IAEA-TECDOC-1523

Optimization Strategies for Cask Design and Container Loading in Long Term Spent Fuel Storage

IAEA
International Atomic Energy Agency

December 2006

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The originating Section of this publication in the IAEA was:

Nuclear Fuel Cycle and Materials Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

OPTIMIZATION STRATEGIES FOR CASK DESIGN AND
CONTAINER LOADING IN LONG TERM SPENT FUEL STORAGE
IAEA, VIENNA, 2006
IAEA-TECDOC-1523
ISBN 92–0–112706–5
ISSN 1011–4289

Printed by the IAEA in Austria
December 2006

FOREWORD

Long term storage of spent fuel is a major topic within IAEA Member States. Issues related to long term storage have been addressed in a number of IAEA publications to date, including: IAEA-TECDOC-1293, Long Term Storage of Spent Nuclear Fuel (2002); IAEA-TECDOC-1343, Spent Fuel Performance Assessment and Research (2003); IAEA-CSP-20, Proceedings of the 2003 International Conference on Storage of Spent Fuel from Power Reactors (2003); and IAEA-TECDOC-1378, Practices and Developments in Spent Fuel Burnup Credit Applications (2003). Given the steadily increasing importance of dry cask storage and the need to strive for efficiencies as both storage quantities and durations extend, the IAEA initiated efforts in 2002 to develop a TECDOC on optimized loading of casks/containers for long term spent fuel storage. Expert consultants convened in November 2002 to identify and discuss principal issues regarding the optimization of cask/container assembly capacity and burnup/age capability in the design of systems for long term spent fuel storage and the related integrity of fuel. The resulting working materials served as bases for a subsequent larger technical meeting of representatives from Member States. These Member State representatives convened in Vienna for a technical meeting on this topic in March 2003, providing national presentations as well as documenting related views of both implementers and regulators. Discussions focused on the following issues relevant to cask loading optimization: fuel integrity, retrievability, zoning, burnup credit, damaged fuel, computer code verification, life of cask components, cask maintenance, performance confirmation, and records management. In June 2004, the consultants reconvened to mould these results into a technical document summarizing current understandings on this topic.

The IAEA wishes to express appreciation to all the experts (identified at the end of this publication) for their contributions to these meetings and in particular to B. McLeod (United States of America, 2004 meeting chair), J. Gago (Spain), K. Kamimura (Japan), B. Kühne (Germany), and C. Vallentin (France) for their assistance in the preparation and review of this TECDOC. The IAEA officer responsible for this publication was W. Danker of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

1 INTRODUCTION

Long term storage of spent fuel is a priority topic within the Member States of the IAEA. Technical meetings held by the IAEA in 1999 and 2000 resulted in IAEA-TECDOC-1293 in 2002 [1] which focused on the challenges to extending the life of existing and new storage facilities for much longer periods of time. IAEA-TECDOC-1343 in 2003 [2] reported on the coordinated research project on spent fuel performance assessment and research conducted from 1997 to 2001. That report identified areas of technical interest such as materials behaviour as storage durations extend, while noting that dry cask storage of spent fuel is playing a steadily increasing role. IAEA-TECDOC-1378 in 2003 [3] reported on the results of the IAEA's third major meeting addressing practices and developments in spent fuel burnup credit applications. In addition, IAEA-CSP-20 in 2003 [4] reported on the results of the International Conference on Storage of Spent Fuel from Power Reactors hosted by the IAEA in June 2003. The proceedings of this conference included presentations addressing storage-related implications of higher burnup fuel, increased storage quantities, and extended durations. In this context and within the framework of the IAEA sub-programme on spent fuel management, a new project was conceived, focusing on issues associated with the optimization of cask/container loading (capacity) with respect to long term storage and the related integrity of fuel.

An initial consultants meeting held in November 2002 identified and discussed principal issues regarding the optimization of cask/container fuel assembly capacity and burnup/age capability in the design of systems for long term spent fuel storage and the related integrity of fuel. Working materials developed during that meeting noted that cask designers currently face a number of new challenges including storage of high burnup fuel with correspondingly higher enrichments, the use of mixed oxide (MOX) fuel, and obtaining regulatory approval for the use of burnup credit. The consulting experts noted that optimization might have different meanings for the cask vendor, the cask owner, the cask operators, and the institution having the ultimate responsibility for spent fuel storage. They also emphasized that safety is paramount and that efforts to optimize the loading of casks and containers are not intended to relax existing regulatory limits. Rather than considering relaxation of regulatory limits toward "physical limits", optimization strategies involve careful consideration of uncertainties and resulting conservatisms as addressed by current regulatory practice.

The working materials resulting from that consultancy were then provided to participants in a larger technical meeting held in March 2003 to obtain country-specific views from both regulators and implementers on optimization strategies. Participants in the technical meeting reviewed the results of the consultancy and then provided country-specific perspectives on the topic. Technical meeting participants formed two working groups to develop both implementer and regulator views on issues identified during the 2002 and 2003 meetings. These groups reviewed the seven open issues identified during the 2002 meeting and added four additional open issues for subsequent consideration. Reports and working materials from these meetings were then made available to consulting experts participating in a 2004 meeting to prepare the resulting technical document on this topic. The open issues identified during the 2002 and 2003 meetings are discussed in summary form in Chapter 10. Since most of these issues are long term, they remain identified as open issues and in some cases may remain so for a significant length of time.

2 BACKGROUND

The purpose of this section is to outline the optimization process for cask design, licensing, and utilization. The general objectives for the design of storage casks, including storage casks that are intended to be transportable, are summarized. The nature of optimization within the design process is described. The typical regulatory and licensing process is outlined, focusing on the roles of safety regulations, the regulator, and the designer/applicant in the optimization process. Based on the foregoing, a description of the three principal groups of optimization activities is provided. The subsequent chapters of this document then describe the specific optimization activities within these three activity groups, in each of the several design disciplines.

2.1 OPTIMIZATION AS A COMPONENT OF CASK DESIGN AND LICENSING

This section describes the general objectives of cask design and the nature of optimization within the design process. The general objectives of cask design are:

(1) To meet the cask weight, dimensional, and other limitations defined by the application,
(2) To meet the operational, safety and regulatory requirements for long term containment, structural integrity, sub-criticality, radiation shielding, heat removal, and operational simplicity and maintainability,
(3) To provide a cask with the largest possible capacity of spent nuclear fuel (SNF) assemblies with the largest burnups and shortest cooling times that are practicable, and
(4) To provide a cask with the lowest life cycle cost of SNF storage and/or transport consistent with the desired cask availability and performance characteristics in the intended application.

The need for optimization arises because many of the application limits such as cask weight limits, and the cask safety limits such as radiation exposure and fuel temperature limits can be met only by imposing limits on the various cask performance measures such as assembly capacity and/or burnup/age capability. Optimization thus includes that part of the design process in which the combination of application objectives, safety limits, design and regulatory practices in each of several technical disciplines, and costs, are innovatively addressed and judiciously balanced in the final design. A primary result of a successful design and licensing optimization is a licensed cask of superior assembly and burnup/age capacity that minimizes the total number of cask loadings required to manage a given SNF inventory over the long term. An equally important and parallel benefit is that this process also results in reduced overall radiation exposure, thereby contributing significantly to ALARA objectives for reducing all radiation exposures. In this sense, both cask designers and regulators have the common ultimate goal of improving cask performance within safety and regulatory limits, and thus of facilitating the optimization process.

2.2 OPTIMIZATION WITHIN THE REGULATORY PROCESS

It is evident from the foregoing that optimization is a multi-dimensional process that cuts across all of the design technical disciplines and across the safety and regulatory areas, with an overriding concern for improving cask performance, always within the safety margins established by the formal regulations. This latter requirement needs to be emphasized: the optimization process does not involve any compromise of the safety margins and related safety levels that have been established by the formal regulations. Actual regulatory practice embodies, but goes beyond the formal regulations, to address the practicalities of the regulatory process. Regulatory practice addresses such important management issues as demonstrable uniformity, consistency, and timeliness of regulatory reviews. As a result, regulatory practice includes many detailed safety analysis assumptions and some specific regulatory guidance that are not part of the formal regulations, but have been historically used and accepted either implicitly or explicitly in recent licensing actions. Many of these safety analysis assumptions have excess safety conservatisms that may facilitate the regulatory analysis and review process, but generally at the expense of cask performance.

Because these conservative assumptions are not part of the formal regulations, most regulatory jurisdictions will consider alternative assumptions with less excess conservatism, provided the applicant clearly demonstrates that the change can be made within the formal regulatory limits. The degree of conservatism in these historic safety analysis assumptions are therefore of interest within the optimization process. Again, because no changes in safety analysis assumptions are ever made without regulatory review and approval, no approved changes in previous regulatory practice involve any compromise of the safety margins and related safety levels established by the formal regulations.

The purpose of this section is to summarize the regulatory process and the how the optimization process functions within the typical regulatory environment. In a broad sense, the regulatory process includes:

(1) Safety limits, related safety margins, and procedures established by formal regulations,
(2) Regulatory practices that include currently acceptable ways of addressing the large number of safety analysis details not covered by the formal regulations,
(3) Regulatory review and decision-making on the licensing applications submitted by designer and/or owner applicants.

In most regulatory jurisdictions, the safety limits established by regulations are prescriptive and remain unchanged, except for very infrequent changes by the regulators in response to significant new circumstances. Regulatory practice complements the formal regulations, addressing such practicalities as the demonstrable uniformity, consistency, and timeliness of regulatory reviews. Current regulatory practices include the many detailed safety analysis assumptions that have been historically used and accepted either implicitly or explicitly in recent licensing actions. Regulatory practices may also include specific regulatory guidance that identifies safety analysis assumptions and/or analysis methods that are currently acceptable to the regulator in a particular area. Regulatory practices tend to be performance-oriented, and are more flexible with respect to justifiable changes that are demonstrably within established regulatory limits. There are two broad types of regulatory practice that are of particular interest to optimization:

(1) Particular safety analysis assumptions, including bounding assumptions, that may have excess conservatism, and
(2) The magnitude of the uncertainties in the safety analysis results that are developed to demonstrate compliance with safety limits, and the uncertainties in the experimental data used to validate the analysis tools and the related design allowances that need to be made because of these uncertainties. There are two general areas of uncertainty in safety analysis results:

    - uncertainties resulting from approximations and/or assumptions made within the analysis tools for modeling the physical behavior of the system under normal and postulated accident conditions, and
    - uncertainties in the experimental data used within the analysis tools, and/or for validating those tools

As a practical matter of regulatory consistency and good management practice, the regulator expects license applications to conform to current licensing practice. Applicants can request and provide sound justification for a specific change in current regulatory practice, it being understood that such requests will require additional regulatory assessment, will normally delay regulatory action, and if approved at all, may not be in the form originally requested. In a typical situation involving a requested change in currently accepted safety analysis assumptions, an applicant will propose a particular design feature whose licensability depends upon regulatory acceptance of the requested change. The applicant will describe and justify the design feature and will fully describe and support the justification of the requested assumption change. If, after review and possible modification of the design feature and/or the requested change, the regulator approves the design feature, the assumption change is also accepted, either by explicit parallel approval or by implication based on the design approval. In either case, the changed assumption becomes part of the then-current regulatory practice.

When there is excess conservatism in a particular safety analysis assumption, overall safety considerations can favour a reduction or elimination of the excess. Such excess conservatism results in imposing additional increments on the already-substantial level of safety that is embodied in the regulatory limits. These additional limit increments translate into incremental reductions in cask performance capability, which in turn typically translate into more cask loadings, greater occupational and public radiation exposures, and the other impacts of cask storage and any related cask transport operations. These added impacts are not accompanied by any meaningful increase in the safety of individual cask operations, because the basic safety level is determined by the regulations, which already include substantial safety conservatisms. To the extent that the excess conservatisms cause an increase in overall impacts, a net reduction in the overall system level of safety could actually result, when these excess conservatisms are present. Thus, assumptions that have excess conservatism result in reductions in licensed cask performance levels that increase the impacts of cask operations, without any meaningful increase, and possibly even a decrease, in the overall system level of safety. Thus, one of the goals of the optimization process is to identify these excess conservatisms in both regulatory practice and in design software and to facilitate their reduction or removal by clearly demonstrating and documenting their excess conservatism, within the regulatory review process.

The regulatory aspects of the cask design process are conceptually depicted in Figure 2.1. The various technical areas of design are depicted as sectors of the overall circle. The three concentric circles depict the levels of regulatory interest. The outer circle depicts the ultimate physical limit. In criticality design, this would be the criticality limit of 1.0, which is the threshold of a criticality event. The next circle going inward is the formal regulatory limit. In criticality, this limit would be the value, 0.95, specified in most national regulations. It is worth noting that, in terms of the highly improbable serial and parallel events that it would physically take to get the contents of a loaded cask from a sub-critical level of 0.95 up to a potential criticality at the physical limit of 1.0, the regulatory limit of 0.95 embodies a very large and conservative level of safety. Because a similar safety level philosophy is used in establishing the regulatory limits in the other design areas, the same observation as to embodying large and conservative levels of safety can be made for the regulatory limits in the other design areas. The innermost circle in Figure 2.1 conceptually depicts the safety level resulting from the current level of regulatory practice. In criticality design, this limit might be about 0.93, with the difference from the regulatory limit of 0.95 being due about equally to conservative assumptions used in the criticality safety analysis and the uncertainties in the criticality analysis program's results, combined with uncertainties in the experimental data used within the analysis program and/or for validating that program's analysis capability. The inner circle can also be thought of as defining the cask design's overall performance capability: to the extent that the inner circle can be enlarged, the cask's performance capability can be increased. Changing perceptions of safety in some areas, such as the risk of terrorism, could also reduce the size of the inner circle. Finally, the darker-colored annulus between the innermost and second circles can be thought of as the area that is the subject of much of the optimization efforts. Here, the conceptual goal is to reduce the size of this annulus, and increase the size of the innermost circle by reducing the excess conservatisms in some safety analysis assumptions and reducing the uncertainties in the results of safety analyses by increasing the accuracy of the physical models embodied in the analysis tools and/or the data used within the models or for validating those models and tools.

The other principal optimization activities are making judicious design tradeoffs within and between the technical areas, and making tradeoffs between costs and various combinations of alternative cask performance characteristics, always within the envelope of then-current regulatory practice. Because of the latter, no tradeoffs involve any compromise of any of the then-acceptable safety allowances, much less any compromise of the overall safety levels defined by regulations.

Figure 2.2 shows a conceptual optimization of a long term dry storage system. Referring to Figure 2.2, the optimization is divided into two parallel stages/activities, each with design, fabrication and operation phases:

- Practice stage, which proceeds with the prototype design, using existing design tools in the four principal technical areas, optimizing/balancing within each area, and then proceeding to prototype fabrication using established methods to test the ease of fabricating the design, and then to testing for design operability and ease of monitoring .
- New Development stage, which proceeds in parallel, without interfering in the parallel prototype design activity, but develops improved design models, programs and data, develops improved fabrication approaches, and new test and monitoring approaches

The overall optimization then proceeds with three sequential "Balancings" as shown in Figure 2.2:

1st Balancing

The first optimization is achieved by selecting the cheaper materials, simplifying the structure, and decreasing design margins within the regulatory criteria, and making cost reductions via tradeoffs between the four technical areas.

2nd Balancing

Mutual adjustments and tradeoffs are made to the prototype design and/or the fabrication approach and/or the overall operating approach to improve overall performance and/or reduce costs. For example, if the design is more robust than anticipated, the inspection and/or monitoring items and frequencies can be decreased.

3rd Balancing

All of the new developments, such as more precise experimental data, validated calculation codes, and an improved quality assurance system, are reviewed as to their beneficial impact on the prototype design, if implemented for the final design. Both design performance improvements and cost changes are considered. These benefits are then weighed against the direct added cost and increased design and licensing schedules that would be incurred by implementing the improvements. Decisions are then made as to which improvements would be implemented for the final design. The optimized final design of the long term storage system is then completed.

