on the repository development program?
- What R&D could lead to more cost-effective waste management for the scenarios that are considered more likely?

It is well known that a series of partial optimizations may not lead to total optimization of the entire system. In other words, partial optimization for individual disposal of specific waste types may not lead to optimization of diverse and varying waste inventories from evolving fuel cycles. Integrated optimization is a complex multidiscipline-multivariate problem, which includes nonlinear relationships due to complex feedback loops. It may be further complicated by the inevitable need to mix both quantitative indicators and qualitative ones. Some technical innovations for treating such complexity may thus be needed for this optimization process.

To deal with this situation and make the problem practical, a structure to integrate partial optimizations as an approximation to the more complete total optimization is examined. This starts from the existing situation in Japan where waste management responsibilities are distributed according to the source and level of radioactivity of the waste and allocated to different disposal options as shown in Fig. 5.



L1: relatively higher radioactive waste
L2: relatively lower radioactive waste
L3: very low level waste

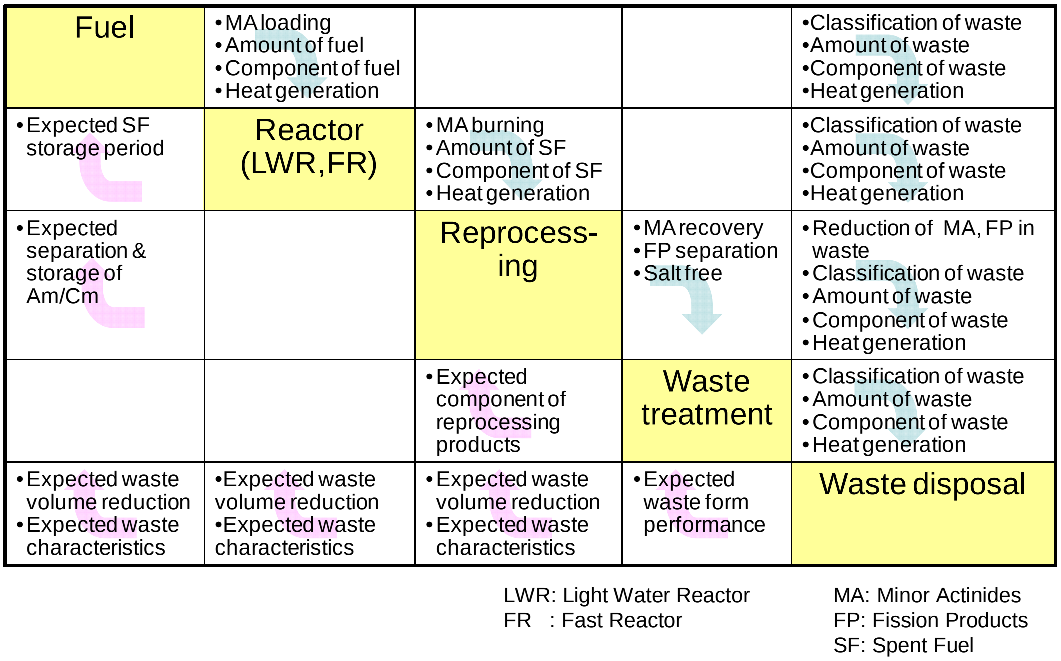
Fig. 5. Current waste disposal flow in Japan (excluding NORM wastes) (after [17])

A first step of optimization could involve development of an integrated inventory of current arisings and an assessment of the disposal system requirements of different waste streams in terms of the need for isolation, containment, retardation and dilution/dispersion in order to develop a robust safety case. Such an evaluation allows a first provisional allocation of wastes between the different repository classes based on pre-established performance levels of these facilities. This optimization process has been initiated by examining existing and possible future regulatory criteria for acceptance of each repository class by the regulators [18].

The second step of optimization takes into account operational safety, cost and environmental impact of the different types of repository and investigates the extent to which total system performance can be improved by altering waste treatment or packaging to allow it to be allocated to a different repository type. At this step, the waste streams are still considered individually.

The third step then considers the integration of disposal of different waste types - for example using lower hazard waste to replace backfill in a higher level repository. This is a complex assessment which requires some lateral thinking to re-examine the basic designs of existing facilities and thence to examine novel repository concepts and their potential to replace or complement existing designs.

Finally, in a fourth step, such stepwise development of the disposal options provides input for a more complete examination of the entire backend with emphasis on future arisings - as indicated in Fig. 6 for waste from fission reactors. This will be extended to include concepts for future treatment and conditioning of wastes from medicine, industry, research or fusion reactors.



Fuel	•MA loading •Amount of fuel •Component of fuel •Heat generation			•Classification of waste •Amount of waste •Component of waste •Heat generation
•Expected SF storage period	Reactor (LWR,FR)	•MA burning •Amount of SF •Component of SF •Heat generation		•Classification of waste •Amount of waste •Component of waste •Heat generation
•Expected separation & storage of Am/Cm		Reprocess-ing	•MA recovery •FP separation •Salt free	•Reduction of MA, FP in waste •Classification of waste •Amount of waste •Component of waste •Heat generation
		•Expected component of reprocessing products	Waste treatment	•Classification of waste •Amount of waste •Component of waste •Heat generation
•Expected waste volume reduction •Expected waste characteristics	•Expected waste volume reduction •Expected waste characteristics	•Expected waste volume reduction •Expected waste characteristics	•Expected waste form performance	Waste disposal

LWR: Light Water Reactor
FR : Fast Reactor

MA: Minor Actinides
FP: Fission Products
SF: Spent Fuel

Fig. 6. Iterative assessment of the backend for the case of fission reactor waste

At each step or iteration step, the optimization process must be clearly described in terms of:

- objective functions expressed using indicators;
- control variables;
- constraints.