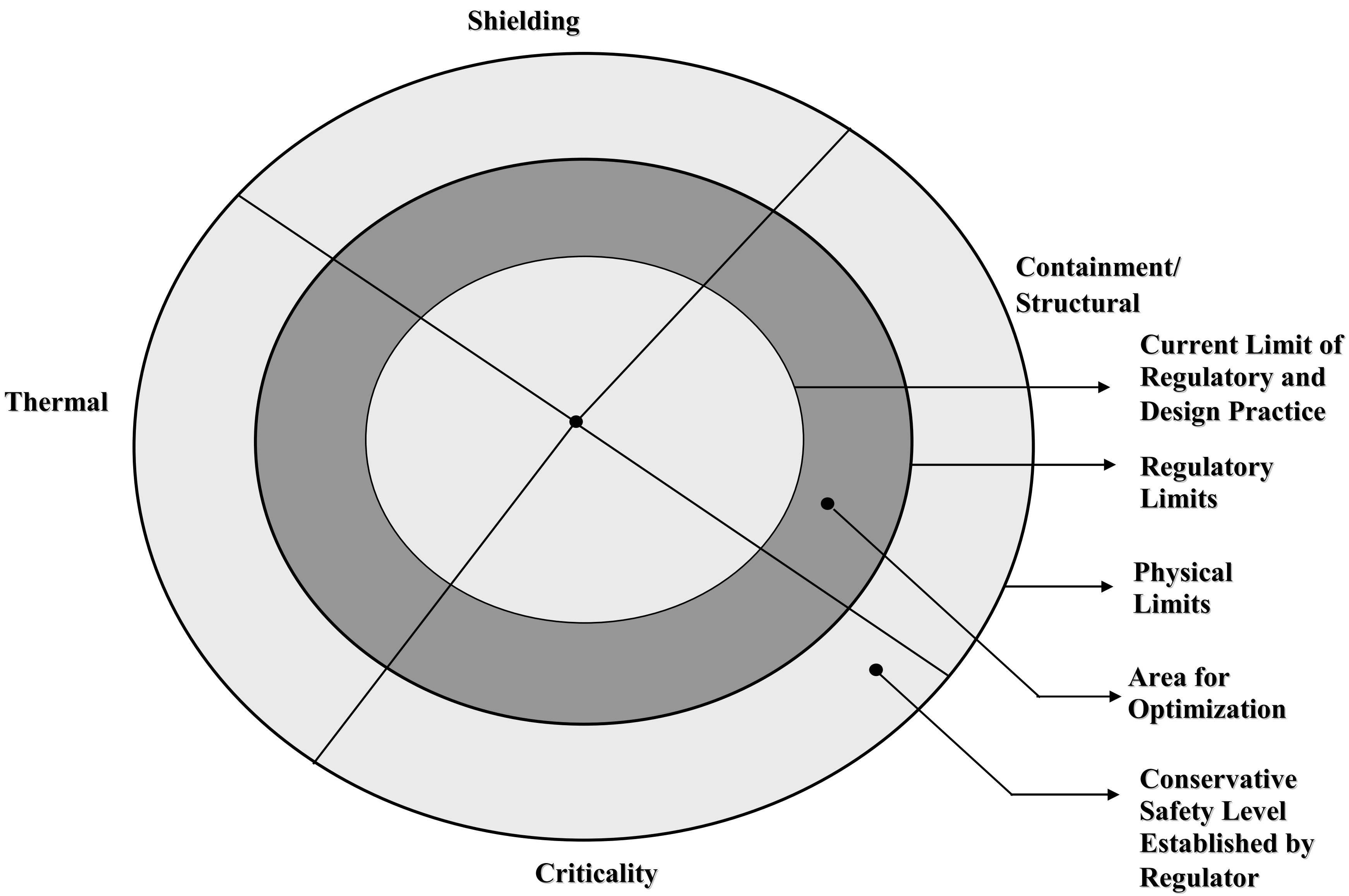


Figure 2.1 Conceptual view of the three levels of regulatory interest.

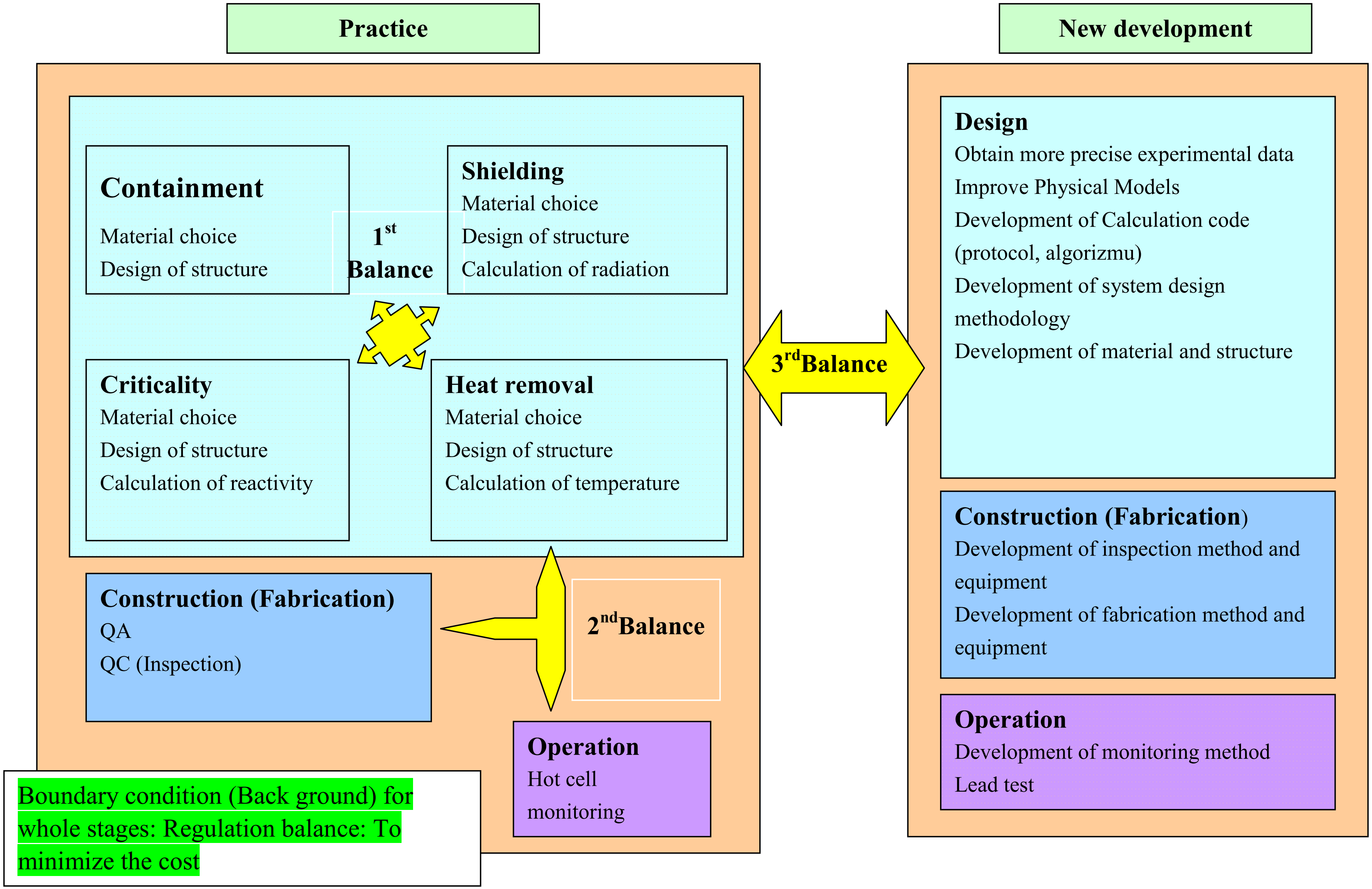


Figure 2.2 Optimization stages for long term dry storage.

2.3 GROUPINGS OF OPTIMIZATION ACTIVITIES

The foregoing discussion has introduced the three principal areas of optimization activity, as follows:

(1) Identifying, analyzing and justifying reductions in excess conservatisms in input assumptions to safety analyses,
(2) Reducing the uncertainties in safety analysis results by improving the accuracy of design tools and/or the experimental data used within, or in the validation of the design tools,
(3) Making judicious design tradeoffs of cask performance characteristics within and between technical areas, and tradeoffs between costs and various combinations of alternative cask design features and related performance characteristics, all of which are within the envelope of then-current regulatory practice.

The remainder of this publication describes the optimization aspects of the cask design process in each of the principal technical disciplines of cask design. The primary focus of this document is on the optimization of cask design within licensing processes based on regulatory limits, rather than on the specifics of cask design, licensing and regulations. Therefore, the latter specifics are described only to the extent necessary to illustrate particular optimization activities, and are not intended to be a comprehensive summary of cask design tools, cask design and licensing practices, or of regulatory limits.

The following chapters address specific activities within the three principal areas of optimization in each of several technical disciplines, followed by an overall summary. Chapter 3 outlines the initial process of cask type selection, its impact on cask material choices, and subsequent optimization via the selection of cask materials. Chapters 4, 5, and 6 describe criticality, thermal and shielding optimization activities, respectively. Chapters 7 and 8 describe optimization considerations in structural design, and in operations and maintenance. Chapter 9 addresses long term retrievability issues, and optimization. Because of the current uncertainties as to long term retrievability, related concerns tend to act in the direction of constraining cask performance, in contrast to the other design disciplines which all appear to increase cask performance. Chapter 10 provides an overview, with particular emphasis on across-discipline tradeoffs, and cost-related tradeoffs between alternative cask performance characteristics. Chapter 10 also summarizes the status of the open issues regarding long term spent nuclear fuel storage.

3 CASK TYPE SELECTION AND RELATED MATERIAL SELECTION AND PERFORMANCE

The purpose of this chapter is to summarize the factors affecting the selection of cask materials as part of the process of cask design and optimization. The typical nature of the cask buyer's cost-sensitive choices of the cask type in its intended application and the resulting important impact on cask material selection is also discussed. Emphasis is given to the functional performance requirements of cask materials as to shielding, structural rigidity, containment, heat removal, and criticality control, and the impact of these performance requirements on the optimization process.

3.1 CASK TYPE SELECTION

The design of a storage system starts with the site requirements, particularly cask weight or dimensional limitations, and the intended approach for ultimate retrieval of the stored fuel assemblies. Selection of the cask type, cask fabrication approach, and materials of construction is the starting point for design and optimization. The first decision is between storage systems based on metal casks, or systems based on canisters, transfer casks, and storage overpacks. Canister-based storage systems tend to have the lowest initial unit costs because of the ability to use inexpensive concrete storage modules, and in spite of the added cost of the transfer system. The principal difference between canister-based and metal cask systems derives from lower temperature limits on concrete and the additional cooling features needed to assure lower concrete temperatures.

The next decision involves the choice between storage-only, and transportable storage systems. Recently, and in part because the cost premium for transportable systems has been decreasing, many buyers have chosen to pay the extra costs for transportability in order to avoid future rehandling of individual fuel assemblies, and also to remove the future need for a reactor pool for spent fuel retrieval and offsite transport. These buyers are implicitly accepting the risks associated with possible future regulatory changes that could adversely impact the future transportability of their casks when cask licenses expire periodically and have to be renewed. The principal difference between storage-only and transportable storage systems is that the cask loading limits for storage typically allow considerably hotter fuel than can be accepted for transportation. To the extent that a transportable storage cask was originally loaded at its storage loading limit, the only way to meet the lower transport loading limit without opening the cask is for the storage period to be sufficiently long that the fuel decays to the maximum acceptable level for transport. For example, if the original loading for storage was double the acceptable heat level for transport, it would take 40 to 50 years of storage before the fuel could decay sufficiently to be acceptable for transport. If a shorter storage period were anticipated, the buyer could decide on a storage-only system, or could have the transportable system redesigned with a lower initial loading limit.

Once the foregoing decisions as to the basic storage system have been made, initial design can proceed to the parallel selections of cask materials and cask fabrication approach. The alternative fabrication types are: monolithic metal, "sandwich" steel, and lead/steel casks (or transport overpacks in canister-based transportable storage systems). Shielding requirements dictate much of the cask's weight and in that sense can dominate the cask's material costs.

The most effective shielding materials, in decreasing order, are depleted uranium metal, lead, steel/iron, and concrete. However, the unit costs of these materials and their fabrication costs are in exactly the reverse order from their shielding effectiveness, such that the fabricated cost of concrete gives the lowest unit costs for shielding materials in storage-only applications, followed by steel/iron and lead shielding. Because depleted uranium is the most expensive, for both material costs and fabrication costs, it is used only infrequently, primarily for smaller, transport-only casks. In transport service, its high costs can be spread over many cask shipments and its superior shielding can result in somewhat higher loading limits for a given cask weight limit. Steel is the preferred material for structural and containment purposes, although paradoxically, the more-expensive higher-strength steels tend to have lower thermal conductivities. For thermal conductivity, copper is preferred, but because of its high unit cost, it tends to get used only in the more difficult heat transfer situations, and steel is normally acceptable for heat transfer, in spite of its only-modest heat transfer capabilities. For criticality control, flat arrays of steel rods holding boron carbide pellets, or steel-enclosed boral are typical of the relatively-expensive neutron-absorber materials.

The above discussion indicates the importance of combined material and fabrication cost factors in the general selection of cask materials for recent storage procurements. As a generalization, concrete (for storage overpacks) and steel are not the first choice for their shielding properties, but tend to be acceptable because of their costs. Steel is probably the first choice for its structural and containment properties and its costs, and steel has only modest heat transfer properties, but again is acceptable because of its costs. As a further generalization, because of the dominance of cost considerations, the materials chosen for the various primary technical areas during initial design tend to have less-than optimal performance in those primary technical areas, and also in the other technical areas that they influence by their presence as a cask material.

Thus the overall optimization challenge is the selection and/or development of materials with improved combinations of concurrent high performance in multiple technical areas, such as shielding, heat transfer, and strength, so as to be more efficient in their overall safety function. An additional goal of the optimization of material performance is the identification of performance margins that lead to the simplification of safety analyses, and to the related simplification of the regulatory review and the conditions of the license.

3.2 DESIGN, SAFETY AND REGULATORY ANALYSIS ISSUES

For the overall storage period, material performance must be compatible with the safety functions that the cask must perform, including:

- Maintaining the complete structural integrity of the containment barrier, and of cask internals,
- Providing radiation shielding,
- Providing sufficient heat removal capability to remain below internal temperature limits,
- Providing neutron absorption capability to ensure criticality safety.

Each of the above requirements must be analyzed, considering the potential reduction of properties and function that may be induced by external and internal influences during the full storage period of the cask and any subsequent transportation. External influences include the atmospheric condition of storage, for normal, extreme natural, and accident conditions. Internal influences include the effects of ionizing radiation, the influence of high temperatures, and the impact of internal corrosion. Particular attention must be paid to the influence of very long term storage periods on the performance of particular materials, including potential degradation of certain materials such as elastomers for O-ring gaskets, and the performance of alternatives, such as metallic seal rings.

All of the safety and regulatory analyses of the cask design are based on the characteristics of the chosen materials and their continued performance within acceptable limits. The characteristics of the various materials as to chemical, thermal and mechanical properties are a significant part of the input data for each of the safety analyses. The safety analyses must demonstrate compliance with the performance safety limits of each of the various materials. These analyses must demonstrate that the material properties are appropriate under the physical loads and thermal conditions throughout the intended storage period, and where appropriate, during any subsequent transportation of the cask.

3.3 OPTIMIZATION ISSUES

The continuing trend of increasing fuel element burnups and/or specific powers, leads to an increase of decay thermal power and source term, especially the additional decay heat and neutron production in MOX elements. At the same time, cladding temperature criteria and limits for fuel elements become more and more stringent.

Optimization consists of the selection of materials with the appropriate combinations of high performance in multiple technical areas, such as shielding, thermal conductivity, and strength, so as to be more efficient in their overall safety function. This may require aggressive development and demonstration of new materials. An additional goal of the optimization of material performance is the identification of material performance margins that lead to the simplification of safety analyses and to the related simplification of the license.

3.3.1 Conservatisms and uncertainties

Each material has its own physical limits. These limits are defined to guarantee the long term behaviour of the material during the storage period. The current regulatory practice does not always consider systematically the source term and thermal power decay during the storage period for the definition of these limits.

The optimization effort in material selection should be done so as to roughly equalize the material’s performance margin between each of the material’s safety functions. Also, voluntary conformance to “generic” standards or codes for the sake of simplicity may lead to conservatism when the service conditions of the cask are significantly lower than the conditions assumed during development of the standard.

3.3.2 Design tools and validation data

Optimization of material choice should be considered for each component of the cask. If an increase in thermal power is one of the goals of optimization, all materials should be compatible with the increase of the temperature associated with such thermal power increase. This issue is not a concern for steel material but it does concern all other materials such as neutron shielding and components made of aluminium or copper. Aging effects also have to be considered. At the same time, the selection of material is of great interest in minimizing as much as possible the effects of the desired thermal power increase, so as to maintain compliance with cladding temperature criteria without a reduction of the cask assembly capacity. Temperature increases can be limited by:

- Improving thermal characteristics by selecting material with higher conductivity and emissivity,
- Improving thermal performance of cask components by selecting material that concurrently performs several safety functions, reduces overall dimensions, and/or reduces the thermal gradient. As an example, the use of boron aluminium for the basket enables the concurrent enhancement of heat transfer, provides all or part of the structural resistance, and accomplishes criticality control.

The concept of concurrent safety functions performed by the same material is of interest not only from the thermal point of view as described above, but for all the other functions. The selection of material with performance benefits in several technical areas is part of the optimization process since it may facilitate a more compact loading of the cask and thereby an increased assembly capacity and/or an increased burnup/age capability. For example, selection of structural material that also has strong neutron absorption properties and high thermal conductivity has the added values of 1) controlling fuel reactivity, particularly of high enrichment or MOX fuel elements, and 2) reducing fuel temperatures through improved heat removal.

The tools used to demonstrate the compatibility of the material with the design limits focus specifically on the material properties under the range of normal and accident conditions, and their conformance with the design requirements for each of those conditions. However, in many situations, and in particular, the development of new materials, little or no material property data are available over the required range of conditions, and new qualification tests may be required. Thus, optimization may involve:

- R&D programs of material characterization that are performed mainly in laboratories for all chemical, thermal and mechanical properties. Additional tests such as scale model testing may be required such as described in Chapter 7 on structural design,
- Additions to the QA system including new manufacturing procedures and operating qualifications so as to guarantee the conformity of the material with its specifications.

3.3.3 Trade-offs and interactions

The material performance area interacts with all other areas, because material performance defines:

- Cask loading limits and long term performance
- Part of the input data and/or criteria for safety analyses,
- Part of the input for maintenance requirements,
- Part of the data to be checked in the manufacturing process,
- Part of the operations to be performed during loading, storage, and transport, as appropriate.

An overall tradeoff that is made in the material selection area is between, on one hand: the delay and cost of material R&D and qualification programs, including more sophisticated manufacturing processes and other implementation changes; and on the other hand, the expected long term benefit in terms of cask performance increases, ease of licensing, ease of manufacturing and control, operational improvements, and overall reductions in future impacts and costs.

4 CRITICALITY AND BURNUP CREDIT

The purpose of this chapter is to summarize the principal criticality aspects of cask design and optimization, including the regulatory limits on the level of criticality, criticality design and the related levels and distribution of fissionable and neutron-absorbing materials in the nuclear fuel contents and internal structures of the cask. The discussion of the criticality aspects of design is done only to the level necessary to support the subsequent discussion of the optimization of criticality design and licensing. The overall optimization challenge is to undertake realistic reductions in the conservatisms in current criticality regulatory practice, to make improvements in current criticality safety analysis methods and in their supporting data, and to achieve the best balance among and within the alternative potential criticality design performance tradeoffs.

The principal criticality design challenge is, for a given distribution and characteristics of the contained (design-basis) SNF assemblies, to provide suitable spacing between assemblies and suitable amounts and distributions of neutron absorbers within the cask basket structure and/or within the fuel assemblies. These features must result in a criticality level no greater than the applicable regulatory limits as reduced by prescribed criticality allowances for computational and experimental uncertainty. This must be accomplished within the cask weight and dimensional limits of the application, and must reflect the additional constraints imposed by the other design areas such as structural and thermal design, and cask basket material selection. For PWR storage casks being designed for future transportability, one of the most important potential improvements in overall current regulatory practice strongly affects the criticality area: making the transition from an assumption of a uniform cask loading of fresh fuel without credit for burnup to a regulatory assumption of burnup credit, including criticality credit for actinide depletion and fission product buildup. Compared to the direct benefits of criticality credit for PWR burnup, and the indirect benefits of improved criticality methods and data, the benefits from other criticality optimization activities are small, but still need to be considered.

4.1 SUMMARY OF CRITICALITY DESIGN, SAFETY AND REGULATORY ANALYSIS ISSUES

Criticality design and regulatory practices for storage casks are typically an adaptation of the practices for the criticality design of transport casks, which also apply to the criticality design of transportable storage casks. The historical criticality design assumption has been that the cask is uniformly loaded with nuclear fuel assemblies at the maximum reactivity condition for the initial enrichment of the loaded fuel, and is flooded with pure water. For typical current pressurized water reactor (PWR) fuel the maximum reactivity condition occurs for fresh, un-irradiated fuel. For typical current boiling water reactor (BWR) fuel, which includes burnable neutron poisons integral with the UO_2 in the fuel pellets, the maximum reactivity condition occurs in the range of 10 to 12 GW.d/MTU burnup. The so-called “fresh fuel” assumption for the criticality evaluation of spent fuel with significant burnups may be the most conservative assumption in cask licensing practice. Its principal consequences are:

- A maximum enrichment limit in the range of 3.8 to 4.2% for transport casks and some storage casks, and corresponding direct or indirect limits on burnup in the range of 40 to 45 GW.d/MTU.
- The need for flux traps in PWR casks so as to avoid even lower enrichment limits, with a resulting drop in PWR assembly capacity.
- Criticality design has been simplified, is in a relatively mature condition, and is already substantially optimized

For storage casks, moderator exclusion during the storage period has been accepted in most regulatory jurisdictions. However for loading and unloading in reactor pools, flooding with pure water must be assumed, except that in many regulatory jurisdictions, criticality credit can be taken for the dissolved boron in PWR pools.

Under the conditions of maximum reactivity, with or without credit for fuel burnup, the loaded cask is typically required to have:

- An effective multiplication factor (k_{eff}) of no greater than 0.95, including all benchmarking uncertainties and biases evaluated with a 95% probability at the 95% confidence level. When the accuracy and any bias of the typical criticality analysis computer program is determined via the analysis of multiple actual critical experiments, this uncertainty and bias typically reduces the acceptable multiplication factor when using that analysis program to the range of 0.93 to 0.94,
- The foregoing applies to both normal and credible accident conditions, including (for transport casks) the possibility of internal structural changes and the assumption of flooding with clean un-borated water.

Typical regulatory practices require evaluation of the criticality impacts of:

- Manufacturing tolerance combinations,
- Pellet-clad gap flooding,
- Assembly positioning within the basket cell,
- Actual versus planar-average rod enrichments within assemblies,
- Axial blankets at assembly tops and/or bottoms,
- Partial flooding and both internal and external moderation,
- Crediting only an appropriate fraction of the nominal neutron poison material content present in the neutron absorber,
- Arrays of multiple casks,
- Combinations of the foregoing.

4.1.1 Burnup credit as an optimization activity

Historically, most regulatory organizations have required the criticality safety design assumption that transport casks be designed assuming a uniform loading of fuel in its most reactive fuel condition. As a result, the criticality design of transport casks has typically been based on the assumption of a uniform loading of fresh fuel, without criticality credit for the significant fuel reactivity decrease associated with fuel burnup. Because many, if not most storage systems are now being designed to preserve the option of future transportability, burnup credit has also begun to impact storage cask design. The lack of burnup credit is already well recognized as a conservative assumption that imposes major limits on the physical and radiological capacities of casks. As a result, substantial national and international efforts have been under way to obtain regulatory approval for progressively increasing levels of reactivity credit for fuel burnup. Burnup credit for geologic disposal of intact fuel assemblies is also of increasing interest. Obtaining credit for fuel burnup is identified as an optimization topic because, among all of the possible results of successful optimization-like activities, obtaining substantial reactivity credit for fuel burnup promises the most significant overall benefits in terms of improved cask performance capability. Specifically, the prospective future availability of increasing levels of burnup credit is expected to significantly increase the criticality-related cask burnup limits, to the extent that shielding or thermal limits could impose the upper limits on cask burnup/age capability. The assembly capacities of PWR transport casks are also expected to increase with burnup credit, due to the reduction of the spacing between PWR assemblies.

The current efforts to quantify acceptable levels of PWR burnup credit, and to define the conditions governing its application has raised new issues in three general areas:

(1) Isotopic depletion, buildup, and decay and impact on criticality,
(2) Spatial distribution of neutron flux and burnup, the spatial alteration of isotopics due to the operational presence of control absorbers, and their impact on criticality,
(3) The accuracy and veracity of assembly burnup records, the prospective need for assembly burnup measurement, and the impact of these issues on the implementation of burnup credit cask loading.

The extensive efforts already under way to address the many issues in each of the foregoing areas have already resulted in regulatory acceptance of various levels of burnup credit in some regulatory jurisdictions. It is also evident that these efforts have, and will result in improved modelling of neutron behaviour, and improved nuclear cross section and other data, including source terms for shielding and criticality data for non-uniform distributions of fissionable material.

In summary, the extensive national and international effort currently under way to establish the safety and regulatory bases for taking reactivity credit for PWR fuel burnup, is an optimization-like activity that is expected to realize substantial improvements in the physical and radiological capacity of transportable casks. Among other published literature, readers are referred to the IAEA TECDOC on burnup credit (ref 3). The topic of burnup credit is discussed here because it is the dominant optimization activity in the criticality area. It is noted that the expected direct benefits from burnup credit are probably the most significant of the benefits from optimization-like activities, and that the indirect benefits of reduced uncertainties in analysis tools and their validation data will benefit several technical disciplines, particularly the criticality and shielding areas.

4.2 OPTIMIZATION ISSUES

The purpose of this section is to describe the principal cask design optimization issues associated with criticality safety, under the three optimization categories identified in Chapter 2.

4.2.1 Conservatisms and uncertainties

As noted above, criticality design without burnup credit is in a relatively mature status, and is already substantially optimized. However, it is already evident that some conservative assumptions are being made in the development of regulatory practices for allowing the use of burnup credit. The following includes potential criticality conservatisms in the application of burnup credit:

Criticality deficit for flooded pellet-to-clad gaps: Among criticality-related regulatory practices is the apparent criticality design practice of assuming that all of the pellet-to-clad gaps inside each fuel rod of each assembly in a loaded transportable storage cask or transport cask are flooded with fresh water. This assumption causes a reactivity change that is design-specific, but it can cause an increase of the order of 0.7% in reactivity, an amount that reduces the acceptable cask criticality loading level. Physically, this assumption may be justified for older fuels in which there were occasional significant fuel failures. However, fuel rod failure rates have been in the range of between 1 rod in 2000 to 1 rod in 10,000 for recent fuel designs in routine operation. Under accident conditions, it may be appropriate to assume some rod integrity failures, but the 100% failure rate implicit in the current assumption appears to be extreme. It is suggested that the basis be developed for a more realistic level of assumed fuel rod failures when calculating the reactivity effect of pellet-to-clad gap flooding.

Cask loadings based on individual assembly versus average characterisrics: The current general cask loading practice is to accept individual fuel assemblies for loading if they individually meet all of the screening criteria for loading. If this practice is followed for burnup credit, assemblies would be accepted if their burnups are no less than the minimum acceptable burnup of the licensed Loading Curve of minimum acceptable burnup vs initial enrichment for the cask being loaded. All assemblies that have less than this minimum burnup are rejected, even if the remaining assemblies have burnups that are significantly above the minimum burnup requirement, and the actual cask loading would consequently be substantially below the overall criticality safety limit. In order to be able to optimize burnup credit cask loadings within the overall criticality safety limit of the cask, a change in the currently proposed regulatory assumption is recommended. Specifically, it is suggested that a group of assemblies be qualified for loading if the average of their deviations, above and below the loading curve is positive and the average positive burnup deviation is greater than a statistically-determined burnup margin that provides a specified level of confidence that the overall criticality safety limit is met.

Cooling time at which burnup credit criticality is determined. Most of the criticality calculations that establish allowable levels of criticality credit for burnup are based on an assumed cooling period following final discharge, typically 5 years. Criticality initially decays for 25–30 years after discharge because of the decay of ^{241}Pu, and the buildup of ^{241}Am and ^{155}Gd. It starts to increase very slowly at about 100 years. At 5 years of cooling, only about 22% of the Pu decay and Am buildup, and only about half of the Gd buildup have occurred. This can represent a substantial amount of lost reactivity credit. This loss can be avoided by specifically assuming a considerably longer decay period, implemented by stipulating to an application-specific minimum age before assemblies can be loaded into the cask.

4.2.2 Design tools and validation data

As noted above, the many diverse activities aimed at defining the safe levels of burnup credit and obtaining regulatory approval of those limits, are resulting in improvements in the neutron behavior models, and in reduced uncertainties in the data needed to validate the improved models. Additional experimental data is needed on:

- Actinides at burnups above 45 GW.d/MTU,
- Fission products at both current and higher burnup levels,
- At least one cask-sized spent fuel critical experiment with well-characterized spent fuel with significant burnup (plus fresh fuel/rods for achieving criticality).

4.2.3 Trade-offs and interactions

The factors that control criticality do not lend themselves to easy tradeoffs. Two of these factors, enrichment and burnup, are not under the cask designer's control. The other two are assembly spacing and the placement of neutron absorbers as close as possible to the fissile materials in the fuel. Increasing assembly spacing works in the wrong direction — it reduces cask assembly capacity. Placement of effective neutron absorbers is limited by the assembly's outer dimensions, unless access can be had to the assembly's interior. Given the foregoing, criticality optimization needs to focus on minimizing the number of assemblies that do not meet the cask's loading curve of minimum burnup vs enrichment. In burnup-credit casks, this can be done in approximate order of preference by:

- Getting the minimum burnups (vs enrichment) in the loading curve as high as possible by maximizing the reactivity credit for burnup.
- Obtaining regulatory approval to mix assemblies below the minimum burnup with assemblies that are well above the minimum burnup
- For PWR assemblies that are below the required minimum burnup, use special absorber rod arrays inserted and locked into the control rod guide tubes within the PWR assemblies

For fuel assemblies that cannot be loaded via any of the above measures, design special casks with large flux traps, neutron absorber plates, and if necessary, special absorber rod arrays inserted and locked into the assemblies.

With respect to tradeoffs between the criticality, thermal, and structural areas, the space between adjacent assemblies within all casks needs to include materials that serve three functions: neutron absorption for criticality control, heat transfer for temperature control, and rigidity for structural integrity. A single material, or a two-material composite with the required properties would be ideal for this situation, and identifying existing materials, or formulating new materials is a worthy optimization activity.