Constraints will include external ones such as legal and socio-political requirements, as indicated in Fig. 1. Based on this hierarchy, optimization activities in each step will be carried out keeping total optimization in mind in a phased and iterative manner. Although clearly less efficient than an integrated, one-step optimization, this is probably more feasible given the current state of system understanding. Fig. 7 illustrates a basic sequence for coherent optimization within the framework for holistic waste management shown in Fig. 1. At this initial stage, a key challenge is developing performance measures for existing repository types and then a catalogue of options for ways in which wastes could be managed together and measures that allow the change in total system performance to be monitored.

Preliminary ideas for indicators, control variables and constraints at each step are listed in Table I. These can allow identification of R&D priorities to provide tools and data for inventory manipulation, advanced repository design and realistic performance assessment. Such priorities will become clearer with progress of optimization activities and will allow effective focusing of limited R&D resources.

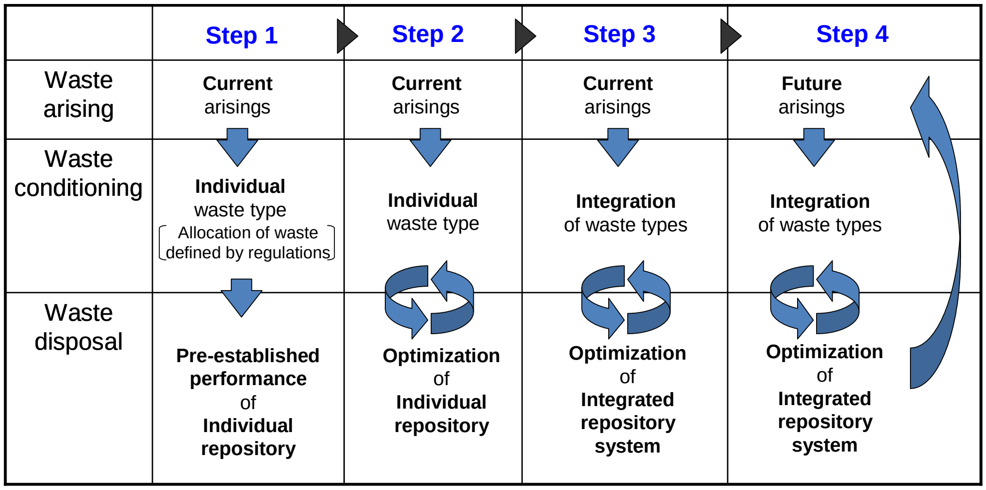


Fig. 7. Basic sequence of optimization within the framework for holistic waste management

Table I. Preliminary Ideas for Indicators, Control Variables and Constraints

Steps	Optimization indicators	Control variables	Constraints
Step 4	☐ Characteristics of generated waste (e.g. handling, simplicity) ☐ Traceability and transparency of mass flow ☐ Safety ☐ Economic competitiveness ☐ Reduction of environmental burden ☐ Efficient use of nuclear resources (e.g. recycling of U, Pu) ☐ Enhancement of nuclear nonproliferation ☐ Social acceptance	☐ Nuclear scenario ☐ Fuel cycle option · MA recovery rate · FP separation rate · Storage period, etc. ☐ Results of comprehensive assessment for integrated repository systems	☐ Politics for nuclear energy use ☐ Regulations ☐ Technical feasibility
Step 3	☐ Comprehensive measures for performance of integrated repository system ☐ Characteristics of wastes for each repository type ☐ Number of repositories ☐ Total footprints of repositories	☐ Options of integrated repository systems ☐ Concept/design for each repository type	☐ Politics for waste management ☐ Regulations, technical requirements (e.g. waste types, disposal types) ☐ Characteristics of wastes (e.g. activity)
Step 2	☐ Long-term safety (e.g. dose, risk, safety functions) ☐ Operational safety ☐ *Engineering feasibility, reliability* ☐ *Retrievability* ☐ *Environmental impact* ☐ Socio-economic aspects (e.g. cost, public acceptance)	☐ Options of repository concepts ☐ Possibilities for modification	☐ Politics for waste management ☐ Regulations, technical requirements (e.g. site selection, safety standard) ☐ *Site conditions* ☐ Characteristics of waste form (e.g. number,

					inventory)

Italics: Basically independent of fuel cycle system

CONCLUSIONS AND FUTURE WORK

The challenge of holistic waste management was launched in 2007 as a 5-year project to provide an improved and integrated approach to waste management to support the case for nuclear expansion, including introduction of advanced fuel cycles. Unlike the present, dispersed system that focuses only on disposal of individual waste streams, development of a holistic waste management approach for the entire backend and also alternative fuel cycles and other sources of radioactive waste has been initiated in this challenge.

One of the most important technical challenges associated with the development of such a holistic waste management approach is introduction of an optimization methodology that couples waste production, conditioning, packaging and disposal. To make such optimization practical, clear structuring and introduction of a stepwise process is essential. Supporting technical work has also been started, mainly focusing on developing the understanding and databases required to differentiate between different fuel cycles. This is complemented by development of potential fuel cycle scenarios, waste inventories and characteristics, advanced repository designs and required performance assessment. It is expected that progress of this study will improve the level of treatment of waste management and emphasize sustainability, safety and security of the entire backend associated with nuclear expansion. Intermediate output from this study will be summarized at the end of the third year of work. It is hoped that this will include prototypes of developed methodologies and databases that could be used on a trial basis.

Although this work is being carried out from the perspective of the Japanese program, it is clear that the evolution of nuclear power displays strong international coupling and hence this is an area where collaboration with other leading national partners could be mutually beneficial.

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