5 DECAY HEAT, FUEL TEMPERATURES AND THERMAL LIMITS

The purpose of this chapter is to summarize the thermal aspects of cask design and optimization, including the regulatory limits on various external and internal cask and fuel temperatures, and the related levels and distribution of decay heat from the spent fuel contents of the cask. The discussion of the thermal aspects of design is done only to the level necessary to support the subsequent discussion of the optimization of thermal design and licensing. The overall optimization challenge is to undertake realistic reductions in the conservatisms in current thermal regulatory practice, to make improvements in current thermal safety analysis methods and in their supporting data, and to achieve the best balance among and within the alternative potential thermal design performance tradeoffs.

The principal thermal design challenge is, for a given level and distribution of decay heat from the contained SNF assemblies, to provide suitable thicknesses and distribution of heat conduction paths within and from the fuel region and the cask shielding to assure that maximum fuel rod cladding temperatures are no greater than the applicable regulatory limits. External cask temperatures and internal temperatures during the accident fire conditions must also be considered. This must be accomplished within the cask weight and dimensional limits of the application, and must reflect the additional constraints imposed by the other design areas such as criticality, shielding, and structural design. One of the most important potential improvements in overall current regulatory practice adversely affects thermal design: making the transition from uniform cask loading to zoned cask loading with regulatory credit for self-shielding of hotter, inner zone assemblies by cooler outer zone assemblies. From a thermal perspective, it would be preferable to place the hotter assemblies in the outer zone and the cooler assemblies in the inner zone. However, because shielding considerations are more difficult to address than thermal considerations in this situation, the cooler assemblies need to be placed in the outer zone, with the hotter assemblies in the inner zone, presenting an additional challenge to thermal design. For transportable storage casks, there is the additional optimization need to achieve the best balance between the cask's near-term performance in the storage mode and its later performance in the transport mode. This latter optimization needs to reflect that the cask loading limits in storage tend to be imposed by fuel cladding temperatures and related thermal loading limits, whereas for subsequent cask transport, the loading limits tend to be imposed by the 2-meter external dose limits.

5.1 DESIGN, SAFETY AND REGULATORY ANALYSIS ISSUES

Thermal input to a cask arises from two different sources. The larger of the two sources is the decay heat coming from the contained fuel assemblies. Initially, this heat source is dominated by the decay heat of the fission products. For longer terms and also for higher burnups, the transuranics make a significant, and ultimately, the dominant contribution to the overall decay heat. The calculation of the decay heat of a fuel assembly is performed with validated computer programs which also calculate the source term (radiological characteristics) based on the initial conditions of the fuel (fuel type and geometry, fissile content, initial enrichment, etc.), irradiation history (residence times at the core, linear power rate, partial and accumulated burnups, re-shuffling schemes, etc.) and the cooling time (age) since its final discharge from the reactor. The most popular of these computer programs include ORIGEN

(USA), KORIGEN (Germany) and other codes, like APOLLO (France), HELIOS (Sweden), etc.

The second source of thermal input to the cask is the heat input from sources exterior to the cask and these vary greatly, depending on the site-specific storage conditions. Among these, the most significant are the solar heat loads (insolation), different ambient temperatures for each operating condition, thermal effects of surrounding stored casks, fires and other potential and postulated accident conditions.

Three different temperature regimes or modes may be defined for long term spent fuel dry storage. An initial mode which would extend from the initial spent fuel storage temperature (normally in the range of 380 to 400 ºC) to 300 ºC, a second one ranging from 300 to 200ºC and a final one, for extended storage which would account for fuel temperatures below 200ºC. As many phenomena involved in the cask behaviour are a strong function of the temperature, fuel and cask material performance has been extensively studied for the most limiting conditions, occurring at cask loading and at the beginning of storage. Time-at-temperature considerations are also important for assuring long term fuel cladding integrity.

The main aim of the thermal cask design, safety and regulatory analyses is to guarantee that:

- Fuel cladding temperatures are kept below their maximum established values for normal, off-normal and accident conditions, as well as during the short term conditions experienced in the cask preparation and transfer operations,
- The cask materials stay within their maximum and minimum temperature criteria under all conditions,
- Thermal related effects, such as the corresponding maximum internal pressure within the cask, thermal stresses, etc. remain within the allowable design criteria established for the cask design under all conditions,
- Cask cooling mechanisms are properly modelled and accounted for in the design

The first two are briefly described and discussed in the following from the perspective of their implications in the optimization of the cask design for long term storage.

Cladding temperatures

The cladding condition at the end of irradiation in the reactor core is a function of both initial (as manufactured) and subsequent irradiation history parameters. Among these, the fuel burnup and the related end-of-irradiation fuel rod internal pressure, the final corrosion layer characteristics, and the hydrogen pickup during irradiation are the more important factors impacting subsequent cladding performance during dry storage. Numerous studies [5, 6, 7] have documented the main potential cladding degradation mechanisms that may occur during dry storage as being due to:

- Clad creep and resultant clad strain,
- Cladding oxidation,

- Hydrogen-induced defects (delayed hydride cracking, hydrogen diffusion in thermal gradients, embrittlement, etc.),
- Mechanical crack propagation,
- Uniform fission product corrosion,
- Localized fission product corrosion.

All these phenomena are temperature dependent and the regulatory limits are normally established in such a way as to limit the maximum storage temperature (or the tangential stress and creep values) to certain thresholds under the different storage conditions, thereby providing a reasonable assurance that the cladding will maintain its integrity during the overall storage period.

Cask material properties

Although all cask materials should be evaluated to fulfill their maximum and minimum allowable temperature criteria, the following thermal related topics are among the most challenging ones with a view to optimizing the cask design:

- Long term performance of certain neutron shielding materials (i.e. polymers and resins) and coatings at high temperatures,
- Behaviour of ferritic materials at very low temperatures (i.e. brittle fracture),
- Maximum local and average temperatures of the concrete when concrete is being used as a cask component with shielding and/or structural functions.

5.2 OPTIMIZATION ISSUES

There are two aspects to be considered when dealing with optimization of the thermal performance of casks: optimization of the loading itself and optimization of the cask design to accommodate a higher thermal load. The "zoning approach" described elsewhere in this document is a clear example of the first consideration together with the strategy of loading fuel assemblies as close as possible to the design basis fuel assembly, saving low burnup and longer cooled fuel for future mixing with higher-burned and/or shorter-cooled fuel. The use of higher thermal payload designs; better shielding materials with higher allowable temperature limits and the employment of more accurate or less conservative computational models and tools are examples of the second optimization route of accommodating higher thermal loads. These considerations are further described in the following sections.

5.2.1 Conservatisms and uncertainties

The main conservatisms and uncertainties associated with thermal considerations are related to the determination of the heat inputs and sinks in the thermal design of a cask and to the conservatisms in the assumptions and models employed in the thermal calculations.

The calculation of the decay heat of a fuel assembly includes a limited number of conservatisms and is considered to be a state of the art technology with at best, only moderate room for improvement. The decay heat of BWR assemblies depends somewhat on the average operating core void fraction during irradiation, influencing the amounts of actinide production and fissions and the resulting decay heat levels. Regulatory assumptions of high void fractions may overestimate actual BWR decay heats. Additional experimental data is needed to support a reduction in the uncertainties associated with decay heats of BWR fuels, high burnup fuels, and MOX fuels.

Regarding the other heat inputs into a cask, insolation and fire accident data for storage conditions are normally taken from the applicable transport regulations, as many of the current storage cask designs are now also intended to perform the transport function. Data for ambient temperatures tend to be more site specific, allowing the use of maximum average values rather than contemplating a high constant conservative one, reflecting the large thermal inertia inherent in these massive casks.

The heat transfer mechanisms that take place inside the cask are usually reduced to conduction and radiation for modeling purposes, while convection is in most cases neglected, providing a conservative bounding analysis. Related to the modelling assumptions, other conservatisms typically employed are the following:

- Fuel assemblies are assumed to be perfectly centered in the fuel basket positions, maximizing the gaps between the fuel assembly and the basket structure,
- Models usually account for the largest possible gaps present in the cask due to tolerances and shrinkage of its components,
- Heat dissipation by the non-fuel assembly hardware (mainly grids, upper and end fittings) is normally neglected,
- The casks are sometimes modeled as semi-infinite cylinders, neglecting axial heat dissipation,
- Use of simplified conservative models and properties for heterogeneous materials.

The topic of limits established for the maximum cladding temperatures (or corresponding associated cladding properties) in dry storage conditions remains one of the most significant fields for improvement, noting that this effort is linked to further developments in the field of cladding materials. With the use of new advanced cladding materials, with better performance and reliability during in-core operations (generally linked to the industry trend to constantly achieve higher and higher burnups), it may be possible to establish higher maximum cladding temperature limits in dry storage applications.

5.2.2 Design tools and validation data

As mentioned above, the current computational tools need further validation studies to better support their use for the determination of temperatures and other cask internal conditions when loaded with high burnup/high heat fuel assemblies. These efforts generally run in parallel to those related to obtaining experimental isotopic data for the detailed radionuclide characterization of high burnup fuel in support of burnup credit applications. However, it must be noted that these experiments should include the determination of certain radionuclides (mainly several fission products as ^{137m}Ba, ^{90}Y, ^{106}Rh, ^{134}Cs, ^{144}Pr, ^{154}Eu) in addition to those generally included in burnup credit isotopic assay experiments. Several experimental programs, such as the one launched by the Swedish company SKB or the CEA PRECCI program [4], plan to provide additional future data related to direct decay heat measurements for high-burnup and modern design fuel assemblies, providing valuable data to use in the validation of the computational tools.

Cask thermal analyses are performed using steady state and transient 3-D finite or volume element codes, which are the state of the art in industrial applications, such as ANSYS, ABAQUS, HEATING, IDEAS, COBRA-SFS and CFD codes such as FLUENT, etc. These codes have been validated against numerous general benchmarks and provide a reasonable representation of the thermal performance of the cask. However, additional thermal measurement programs of fuel clad and other temperatures within full scale loaded casks of recent design are needed, in order to increase cask performance by reducing the conservatisms and uncertainty allowances generally employed in cask design activities.

One or more systematic non-proprietary long term programs are needed for storage performance assessments on high-burnup fuel that include periodic cask openings and direct assembly inspections. Such programs would develop the quantitative data for improving current understanding and modeling of the principal factors that influence long term cladding performance. Such long term programs would also be able to anticipate unexpected difficulties and, if appropriate, provide the basis for remedial action, well before the situation became serious.

5.2.3 Trade-offs and interactions

The principal trade-off and interaction in the potential optimization of cask thermal performance takes place between the thermal, shielding and criticality areas when dealing with zoned cask loading approaches. Considering a simple two zone cask loading, from a thermal perspective, it would be preferable to place the hotter fuel on the periphery (outer zone) and the cooler fuel in the center (inner zone). From a shielding perspective, the picture is just the opposite. From a criticality standpoint, the situation tends to be more cask specific with a tendency to place the more reactive (usually associated with lower burnups or fresh fuel) in the periphery where neutron leakage from the configuration is expected to be higher. Because acceptable cask shielding performance is more difficult to achieve than acceptable thermal and criticality performance in this situation, the tradeoff that is normally made favors the shielding perspective, with the cooler fuel placed in the outer zone. However, it is reasonable to expect that thermal considerations could limit the heat loading of the inner zone. It is also possible that criticality considerations might impose additional loading restrictions. The zoned loading approach is discussed in more detail in the following chapter on shielding design and optimization.

Another trade-off in the optimization of the cask thermal performance is related to the prospective use of better heat conducting materials in the fuel basket design, but with a potential adverse impact on structural design because these materials tend have less structural capability to withstand the stresses under potential accident conditions. Likewise, taking design credit for convective heat transfer mechanisms inside the cask may improve cask loading limits, but at the same time could impose time restrictions for those operations in which the cask may have to be rotated to the horizontal position (i.e., transfer operations to exit the reactor building), in which heat transfer takes place mostly via conduction and radiation, with convection being greatly reduced in comparison to that cask in a vertical orientation.

6 RADIATION SOURCE TERMS, SHIELDING AND DOSE LIMITS

The purpose of this chapter is to summarize the shielding aspects of cask design and optimization, including the regulatory limits on various external radiation dose rates, shielding design, and the related levels and distribution of the gamma and neutron radiation sources within the nuclear fuel contents of the cask. The discussion of the shielding aspects of design is done only to the level necessary to support the subsequent discussion of the optimization of shielding design and licensing. The overall optimization challenge is to undertake realistic reductions in the conservatisms in current shielding regulatory practice, to make improvements in current shielding safety analysis methods and in their supporting data, and to achieve the best balance among and within the alternative potential shielding design performance tradeoffs.

The principal shielding design challenge is, for a given level and distribution of radiation from the contained SNF assemblies, to provide a suitable thickness and distribution of gamma and neutron shielding to reduce the cask external dose rates to no greater than the applicable regulatory limits. This must be accomplished within the cask weight and dimensional limits of the application, and must reflect the additional constraints imposed by the other design areas such as thermal, structural and criticality design. One of the most important potential improvements in overall current regulatory practice strongly affects the shielding area: making the transition from uniform cask loading to zoned cask loading with regulatory credit for self-shielding of hotter, inner zone assemblies by cooler outer zone assemblies. Another principal optimization challenge is to achieve the best balance in the tradeoff between the largest practicable assembly capacity of the cask and the cask's burnup/age radiological capability relative to the spectrum of fuel types and characteristics in the intended application. For transportable storage casks, additional optimization is needed to achieve the best balance between the cask's near-term performance in the storage mode and its later performance in the transport mode. This latter optimization needs to reflect that the cask radiological loading limits in storage tend to be imposed by fuel cladding temperatures and related thermal loading limits, whereas for subsequent cask transport, the loading limits tend to be imposed by the 2-meter external dose limits.

6.1 DESIGN, SAFETY AND REGULATORY ANALYSIS ISSUES

Compliance with acceptable radiation and dose rate limits is one of the major constraints leading to the definition of the geometry (overall dimensions) and weight of the package.

The primary safety criteria are the various dose rate limits, including:

- Dose rates applicable to the loaded cask during storage,
- Dose rates applicable to the overall storage facility (e.g. Boundary),
- Dose rates applicable to the cask during transportation,
- Dose rates and limits during cask loading, handling, and transport operations,
- Dose rates and limits applicable to postulated accident situations.

In addition, the application of the ALARA principle requires the use of reasonable measures or design features that reduce radiation levels as far as practicable below the various dose rates and exposure limits.

The regulations that define the various radiation level criteria applicable to storage packages may differ between regulatory jurisdictions. In some cases (Belgium for instance), the criteria applicable to casks in the storage mode have similar values to those applicable in the transport mode but are directly applicable to the external surface of the cask: the radiation level shall not exceed 2 mSv/h at any point on the external surface of the package and 0.1 mSv/h at any point 2 m from the external surface. In other cases (Switzerland for instance), additional requirements define a radiation level that shall not exceed 0.5 mSv/h on average at the surface of the package.

The shielding design function requires definition of the candidate spent fuel loads and their related radiation source terms, the evaluation of the radiation absorption performance of the shielding material, and the resulting total of exterior gamma and neutron dose rates and their compliance with the regulatory limits. The shielding design includes a balancing between neutron shielding that is typically a low density material (such as rubber, resin) and gamma shielding that is a high density, heavy material (such as lead and steel). The shielding materials also perform other safety-related functions, including heat transfer, and are important to cask structural integrity and to containment. Optimization can thus be understood both as an optimization of the safety functions of the shielding and other materials and as an optimization within the shielding analysis itself.

The principal shielding-related cask features under design control are also the focus of optimization activities, and are:

- The balance between the cask performance objectives of a large assembly capacity, versus a superior burnup/age capability. These competing objectives need to be balanced in the normal situation in which the cask design is constrained by cask weight and/or dimensional limits, and by the quantities and radiological characteristics of the particular fuel inventory,
- The choice of gamma and neutron shielding materials, the relative amounts of gamma and neutron shielding, and the spatial distribution of the shielding materials,
- The spatial (radially zoned) distribution of hotter and colder assemblies within the cask cavity,
- The design and licensing choice between providing loading flexibility as to assembly types and characteristics with a simplified licensing approach, using generalized loading limits with considerable conservatism, versus the analysis-and-licensing-intensive assessment of the relative importance of each internal assembly storage location to the external dose limits, allowing pre-determination of assembly choices for maximizing individual radiological cask loadings and/or minimizing the total number of cask loadings over extended time periods.

6.2 OPTIMIZATION ISSUES

The main objective of shielding design optimization is to pursue and balance the two basic and competing goals of obtaining:

- An increase in the assembly capacity of a licensable cask: for a given population of fuel assemblies to be stored, this reduces the required number of casks, and
- An increase in the burnup/age capability of the licensable cask. This is particularly important because of the continuing increase in fuel burnup and enrichment, decreases in cooling time, and/or the growing need to store MOX fuels.

In the special situation of limited storage area, it may also be possible to reduce the dimensions of each storage cask while maintaining the same assembly content. Then, for a given size of the storage area, an increase in overall storage capacity may be possible. This optimization of cask performance and storage area usage must also deal with increasing burnup and enrichment, decreased cooling times and with the special characteristics of MOX fuel, where applicable.

The fundamental limitation on the assembly capacity and/or the burnup/age capability in cask design is imposed by the weight and/or geometrical limits imposed by the application. Within those limits, and after innovations in material selection and design features, this means that the degree of optimization of the shielding analysis is directly linked to the sophistication of the shielding design tools being used and to the level of design analyses that are undertaken. A more elaborated shielding analysis leads to improved cask performance, and a better exploitation of the cask's inherent capability, within all safety requirements.

To improve the credibility and optimization capability of shielding analysis methods, more advanced computational analysis techniques and data are necessary. The goal is to improve the detailed design methods and the supporting experimental data, to permit better consideration of such issues as:

- The geometrical discontinuities in unique areas, such as trunnion inset areas,
- The spectrum of differences among the fuel assemblies to be loaded, and the benefits of deliberate non-homogeneous loading, in general, and zoned loading, in particular.

6.2.1 Conservatisms and uncertainties

Current storage licenses define acceptance criteria governing the characteristics of the individual fuel assemblies authorized to be loaded. Typically, these criteria include the maximum burnup, maximum decay heat, maximum enrichment, maximum initial uranium weight, and minimum cooling time.

The definition of these fuel assembly characteristics is of great interest for fuel management at the site of the storage cask application. The traditional approach used to date for cask design and licensed loading, considers only a uniform, homogeneous loading of the cask with every loaded assembly assumed to have the same limiting characteristics, such that the most-limiting external dose rates are at the regulatory dose rate limit. This can lead to a cask design based on a single set of burnup/cooling time values, applied individually as a maximum burnup and a minimum cooling time to be met by all loaded assemblies. This results in substantial conservatism when the cask is loaded with fuel having the typical spectrum of characteristics that is encountered in practice. This spectrum of characteristics is such that the candidate pool assemblies that are the closest to, but no greater than the loading limit have an average loaded characteristic that is well below the loading limit. It is unlikely that any pool ever has a complete load of assemblies for a homogenious cask loading that are just at the cask-loading limit. The magnitude of the considerable conservatism that results from applying the individual loading limits individually to each assembly is measured by the amount by which the actual loaded external dose is below the regulatory dose limit. In many regulatory jurisdictions, a loading curve of maximum burnup versus age is used, which means that a range of cooling times is acceptable, provided the corresponding burnup is no greater than the maximum (design curve) burnup for that cooling age. There is still considerable conservatism due to the typical situation in which there are only a few assemblies that are close to the loading limit, and the average is well below the limit. The loading conservatism inherent in applying loading restrictions on an individual assembly basis could be reduced by some regulatory recognition of average loading. This could be done by allowing acceptance of a few assemblies whose characteristics were somewhat above the established loading limits, such that the average loading could more closely approach the regulatory loading limit.

To the extent that the existence of known conservatisms provides the qualitative justification for some operational flexibility in fuel management and/or a reasonable simplicity in the licensing scope, reduction of these conservatisms could reduce operational flexibility and/or increase licensing complexity. The point at which this occurs needs to be understood so as to maintain an operationally-reasonable generic treatment of fuel assembly loading limits.

The current regulatory practise for dose rate management on the site does not generally acknowledge the reality that the loaded casks do not arrive simultaneously in the site. Then the consideration of the source term decay of the stored fuel assemblies is not taken into account.

Then improvement of regulatory practise can result in realistic long term dose rate management on the site. Source term decay during the storage period needs to have regulatory acknowledgment. Furthermore, if there is a deliberate bias in favour of neutron shielding relative to gamma shielding in the original design, the subsequent slower decrease of neutron/gamma shielding trade-off had been made in the original design (as illustrated in Figure 6.1).

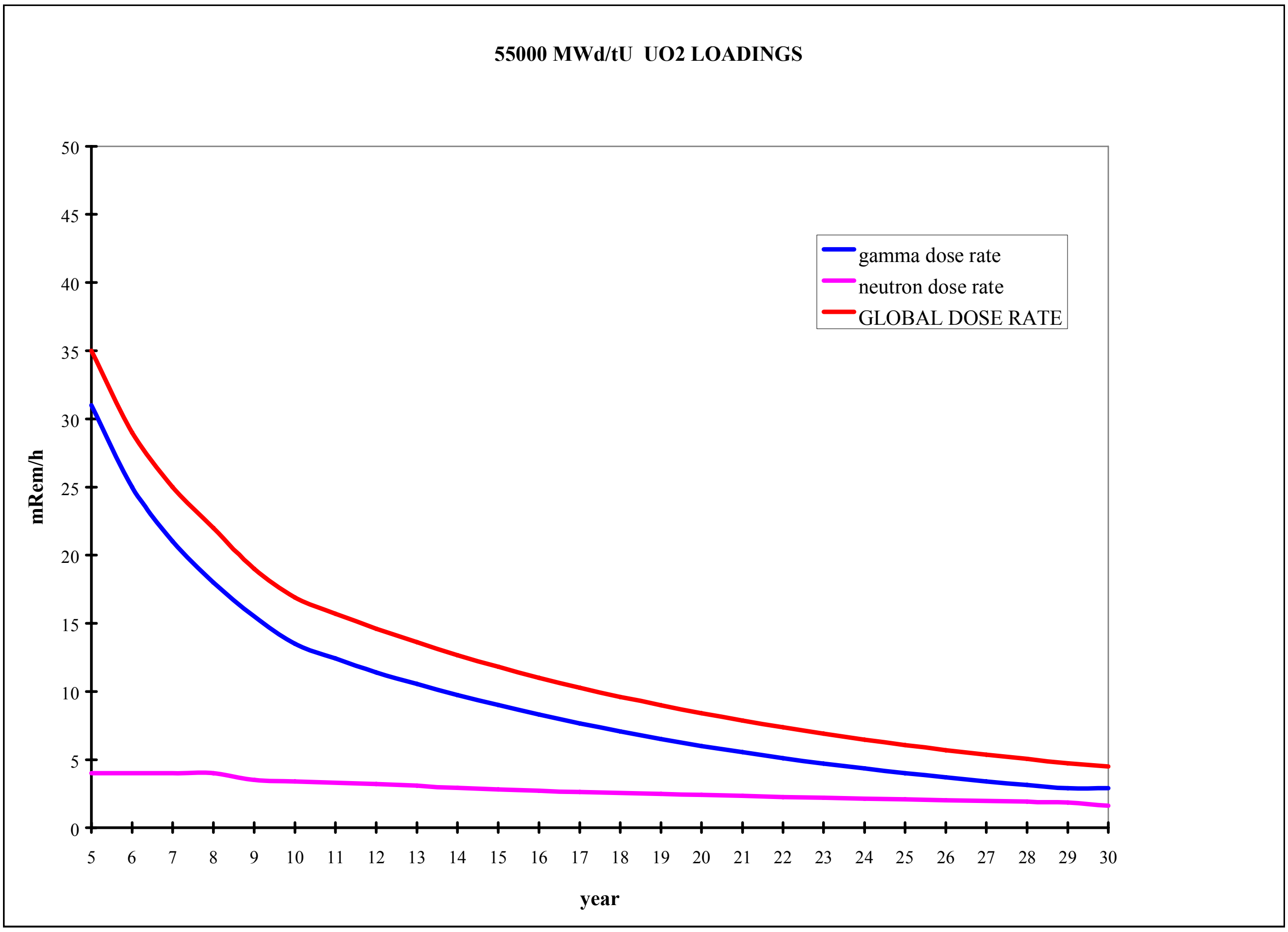


Figure 6.1 Decay rates of gama & neutron doses.

Ultimately, the foregoing approaches open the possibility, over the storage period, to admit more casks without increasing dose rates allowed in the facility.

When cask burnup/age loading limits are based only on the assembly type with the highest kgU loading, and other acceptable assembly types have lower kgU loadings, it is conservative to use that same burnup/age loading limit for the lighter assemblies. Therefore higher burnup/age loading limits should be developed for the lighter assembly types.

6.2.2 Design tools and validation data

Several types of design tools are available for reference, corresponding to increasing rigour in the design analysis software [3, 8], as follows:

- One-dimensional Sn codes for evaluating the dose equivalent rates from neutrons and from the secondary gamma rays from neutron capture,
- Three-dimensional point kernel codes (such as MERCURE V used in France) to evaluate dose equivalent rates from active fuel primary gamma rays,
- Three-dimensional Monte Carlo codes for dose equivalent rate calculations (TRIPOLI used in France) from neutrons and gamma-rays (both from active fuel and secondary gammas from neutron capture).

There is no doubt that the third calculation procedure is the most accurate, as only minor approximations are made for the description of the geometry and the resolution method of the transport equation. It is therefore an appropriate tool for design optimization because it allows consideration of exact geometry and source term variation along the length of the fuel assembly. It should be noted that the ability to include the assembly axial burnup profile is particularly important for the calculation of neutron dose rate. An accurate consideration of activated fuel element end fittings for the gamma-ray dose rate is also of importance in the optimization process.

The disadvantage of such 3D Monte Carlo calculations is the excessive consumption of computer time. For these reasons, the two first calculation methods are still useful, due to their ease of use and their reasonable computational times. Nevertheless, their results require additional qualification due to the different approximations that they use. The main approximations of these methods can be classified as (1) their multi-group energy representation, and (2) their more limited description of geometry. The additional qualification consists of a shielding benchmarks analysis and concerns both radiation source generation and transport calculations.

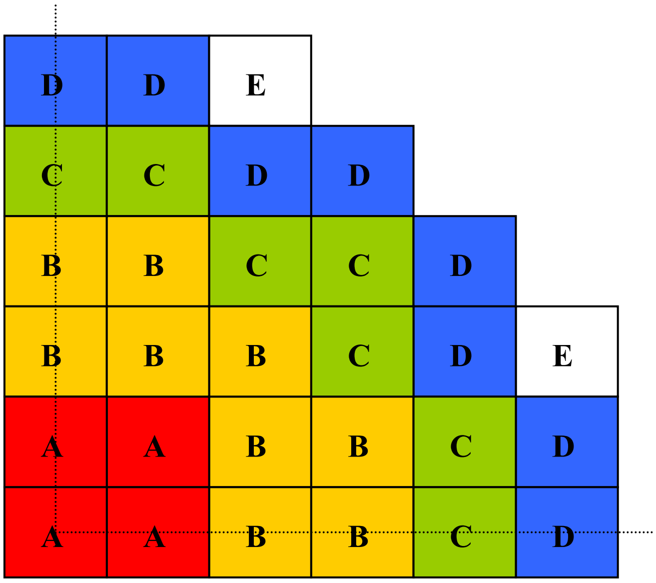
At this stage, design tools are available to adequately take into account unique geometries. In the optimization process, this allows the cask sections with excessive cask shielding thickness to be identified. Unique cask areas, trunnion locations for example, can be optimized by identifying additional shielding devices to be put in place in specific circumstances, such as storage, without incurring an overall penalty in the general usage, such as in transport or loading. The limits on implementing the results of these types of analyses are the simplicity of design that is needed to assure the necessary simplicity of the cask design required for economic manufacturing.

The next step, and one of the most significant steps in the optimization process is to reconsider the homogeneous model of the content so as to take advantage of the normal disparity among fuel assemblies to be loaded, and the self-shielding of inner assemblies by the outer assemblies. A general discussion of the substantial technical and logistic advantages of non-uniform (non-homogeneous) cask loading is provided in Appendix 4.

The simplest method of non-homogeneous cask loading could be called the "zoning approach", in which defined groups of locations (zones) of the cask basket are loaded with spent fuel of similar characteristics within each zone, but with different characteristics between zones. The basic objective is to increase the burnup/age capability of the cask by exploiting the fact that inner assembly locations are shielded by the outer locations, and contribute less to the total external dose than the outer assemblies. It could be implemented by defining loading patterns in the design license that contain fuel of defined characteristics, and would be achieved and verified during the loading of appropriate fuel elements into the cask. This approach could be used for increasing shielding effectiveness, with fuel elements with higher source term in the central area of the cask cavity so as to use the self-shielding properties of outer fuel elements.

In the implementation of the zoning approach, a balance should be made between the advantages (in terms of capacity) given by the zoned loading pattern and the flexibility needed by the utilities for loading the cask with a large variety of fuel elements. The difficulties raised by potential lack of flexibility are avoided in the case of a fuel inventory that is known and fixed prior to cask design. Cask optimization in this particular case could be very efficient in term of an appropriate choice of cask capacity.

The general approach to cask zoning can be illustrated by Figure 6.2 representing a quarter-cask loading pattern with five zones, optimized from the shielding point of view.



Burnup and cooling time of elements of each group are defined such as source term of fuel assembly decrease from group A to group E

Fig. 6.2. Five-zone loading, quarter-cask array.

As noted previously, the limit of applying this method is the need to maintain reasonable flexibility in spent fuel management for the long term.

Two different approaches for addressing this difficulty are:

- The definition of typical loading cases to check the performance of the cask and its capability to comply with regulatory criteria. Those cases do not define absolute limits of fuel assembly characteristics (in terms of burnup and cooling time) but are representative of what could be loaded. The operator is charged with performing more advanced calculations prior to loading with the actual data on the fuel to be loaded to be sure of compliance of the loaded cask with the regulation. The formal proof of compliance with the external dose regulatory limit will be provided by the post-loading measurement of external cask dose rates.

- The definition of the level of radioactivity authorized in each individual location of the basket, taking into account loading of the other locations so as to comply with the overall loading criteria. This leads to defining the individual contribution of each fuel assembly location to the external dose, taking into account its position in the cask basket and its source term. The operational use of these data for cask loading can be implemented by developing equations that can be checked by plant operators prior to the loading of fuel assemblies.

The advantage of the first approach, above, is that the licensing is less complicated. The acceptance criteria are the compliance of the dose rate measurements with the specified limits at the external dose measurement locations. The typical loading case for licensing should be chosen so as to cover the majority of the actual loadings that will be done. Additional calculations are needed when not covered by the typical case. As it is not part of the license, an explicit calculation can be performed, once the actual loading is fixed, using explicit definition of the source term, taking into account the scheduled time of the cask loading to define the actual cooling time.

The advantage of the second approach, above, is that it does not require any dose rate calculation at each loading. The offsetting major disadvantage is the large amount of calculations that must be performed for regulatory review and licensing.

As licensing of casks for zoned loading develops, there will be a need for new shielding benchmarks to provide measured doses from one or more zone-loaded casks with well-characterized fuel assemblies.

6.2.3 Trade-offs and interactions

The main optimization balancing that needs to be done in shielding design, considering the above-described methodologies and issues, is between all of the following points:

- Cask assembly capacity,
- Cask burnup/age capability, including the use of non-uniform zoned loading,
- Operational flexibility in the management of the spent fuel inventory,
- Sophistication of the license regarding extended calculations to be performed at the time of cask licensing or at the time of cask loading,
- Manufacturing cost penalties due to the sophistication of the design,
- Pay load of the cask regarding storage site capacity.

The shielding design/dose technical area also has a significant interaction with the structural design area. Currently the gamma shielding is performed by the material of the components that also ensure the containment of the radioactive content. Under these conditions, gamma shielding design interacts strongly with structural design, within the weight limits of the application. In cases in which containment vessel thickness is not imposed by the structural analysis, an optimization of the neutron shielding allows either the reduction of the gamma shielding thickness and reduced weight, or increased gamma and neutron shielding at the application weight limit.

It should be noted that the loading pattern which results from the shielding optimization of a cask is the opposite of the one required by a thermal optimization. Indeed, shielding considerations require that the fuel assemblies with highest source terms be in center of the basket while thermal considerations would prefer those same assemblies to be positioned in the outer positions of the basket so as to reduce the cladding temperature as much as possible.

Therefore, the possibility of optimizing the zoned loading pattern, case by case, is of great interest. It may be achieved by:

- Taking advantage of the explicit characteristics of the fuel element inventory. There is an incentive to avoid standard conservative values such as maximal burnup and minimal cooling time in the license,
- Developing important advanced calculation methods using qualified three dimensional codes such as described above.

It should be kept in mind that the efficiencies of the zoned loading approach are considerably reduced once no cold fuel elements are available in the inventory list. This strongly favours the use of zoned loading of re-licensed existing casks and/or the use of high performance casks as soon as possible in the overall management of fuel inventory. This will minimize the removal rate of cold fuel elements, thereby extending their period of beneficial usage as a key component of the zoned loading approach.

With or without burnup credit, for any given cask weight limit, there is a maximum burnup/age limit for cask loading. Handling that part of the fuel inventory that exceeds this upper limit requires either:

- A cask with thicker shielding and hence a smaller assembly capacity, or
- Using the same cask body, but using non-fuel shielded dummy assemblies in selected outer cask locations to provide the extra shielding, and using the remaining inner locations for the loading of fewer, but hotter assemblies.

A shielding/operations tradeoff evaluation is needed to evaluate these two alternatives. It should include an evaluation and comparison of transport cask fleet costs, logistics and the operational flexibilities for cask fleets using the single cask body and dummy shield assemblies, with the cask fleet using two or more different cask bodies.

7 STRUCTURAL DESIGN AND PERFORMANCE

The purpose of this chapter is to summarize the structural aspects of cask design and optimization, including the regulatory requirements for structural integrity and containment of the cask contents under normal, off-normal, accident, and beyond-design-basis accident conditions. The discussion of the structural aspects of design is done only to the level necessary to support the subsequent discussion of the optimization of structural design and licensing. The overall optimization challenge is to undertake realistic reductions in the conservatisms in current structural regulatory practice, to make improvements in current structural safety analysis methods and in their supporting data, and to maximize the use of all shielding, neutron absorbing and heat conduction materials as structural members.

The principal structural design challenge is, for a given weight and distribution of the contained SNF assemblies, to provide suitable structural members between and surrounding the assemblies so as to maintain the integrity of the containment and the relative positions of the assemblies, and the shielding, neutron absorbers, and heat transfer paths under normal and accident loads. The structural impacts of the heat transfer from the cask internal components and fuel during the accident fire conditions must also be considered. A principal measure of structural performance is the ability to meet the very low regulatory limits on the release of the cask radiological contents under all credible conditions. These various design goals must be realized within the cask weight and dimensional limits of the application, and must reflect the additional constraints imposed by the other design areas such as criticality, shielding, and thermal design.

7.1 DESIGN, SAFETY AND REGULATORY ANALYSIS ISSUES

The structural design philosophy depends on the intended type of cask. It is important, whether a monolithic metallic cask, a “sandwich” cask or a canister based storage system is intended to be used, and whether the cask is intended to be transportable. The more important parameters that define the major structural features of the cask are:

- The weight limit, dimensional limits, or other design limits specified by the user,
- The desired inventory (number, size and weight of fuel assemblies); the desired source term (burnup/age capability); and the overall criticality control approach (flux traps, burnable absorber rod inserts, burnup credit),
- The maximum acceleration allowed in accident conditions, and the related balance between cask and impact limiter/shock absorber design,
- Welded vs bolted closure.

The detailed design process requires determining and fixing the balance between:

- Keeping the weight limits, but
- Strengthening the structure against mechanical and thermal loads,
- Improving the shielding,
- Increasing the heat transfer,
- Reducing the acceleration in accident conditions,
- And possibly reducing the spacing between fuel assemblies.

The starting point for the design iteration depends on the internal design procedures of each cask vendor, such as beginning with shielding, verifying sufficient heat transfer and sub-criticality margins and then proving the strength of the structure. The primary design criteria for the structure are related to

- Maintaining structural integrity, and
- Assuring that any radiological releases are within applicable regulatory limits.

Derived design criteria are:

- Integrity of the cask internals to maintain spacing between fuel assemblies,
- Sufficient function of heat transfer paths in both normal and accident conditions,
- Limiting the acceleration in accident conditions,
- Sufficient shielding in both normal and accident conditions,
- Stiffness against local impacts (pins, trunnions).

7.2 OPTIMIZATION ISSUES

7.2.1 Conservatisms and uncertainties

The conservatisms and uncertainties related to structural design vary on the basis of the chosen cask systems (e.g. cask, canister) and materials (steel, cast iron, concrete). In general, innovative designs and sophisticated cask body materials have the greatest uncertainties and naturally include extended conservatism.

The uncertainties of the structural design are mostly related to the behavior (e.g. pin drop impact) and the margins (e.g. load level on critical areas, such as gasket path) in accident conditions. This includes the cask body as well as other components like lids, lid screws etc.

The uncertainties in cask body material performance are also related to the behavior (e.g. brittle fracture) and the margins-to-failure limits (e.g. acceptable stress level). Additional uncertainties need to be addressed when using non-metallic cask body materials (e.g. concrete). A specific example is the uncertainty in concrete's long term behavior under sustained heat loads or its resistance to heat loads resulting from fire.

7.2.2 Design tools and validation data

Apart from the application of existing rules and regulations (e.g. ASME code) extensive testing of both materials and structural designs, including important components, is the most promising approach to reducing conservative margins. The extensive testing will not only verify the designed structure and material properties and behavior, but will also result in a broad and sound database. This database can be used as the validation basis for the sophisticated software tools that are used by both cask vendors and independent authorities.

The application of three-dimensional finite element computer codes requires an extended and highly developed measurement program in support of cask and component testing. As a general rule, the closer the design and material of a new cask compared with the tested original, the smaller will be the acceptable margins to failure limits.

7.2.3 Trade-offs and interactions

Structural design and cask body material selection have interactions with almost all areas of cask design. Shielding cannot only be influenced by the thickness and design of the cask body (e.g. allocation between gamma and neutron shielding), but also by the density of cask body material. Sub-criticality is determined by the spacing maintained by the structural design of the cask interior basket. The degree of degradation of the inner cask structure and the fuel assemblies under accident conditions is also determined by structural design and the maximum accident acceleration, which define the accident loads. Designing structures to limit accident degradation is relevant for ensuring both sub-criticality and heat transfer. Further, the structural design of the cask has a definite impact on the thermal capacity since heat transfer through the structural members of the cask internals and wall partially determines cask thermal capacity. Selection of materials for components other than the cask body can raise questions about material compatibility. Last but not least, operational factors are widely impacted by the structural design, particularly by the cask's size, weight, and closure method.

Potential tradeoffs accessible by improving the structural design are:

- Increasing the fuel assembly capacity without increasing the cask weight,
- Improving neutron shielding, with the benefit of reduced cask body mass,
- Reducing the acceleration in accident conditions by enlarging or redesigning the shock absorbers (and maintaining the package weight limit).

7.3 ACCIDENT LOADS AND TESTING

In line with the IAEA regulations for transport, the tests of the strength of Type-B casks under accident conditions consist of cumulative mechanical and thermal impacts. The mechanical test for massive transport casks consists of two drop tests:

- Drop test I, in which the test specimen has to drop from 9 meters height,
- Drop test II, in which the test specimen drops from 1 meter height onto a steel bar.

Since the least favorable dropping position can be different for various different cask areas, several dropping positions and drop sequences have to be tested. The mechanical tests are followed by a heat test in which the effects of a 30-minute-long fire fully engulfing the specimen with an average flame temperature of 800 °C has to be assessed.

At the end of this series of tests, the cask's integrity and the leak tightness have to be demonstrated. Apart from the activity release, the dose rate of the cask is also limited. For packages or transport cask containing fissile materials it also has to be shown that the configuration will remain uncritical even after an accident.

The requirements for casks intended for long term storage result from the licensing procedures for the individual facilities, but the fundamental protection objectives are the same as for transport. The postulated accident loads for storage are mainly covered by those defined for transport. One exception is the ongoing discussion regarding cask design against severe accidents and the provision of measures for the reduction of the damage consequences of such beyond-design-basis events as the crash of an aircraft.

The test requirements of the IAEA cover a wide spectrum of severe accidents situations. However, they cannot and are not intended to cover 100% of all accident scenarios. The accident tests are defined in the transport regulations on the one hand to postulate damage to the package that is equivalent to the damage suffered in a very severe accident, but not necessarily all conceivable severe accidents. On the other hand, the tests were formulated as requirements, serving as a design basis.

Accident scenarios that may occur during transport or interim storage with potential beyond-design loads acting on the casks might be:

- Drop heights > 9 m, impact velocities > 50 km/h,
- Impact loadings from aircraft crashes,
- Risk to the casks posed by pieces of wreckage following an aircraft crash,
- Long-lasting fires involving high temperatures (tunnel, aircraft crash).

It is irrelevant for the assessment of the cask whether the initiation events occur by chance or as an act of terrorism. For some of the casks these scenarios have been analyzed. The results (ref 10), even in beyond-design-conditions, show sufficient safety margins to the physical limits that the integrity of the package is ensured.

The behavior of transport and storage casks for spent fuel assemblies and vitrified HAW under load conditions has been the subject of numerous experiments worldwide during the last decades. Apart from being used as effective public demonstrations of the safety margins, these experiments always served for the development of theoretical models. Furthermore, analyses of the behavior under extreme loads are currently in the process of being used for risk analyses to determine the residual risk.

In Appendix III, the most important experimental investigations that are relevant for the assessment of extreme mechanical and thermal loads acting on the casks are compiled. These are the following categories:

- Drop tests,
- Other extreme mechanical loads,
- Aircraft crash,
- Tank wagon explosion,
- Fire.

Detailed consideration has been given as to the extent the scenarios tested cover the load cases currently debated among the general public, especially the deliberate crash of an aircraft, and whether the available results can be applied to other transport and storage casks. In all these experiments with increased mechanical load impacts – which usually go beyond the test requirements of the IAEA regulations that already cover severe accidents – the casks showed no loss of integrity.

8 OPERATIONAL AND MAINTENANCE FACTORS

The purpose of this chapter is to summarize the principal operational aspects of cask design and optimization. Because the various cask design disciplines discussed above anticipate cask operations, the overall cask design features inherently facilitate cask operations. For example, one of the overall goals of optimization is to minimize the number of cask loadings for managing a given fuel inventory, and this inherently benefits cask acquisition, cask operations, storage space, and possibly, final disposal. Another issue addressed in design is making the tradeoffs between a high degree of operational flexibility/standardization with lower average burnup/age loadings, as compared to less operational flexibility/standardization but higher average burnup/age loadings. This chapter addresses the optimization of those cask design features and operational practices that are more directly operational in nature. This includes the design of attachments and accessories, ALARA compliance, fuel selection planning, administrative controls, and loading compliance.

8.1 OPERATIONAL FLEXIBILITY NEEDS AND LIMITS

Operation and maintenance are largely conditioned by the design. When the systems are designed taking operation and maintenance into account, most difficulties can be avoided. The issues most directly related to operation and maintenance include the design of simple-to-use equipment, the development of fail-safe procedures, the operational impact of cask size and weight, and compliance with the ALARA principle. Design includes a variety of features, such as:

- Fail-safe systems, so that parts cannot be misused, switched, misassembled,
- Limitation of moving parts, of active parts, of external power requirements,
- Avoidance of small items that are difficult to handle with gloves, and can be dropped in the cask or in the fuel pool, and become inaccessible,
- Easy removal of all subassemblies and parts,
- Reasonable torques and weights, standard tooling, simple kinematics,
- Sufficient "elbow room" and storage space in the considered premises,
- Additional shielding equipment,
- Short operation duration,
- Cask-maintainability, including features that facilitate external and internal decontamination.

Both operation and maintenance will be impacted by the size of casks. In order to increase the amount of fuel in a cask, designers will stretch size and weight. For operation and maintenance, this will limit the margins for lifting equipment and ground load, and reduce the clearance to walls and working areas. Ancillary systems may have to be modified in order to accommodate new casks. Particular issues such as drying equipment, re-cooling and re-flooding equipment, ventilation, and long term radiological monitoring should be addressed, as modifications may be necessary. The corresponding instruction manuals, procedures and maintenance specifications should be prepared or revised accordingly. The weight of the cask and the free-fall height in shafts may require specific energy-absorbing structures or devices. The lifting capacity may have to be upgraded, as well as any overflow area such as parts of spent fuel pool bottom.

8.2 FUEL CHARACTERISTICS DATA AND FUEL SELECTION

The extent of fuel data needed for the preparation of cask loading depends on the margins and limits specified in the license. The initial fuel mass, the initial enrichment, the burnup and discharge date (age, source term, and thermal power), and the geometry of the fuel assembly are obligatory. In terms of shielding, minimum initial enrichment, maximum burnup and decay time, peaking factor, Co-60 content in fuel assembly end-fittings, the initial Pu-content of MOX assemblies, and the maximum specific power during reactor operation are of importance. With respect to criticality, the maximum initial enrichment, three-dimensional enrichment distribution, the initial Pu-content of MOX assemblies and burnable neutron absorbers are essential. In the case of burnup credit applications, additional data are required to verify the burnup and its uncertainty (e.g. results of measurements or reactor operating records), and the presence of control rods, absorber rods, and/or proximity to MOX assemblies while in core. Burnup uncertainty is also needed because burnup uncertainty is subtracted from the Minimum Burnup vs Enrichment loading limit curve. Burnup uncertainty can be calculated if the detailed operational measurements and power distributions have been saved. Otherwise burnup uncertainty must be estimated, in which case it will be more uncertain (ie, larger) and will result in excluding more assemblies.

In certain cases, detailed information concerning deformation of fuel assemblies is requested in order to ensure the positioning in the basket. In the case of damaged fuel, additional information regarding the nature and extent of the damage is required.

The fuel selection for cask loading is broadly defined by three factors:

- The long term policy of the utility regarding interim storage and spent fuel disposal,
- Pool-stored fuel assemblies available for loading into casks,
- Capability of casks available.

The increasing thermal power of fuel assemblies that parallels the trend to higher burnups and the increasing number of MOX assemblies in some countries needs to be included as part of any long term policy with respect to spent fuel disposal for individual NPPs. The selection of specific fuel assemblies for loading is not defined only by the decay time. Although new casks of increasing sophistication will continue to be licensed, the criteria for optimizing fuel selection will always depend, in part, upon the then-current spectrum of assembly characteristics available for loading. In terms of the most effective and economic usage of available casks, a sensible mixture of hotter, more radioactive fuel assemblies and colder, less radioactive assemblies is almost always preferable to a coldest/oldest-first loading, even when the cask is not licensed for zoned loading. Therefore, cask design optimization for operations needs to include not just design features that facilitate physical loading operations, but also, a long term assembly selection plan, particularly in conjunction with the availability and use of zoned loading. In all cases, all the limits given in the cask license for each assembly location within the cask, and for the cask itself, have to be maintained.

In special cases, such as reaching the capacity limits of spent fuel pool or nuclear plant decommissioning, the application of specific shielding, the use of new neutron absorber elements, and/or the partial loading of casks could be an option, once the cask has been licensed for these actions.

Specific attention has to be paid to the preparation for loading of damaged fuel. If the license allows loading of damaged fuel assemblies, particular containers and additional devices, e.g. water absorbers, are generally applied.

It is a common administrative practice of nuclear plant operators to plan transport cask loadings so that the casks would be loaded so as to be a defined amount below their licensed external dose rate loading limits. The intent of this practice is to have an allowance for planning, assembly burnup uncertainties, and shipper/receiver measurement uncertainties, and to avoid having to unload and reload the cask, if post-loading measurements indicate it is above external dose limits. The result of this practice is that the average cask radiological loading is below the licensed loading limit by approximately the administratively-defined amount. The overall consequence for the fuel inventories at most operating reactors is that more shipments will be required than if the casks had been consistently loaded at the regulatory limit. Also, because of the increased number of shipments, the total population dose for all the cask loads and shipments for a defined fuel inventory would be approximately the same as if the casks were always loaded at the dose limit. Thus, the overall consequence of planning to load all casks below their dose limit is that the total external dose for all of the cask loads does not go down, but more shipments are required.

There is a consequent increase in the physical and cost impacts of transport. Because of the increased impacts, the overall level of safety may actually be lower, and the costs are most certainly higher than if casks were loaded very close to their dose limits and no extra shipments were necessary. It is therefore legitimate for both the cask owner/operator and the regulator to consider reasonable alternatives for improving on current regulatory and related operator practices with respect to the need for operational external dose margins at the time of cask loading.

There appear to be two issues to consider:

(1) What are the actual safety consequences if some casks were to slightly exceed external dose regulatory limits, provided that the average of all casks loaded at the site is at or below the regulatory limit?
(2) What insights can be derived from consideration of those ALARA criteria that facility operators use in deciding how much added cost is justified when reducing operator radiation exposure by an additional increment?

With respect to the actual safety consequences of a single cask exceeding the regulatory dose limit, the safety consequences of dose are traditionally treated as linear with exposure over the low exposure levels typically associated with the external doses from casks. In effect, the linearity of dose and safety consequences translates into the conclusion that if the average dose rate from casks loaded up to and including the current cask are at or below the regulatory dose limit, there are no actual safety consequences of having the spectrum of casks include some casks with exposure rates somewhat above the regulatory limit.

With respect to those ALARA criteria that are intended to guide facility operators in deciding how much added cost is justified for achieving incremental reductions in radiation exposures, some regulatory jurisdictions provide quantitative values. For example, the US Code of Federal Regulations specifies $US 1000 per person-rem (10CFR50, Appendix I), beyond which additional expenditures do not have to be made. To be conservative, some US utilities spend considerably more than $US 1,000 to achieve a dose reduction of 1 person-rem. The following uses the foregoing in an illustrative example using specific assumptions, but the results are useful for providing perspective on this issue.

Consider the use of the foregoing ALARA guidance in connection with a transport cask loading, the radiological contents of which have been administratively reduced to 90% of the US regulatory limit. Further assume that at the regulatory limit, one shipment of the cask loaded at its regulatory limit results in a total population dose of one person-rem. At the administratively-reduced loading, the transport of ten casks would result in a total population dose of 9 person-rem, a reduction of 1 person-rem compared to loading the casks at 100% of the regulatory limit. However, because of the reduced limit, it is estimated that one extra shipment is required to ship the same amount of radioactivity. The ALARA-based credit for the reduced total population dose of 1 person-rem is $1,000 (without subtracting the dose from the additional shipment and the resultant loss of most of this credit). However, the total cost of transporting an additional cask is many times $1,000. Thus the ALARA-based "value" of the administrative reduction in dose is one to two orders of magnitude less than the cost increases incurred for the additional shipment. These cost increases result directly from the administrative reduction that is intended to assure the compliance of each individual shipment with the regulatory limit, using the current regulatory practice of applying the limit to each individual cask loading.

The foregoing observations reflect the large safety margins and the considerable safety conservatism in the regulatory limit itself. They also emphasize the low safety consequences of a single cask exceeding the regulatory dose limit, based upon the measure of safety consequences quantified by the ALARA guidance. The overall safety consequences over many shipments from the site would be zero if the average of all cask loadings to that point were at or below the regulatory loading limit.

The forgoing suggests consideration of a change in current regulatory practice with respect to applying the external dose regulatory limit to individual cask loadings. An alternative to the current practice would be to base compliance with the external dose limit on the actual long term site average of doses, in which individual casks could be, for example, up to 10% above the compliance limit, provided that the long term average at that site would always remain below the compliance limit. This would substantially avoid the current situation in which there are large administrative and other consequences from a cask loading that is, for example, measured by the shipment receiver to be a minor amount above the regulatory limit. The suggested change in regulatory practice would significantly simplify the regulatory compliance process for cask loading, and at the same time would minimize the number of cask loadings, one of the primary goals of optimization.

8.3 ADMINISTRATIVE CONTROLS AND POTENTIAL LOADING ERRORS

Administrative controls focus on two subjects. One is the correct loading according to the approved cask loading documentation. The second area of controls is related to the cask conditions and performance.

The correct loading of the cask is controlled by verifying the fuel assembly identification mark on the head of the assembly with the mark in the loading documentation. For each of the fuel assemblies to be loaded into the cask, a certain position in the cask and orientation within the position is precisely defined. The loading procedure includes the sequence in which individual assemblies are loaded. After the positioning of the fuel assembly in the cask the identification mark, the position and the orientation is cheeked again, independently, by both plant personnel and local authorities.

Potential loading errors are of little practical consequence if the cask is designed covering all relevant fuel data of the assembly inventory. In other case criticality, shielding and thermal design safety could be affected, but only to the extent that design margins to the safety limits are exceeded. The ultimate indication of some adverse loading errors is obtained from the radiation measurements on the cask surface. In that case the cask has to be re-opened and the loading error has to be corrected.

Administrative controls related to cask conditions and performances are structured as follows:

- Preparation for loading,
- Loading of spent fuel,
- Preparation for transfer or transport,
- Transfer or transport,
- Preparation for storage.

Some topics of administrative controls are:

- Avoidance of contamination,
- Protection of surfaces important to leak-tightness (for bolted casks),
- Avoidance of corrosion,
- Monitoring of radiation levels,
- Control and inspection of handling tools, components and spare parts.

8.4 DEMONSTRATING LICENSE COMPLIANCE

The final fuel assembly selection is defined by the utility in accordance with their fuel management policy and the limitation of the licensed casks. The selected loading is given in cask related documents. Depending on the cask license, loading compliance can be shown either by a simple comparison of the fuel data with the limits of the license, or by making specific calculations using the fuel data to demonstrate compliance. The latter approach increases the amount of engineering work, but gives options for reducing unnecessary margins by using individual assembly data and specific loading patterns. In general, the compliance of the loading with the license has to be approved by the regulatory authority.

The final compliance tests are the radiation measurements 2 m from the cask and on the cask surface after loading. Any deviation from the expected range is an indication of abnormal conditions. In case of exceeding licensed limits, unloading of the cask could be necessary. In certain cases, thermal measurements are applied to verify the heat load.

9 RETRIEVABILITY

The purpose of this chapter is to summarize the principal retrievability considerations in cask design and optimization, including the fuel and cask integrity factors affecting retrievability. By its nature, storage is not permanent. Retrieval is the final step of storage and therefore needs to be addressed as a part of storage cask optimization. The goal of achieving a normal retrieval of cask-stored fuel is one of the principal goals within two of the major technical design areas of:

(1) Thermal design, specifically the safety limits on cask thermal loadings and related cladding temperature limits for protecting fuel cladding integrity, and
(2) Structural design, specifically the general requirement for robust cask and basket structures, capable of maintaining configuration and containment for all normal, abnormal and credible accident conditions during cask loading, possible transport, storage, and unloading operations.

9.1 DESIGN, SAFETY AND REGULATORY ANALYSIS ISSUES

9.1.1 Definition and significance of retrieval and retrievability

Retrieval is the process of removing bare fuel bundles (including rods) from a cask or a canister. Retrievability refers to the relative ease or difficulty of retrieval. For the purposes of optimization, the goal is to facilitate untroubled retrievability and subsequent handling, without complications from either deterioration of the fuel rod cladding or assembly structural integrity, or difficulty with the cask, such as in lid removal or distortion of the cask basket as a result of cask handling and storage conditions. Specifically, the desired conditions at the time of retrieval are:

- No leaks in the fuel rod cladding,
- No failure or distortion of the fuel assembly structure,
- No failure or distortion of the lid or the internal structure in the cask,
- The original design of the lid structure and sealing of the cask facilitates relatively easy cask opening and access to the stored assemblies,
- The design of the fuel bundle grapple facilitates assembly removal and subsequent transfer handling.

The most dominant among the primary factors which control retrievability, are the assured integrity of the fuel cladding and assembly structure, and the robustness of the cask internals configuration. Also, the design of the cask closure and sealing needs to include a requirement that such design reflect a reasonably simple process for opening the cask under both normal and post-accident conditions. If these factors are adequately addressed, there would be reasonable assurance of relatively routine assembly retrieval and normal subsequent handling, regardless of current or future decisions as to the next step in the process of ultimate SNF disposition (direct disposal, or reprocessing/recycle/HLW disposal).

Since storage is not permanent, retrieval from storage is a requirement that is independent of the national fuel cycle management policy that is in place. However, national policy combined with the political ability to implement it, can have a strong influence on the prospective duration of the storage period. Those national policies that favor storage, or that have not defined a final disposition strategy, will tend toward long prospective storage periods, possibly involving multiple renewals of storage cask licenses. Retrievability concerns increase progressively as the duration of storage increases, particularly for planned extended storage or storage for an initially undefined duration.

9.1.2 Additional retrievability considerations

Even after the foregoing primary factors are addressed, specific aspects of the storage cask design and/or storage facility location, capabilities, capacity, and layout will need to include consideration of the following factors that will affect the timing and location of retrieval.

- The purpose and duration of storage: SNF management policy of the storage facility owner and/or government.
  - Once Through: storage and cooling before direct assembly disposal, with storage duration determined by the availability of the disposal repository and the SNF disposal priority sequence and related delivery schedule to the repository. Depending upon the cask-stored inventory and the delivery rate, the period of retrieval could extend over many years.
  - Reprocessing/Recycling/HLW Disposal: storage and cooling before reprocessing, with storage duration determined by the availability of the reprocessing facility and the SNF reprocessing priority sequence and the related delivery schedule to the reprocessing facility.
  - Wait and See Policy: Indefinite storage and cooling until the policy for ultimate SNF disposition is determined, with storage duration determined by the policy decision date plus the time required for implementation and subsequent scheduling priorities. Depending upon the cask-stored inventory and the delivery rate, the period of retrieval could extend over many years.
- The location of retrieval, and disposition of retrieved assemblies:
  - Storage-only Cask Design: Capability is needed at the storage site to unload assemblies, and possibly to interim-store and/or inspect them. Depending upon storage location, the assemblies would then be: loaded into a transport cask for offsite transport; transferred to an on-site waste packaging facility prior to direct disposal; transferred to an on-site receiving facility of a reprocessing plant; or loaded into a new storage cask.
  - Transportable Storage Cask: If the transport license is current, cask inspection and monitoring results give no indication of abnormality, and the cask meets the license requirements for transport, the cask is prepared and certified for transport and shipped offsite to its intended destination. If the cask transit were normal and accident-free the cask opening and unloading, and the assembly retrieval would proceed in the expectation of normal assembly removal and subsequent handling. If one or more of the foregoing transportability criteria could not be met, the cask would be returned to storage, or would be treated as described above for storage-only casks.

- Cask and fuel condition at retrieval:
  - For a cask in normal condition based on cask inspection and monitoring results, with no direct evidence of deterioration, nor adverse experience of others with similar storage conditions and durations: cask opening and assembly retrieval could proceed in the expectation of normal assembly removal and subsequent handling. F
  - For abnormal cask or fuel conditions, based on direct evidence of deterioration, accidents, or adverse experience of others with similar storage conditions and durations: the retrieval process could proceed, but with the expectation of a non-routine retrieval, and always in accordance with applicable regulatory requirements. This would include the development of situation-specific procedures, which have received appropriate independent review and approval prior to use.

9.1.3 The technical requirements for retrievability

In some jurisdictions there may be legislative, policy or regulatory stipulations requiring retrieval within a specified period. However, in most cases there are few, if any, explicit technical requirements directing the process of cask unloading and assembly retrieval. There are several cask safety design requirements whose primary goal is the long term containment of radioactivity. These direct design requirements in other technical design areas serve as indirect requirements for normal retrieval, as can be seen in the following listing:

- Long term containment of radioactivity is facilitated by imposing design limits on cask thermal loading and cladding temperature, to preserve the integrity of fuel rod cladding. This improves future retrievability by reducing the probability of fuel cladding and assembly structural failures.

- The design requirements for structurally robust cask body, lid, and internal basket designs assures containment and criticality safety and indirectly benefits retrievability via minimizing cask opening difficulties and basket structural distortions.
- Because a normal retrieval is basically a sequence reversal of the cask loading and sealing processes, for which provisions are made in cask design, retrieval is the indirect beneficiary of these initial design considerations.

There are also beneficial impacts from certain common regulatory practices:

- Retrieval is an indirect requirement of storage cask licenses, which have a specified license termination date: in order to be in compliance with the license conditions, the licensee must either unload the cask or seek and receive a license extension prior to license expiration. The need for periodic license renewal forces periodic reevaluation of continued safe fuel storability, thereby providing a process that could anticipate retrieval problems before they become major problems.

- There are typically general requirements in facility and cask licenses, requiring that activity-specific procedures be developed and independently reviewed and approved, before any activities with safety implications can be initiated. These general requirements assure that appropriate procedures will be developed for cask unloading and assembly retrieval. They also assure that situation-specific procedures will be developed to address all special activities that are needed to address retrieval complications, and to safely complete such retrievals. This means that all actions necessary to deal with unexpected adverse situations in future retrievals will be completed using safe working practices and in compliance with then-applicable regulatory requirements.

There appear to be some firm plans for an important activity that is needed to support both safe long term storage and ultimate retrieval. One or more systematic non-proprietary long term programs are needed for storage performance assessments on high-burnup fuel that include periodic cask openings and direct assembly inspections. Such programs would be able to anticipate unexpected difficulties and, if appropriate, provide the basis for remedial action, well before the situation became serious. Specific data could include:

- The results of lead-assembly fuel surveillance examinations (direct appearance and measurement of fuel, sipping tests, destructive tests),
- Analysis of the atmosphere (cover gas) of the fuel concerned,
- Correlation of the monitoring results for several storage casks, with a range of fuel burnups and other key fuel characteristics.

Cooperative international programs in this area would have the benefit of being more generic, would reduce individual participant costs, could draw on a wider base of expertise, and could be more comprehensive in scope.

By way of summary, Table 9-1 (ref 9) shows the effective factors and phenomena to be considered regarding spent fuel integrity under long term storage.

9.2 OPTIMIZATION ISSUES

Normal retrieval of stored spent fuel is likely to occur if the two aforementioned design requirements regarding clad temperature limitations and robust structural design are successfully achieved. There is some unavoidable uncertainty as to their ultimate attainment, primarily because the needed long term performance data at recently achieved high burnup levels cannot realistically be obtained by accelerated testing. It can only be obtained as a consequence of real-time long term performance measurement beginning in the present. It is probable that the current clad temperature and thermal limits will prove to be conservative, but the proof is many years in the future. Therefore there is a current risk that there may be future retrievability problems. However, the level of risk is at best, quite uncertain.

It has been further noted that if future retrieval difficulties are encountered, these will be resolved in a safe manner, because of the general requirement for the development of situation-specific procedures that assure the use of safe recovery processes. This means that the principal risks of future retrievability are financial risks, and not safety risks. Although this appears to present the classic optimization situation of trading off current performance to reduce future financial risk, the latter are so uncertain, that it would be imprudent to make such a tradeoff in storage cask design.

The other possibility for retrieval-associated optimization is the optimization of costs versus benefits of a long term cask/fuel storage performance monitoring program. However, because this is a program to obtain fuel clad performance data for cask thermal design, it should be addressed as a thermal design issue, not as a retrieval issue.

It is therefore concluded that, although retrievability is a valid concern, the issues that it raises, the long term integrity of cladding and of the fuel assembly structural components, and no deterioration of the cask internals or lid, are addressed in conjunction with thermal and structural design. Retrievability does not have significant, unique, and concisely definable optimization characteristics that go beyond the issues already addressed.

TABLE 9-1 FACTORS AFFECTING SPENT FUEL INTEGRITY DURING LONG TERM STORAGE (1/2)

Classification	Effective factor		Phenomenon	Related Parameter	Related Cask Property
Age degradation	Creep		Creep strain generated by cladding hoop stress according to internal pressure of fuel rod. Cladding temperature is restricted so that the accumulated creep strain within a design storage period may not exceed 1%.	Fuel temperature under storage	-The degradation of cask cooling performance
				Fuel temperature at the time of vacuum drying	- Vacuum-drying conditions (The degree of vacuum, time)
	Hydrogen effect	Hydrogen embrittlement	Possibility of affecting cladding mechanical properties by hydrogen absorption in the atmosphere in a cask The amount of hydrogen absorption during irradiation in reactor does not affect a mechanical property.	The atmosphere ingredient in a cask	- The atmosphere ingredient in a cask (degradation)
		Hydride reorientation	Although the hydrogen, which exceeded terminal solid solubility, precipitates as hydride during cool-down, if excessive hoop stress is acting on a cladding, hydride may precipitate in the radial direction and may affect mechanical properties.	Fuel temperature under storage	-The degradation of cask cooling performance
				Fuel temperature at the time of vacuum drying	- Vacuum-drying conditions (The degree of vacuum, time)
		The axial diffusion and migration of hydrogen	The hydrogen in a cladding may diffuse according to the direction temperature gradient of an axis at the degree side of low temperature, and may affect a mechanical property.	Fuel temperature under storage (distribution)	-The degradation of cask cooling performance
	Irradiation-hardening recovery		The irradiation hardening (higher strength, lower ductility) recovers according to recovery of radiation damage by high temperature maintenance under storage. At the time of the transportation after storage, when using the mechanical property of irradiation material for evaluation of fuel integrity, it is required that irradiation-hardening recovery should not occur.	Fuel temperature under storage	-The degradation of cask cooling performance
				Fuel temperature at the time of vacuum drying	- Vacuum-drying conditions (The degree of vacuum, time)
	SCC (Stress corrosion cracking)		According to the combinations with corrosive FP(s) (iodine etc.) and the hoop stress by internal pressure in a fuel rod, SCC may occur.	Fuel temperature under storage	-The degradation of cask cooling performance
	Oxidation		Cladding oxidation by reaction with oxygen in the atmosphere in a cask, = Effect on mechanical property	The atmosphere in a cask	-The degradation of atmosphere in a cask

TABLE 9-1 (CONT'D) FACTORS AFFECTING SPENT FUEL INTEGRITY UNDER LONG TERM STORAGE (2/2)

Classification	Effective factor	Phenomenon	Related Parameter	Related Cask Property
Age degradation	Helium generation by alpha decay	The helium produced by alpha decay in a fuel pellet, causes internal pressure in a fuel rod to increase during storage.	Fuel temperature under storage	-The degradation of cask cooling performance
	Physical-properties change of a pellet	The lattice constant of a pellet changes with alpha irradiation, and swelling (volume expansion) is started.	-	-
External phenomenon	Earthquake	Load acts on the spent fuel inside a canister according to an earthquake.	Load in case of an earthquake	-Ant earthquake design -Cask structure design

10 SUMMARY

The purpose of this chapter is to summarize the most important of the aspects of cask design optimization that have been discussed in the preceding chapters of this TECDOC. The nature and the need for optimization, and the manner in which optimization always proceeds within regulatory safety limits are reviewed. Cask buyer requirements and resulting cask material selection are then described. The next three sections then summarize specific optimization activities in each of the technical areas, under the three principal optimization activity categories:

- Assumptions having excess conservatism,
- Improving design tools and validation data, and
- Tradeoffs and interactions.

Finally, the open issues identified in the 2002 and 2003 meetings are summarized, with some of the issues that address parts of an overall issue being combined.

10.1 THE NATURE OF OPTIMIZATION WITHIN THE REGULATORY PROCESS

Optimization is that part of the design process in which the combination of application objectives, safety limits, design, regulatory practices, and costs, in each of several technical disciplines, are innovatively addressed and judiciously balanced in the final design. Optimization is needed because:

- Current regulatory practices typically include the traditional use of assumptions with excess conservatisms that result in cask designs having reduced capabilities without any meaningful increase in safety.
- Cask performance measures such as assembly capacity and/or burnup/age capability can be improved, in spite of fixed cask safety limits such as external dose rates and fuel temperature limits. These improvements can be realized by improving design software and experimental data, and by innovative design.
- When additional cask designs have different costs and different cask performance measures, such as a lower assembly capacity but greater burnup/age capability, life cycle cost evaluations can provide the additional input to make the tradeoff between cask performance measures and costs.

A primary result of a successful design optimization is a licensed cask of superior assembly and burnup/age capacity that minimizes the total number of cask loadings required to manage a given SNF inventory over the long term. An equally important and parallel benefit is that this process also results in reduced overall radiation exposure, thereby contributing to ALARA objectives for reducing all radiation exposures. In this sense, both cask designers and regulators have the common ultimate goal of improving cask performance within safety and regulatory limits, and thus of facilitating the optimization process.

Optimization always occurs in strict compliance with the safety margins and related safety levels that have been established by the formal regulations. Regulatory practice embodies the formal regulations, but also includes the use of many conservative standard assumptions that have been historically used and accepted for addressing the many details of safety analysis. The historically-used detailed assumptions of regulatory practice are an additional layer of conservatism over and above the safety margins established by regulation. Because these conservative assumptions are not part of the formal regulations, most regulatory jurisdictions will consider alternative assumptions with less excess conservatism, provided the applicant clearly demonstrates that the change is valid and can be made within the formal regulatory limits. To the extent that the proposed change is accepted, the alternative assumption becomes part of accepted regulatory practice. Because the historic assumptions of regulatory practice never encroach upon the safety margins established by regulation, justified and approved changes in these historic assumptions do not encroach upon those safety margins. When there is excess conservatism in the various historic safety analysis assumptions, cask capabilities are reduced without a meaningful increase in the substantial safety levels established by the formal regulations. These excess conservatisms are therefore of interest within the optimization process.

The three general groupings of optimization activities within many of the individual technical disciplines include two areas of regulatory practice, plus the development and evaluation of design tradeoffs between alternative cask performance measures, as follows:

(1) Identifying, analyzing, and justifying reductions in excess conservatisms in the historic, detailed input assumptions to safety analyses
(2) Reducing the uncertainties in safety analysis results by improving the accuracy of design tools and/or reducing the uncertainty in the experimental data used within the design tools, or in the validation of those tools
(3) Making judicious design tradeoffs of cask performance characteristics within and between technical areas, and tradeoffs between costs and various combinations of alternative cask design features and related performance characteristics, all of which are within the envelope of then-current regulatory practice.

10.2 BUYER REQUIREMENTS, MATERIAL SELELECTION AND OPTIMIZATION

The buyer’s requirements, including the intended storage application and the requirement for low costs, have a strong impact on the selection of cask materials. This section summarizes the factors that are determining current buyers’ choices of storage technologies, and how these choices influence the nature of optimization activities.

The buyer-imposed limitations include either direct or indirect limits that establish maximum cask weight. Because the weight of shielding dominates the total cask weight, the choice of shielding material is one of the first decisions that are required. There is a tradeoff between shielding effectiveness and the cost of shielding materials and fabrication. In priority order of decreasing shielding effectiveness, the candidate shielding materials are depleted uranium, lead, iron/steel, and concrete. In priority order of increasing cost, the foregoing order is exactly reversed. Cost factors turn out to dominate because the differences in shielding effectiveness are much less than the cost differences. The results are the following typical cost-based preference priorities for shielding materials in both cask-based and canister-based systems:

- For storage-only: concrete, followed by iron/steel.
- For transportable storage: iron/steel, followed by lead/steel (concrete storage modules are first priority for canister-based systems – concrete-based transportation casks are not yet accepted in some regulatory jurisdictions).

Much of the remaining cask weight is for the structural materials that maintain the integrity of the cask, its basket and the containment envelope during normal and postulated accident situations. The material preference here is for steel, based on both its technical superiority and its material and fabrication costs. The remaining choices of principal materials are for the heat transfer and criticality control functions. The preferred heat transfer material is copper, but because of its cost, copper tends to be used only if the other materials are unable to remove enough heat. For criticality control, flat arrays of steel rods holding boron carbide pellets, or steel-enclosed boral are typical of the relatively-expensive neutron-absorber materials.

The foregoing indicates that cask material choices tend to be dominated by cost considerations rather than by the availability of materials with superior characteristics. Furthermore, all cask materials perform shielding, structural, heat transfer and criticality control functions with different levels of effectiveness. Materials with only modest characteristics are tolerated because of costs, if the performance of the composite of materials in each functional area is adequate. *This provides a fertile situation for the practice of optimization.* The overall optimization challenge is the identification and/or development of materials with the appropriate combination of concurrent high performance in multiple technical areas, such as shielding, strength, heat transfer, and neutron absorption, so as to be more efficient in their overall safety function. A new material with superior neutron absorption, structural, and heat transfer characteristics would be particularly valuable as the basket material between every assembly location in the cask. An additional goal of the optimization of material performance is the identification of performance margins that lead to the simplification of safety analyses, and to the related simplification of the regulatory review and the conditions of the license.

10.3 ASSUMPTIONS HAVING EXCESS CONSERVATISM

This section provides a summary of the assumptions having excess conservatism that have been discussed in the individual chapters of this report. These particular examples are representative of the types of conservatism that may be encountered in some regulatory jurisdictions, but are not intended to be a complete listing. Because each regulatory jurisdiction may have regulatory practices that are unique to their own situation, it is important to examine all regulatory practices for the presence of excess conservatism.

Criticality control

The most conservative of historic regulatory practices is the practice that requires the cask designer to evaluate cask criticality safety assuming that all assemblies are at the same maximum reactivity condition, without credit for burnup, and with the cask flooded with clean water. Obtaining credit for fuel burnup is identified as an optimization topic because, among all of the possible results of successful optimization-like activities, obtaining substantial reactivity credit for fuel burnup promises the most significant overall benefits in terms of improved cask performance capability. Specifically, the prospective future availability of increasing levels of burnup credit is expected to significantly increase the criticality-related cask burnup limits, to the extent that shielding or thermal limits could impose the upper limits on cask burnup/age capability. The assembly capacities of PWR transport casks are also expected to increase with burnup credit, due to the reduction of the spacing between PWR assemblies.

Because of the relative simplicity of criticality design using the historic assumption of uniformly-loaded fresh fuel, the benefits of optimization have already been substantially realized. The following are conservative assumptions that are beginning to be made in some regulatory implementations of burnup credit:

- Because of the spectrum of available fuel assembly characteristics, the average characteristic of individually-screened assemblies in a cask loading can be significantly below the screening limit based on Minimum Burnup vs Enrichment. Changing regulatory practice to allow an averaging of above-limit and below-limit assemblies would reduce much of the conservatism in the current practice.

- Typical regulatory practice specifies a conservative cooling time (such as 5 years) at which burnup credit criticality is determined. This considerably reduces the criticality benefit that is actually available. Specifying a longer minimum cooling time before cask loading could yield significantly greater criticality benefits from burnup credit.

- When the pellet-to-clad gaps of all fuel rods in all assemblies are assumed to be flooded, the resultant reactivity penalty could be significantly reduced by a more realistic assumption as to the fraction of fuel clad failures.

Thermal design

- When it has been assumed that convection effects, axial heat transfer, and/or heat transfer by non-fuel assembly hardware can be ignored, benefits can be realized by including these effects.

- When conservative, high values of site ambient temperatures have been assumed, use actual maximum average site ambient temperature

- When conservative high operating void fractions have been assumed in the calculation of BWR spent fuel decay heats, justify and use lower operating void fractions.

- If worst-case assumptions are used as to gap spacings for all fuel-to-basket and all other internal gaps, develop a statistical treatment of gap spacing for evaluating the heat transfer impacts of fuel-to-basket and other internal gaps

Shielding design

- The assumption that all assemblies are to be at or below the cask's Maximum Burnup vs Cooling Age loading curve prevents the benefits from increased cask loading limits via the use of zoned loading. Changing regulatory practice to allow zoned loading with shielding credit for cooler outer assemblies shielding the hotter inner assemblies, would increase the average overall loading limit of the cask and in addition, would provide significant long term logistics benefits. See Annex IV.

- Because of the spectrum of available fuel assembly characteristics, the average characteristic of individually-screened assemblies in a cask loading can be significantly below the screening limit based on Maximum Burnup vs Cooling Age. Changing regulatory practice, to allow an averaging of above-limit and below-limit assemblies, would increase the effective loading limit of the cask, and reduce much of the excess conservatism in the current practice.

- When cask burnup/age loading limits are based only on the assembly type with the highest kgU loading, and other acceptable assembly types have lower kgU loadings, develop higher burnup/age loading limits for the lighter assembly types.

Operational factors

- Optimization includes fuel assembly selection for cask loading. The zoned loading approach is always superior to coldest-first loading because it conserves the use of the coldest assemblies, allows them additional cooling time, and doubles the number of cask loadings that contain the cold assemblies. Even with casks licensed only for uniform loading, logistics benefits can be obtained by loading approximately equal numbers of the coldest assemblies and hotter assemblies that are as close as possible to the loading limit for uniformly-loaded fuel. With regulatory credit for self-shielding, the inner assemblies can be hotter, there are more assemblies that can be classified as cooler, and the benefits from zoned loading increase considerably.

- To avoid encroaching on limits, it is a common administrative practice to plan cask loadings so that they are a defined amount below their licensed loading limits. The result of this practice is that the average loading is approximately the defined amount below the licensed loading limit. The ultimate consequence is that more shipments will be required than if the cask had been consistently loaded at its limit. This situation could be improved if compliance with the standard were based on compliance with a long term average, and individual casks could be, for example, up to 10% above the compliance average, provided that the average at that site would remain below the compliance average.

10.4 IMPROVING DESIGN TOOLS AND VALIDATION DATA

This section summarizes the principal improvements in cask design tools and validation data that have been discussed in the various chapters of this report. It is noted that improvements can still be made in most design tools. With regard to validation data, there are some suggestions for long term test programs, the most significant of which is for the development of data on the long term performance of cask-stored spent fuel and cladding.

Criticality control

The design tools and data supporting no-burnup-credit designs are essentially state-of-the-art. Significant resources are now being invested to improve the tools and data that support burnup-credit cask design and usage, in three general areas:

(1) Improving models and data on isotopic depletion, buildup and decay, particularly on actinides at higher burnups and fission products at all burnups.
(2) Improving models and data for calculating the spatial distribution of neutron fluv and burnup, the related spatial alteration of isotopics, including effects due to the operational presence of various control absorbers, and the impact of these factors on criticality. A recommendation is made for at least one cask-sized spent fuel critical experiment with well-characterized spent fuel with significant burnup (plus fresh fuel/rods for achieving criticality).
(3) Developing improved data regarding the accuracy and veracity of assembly burnup records, the prospective need for assembly burnup measurement, and the impact of these issues on the implementation of burnup credit cask loading via the development and prospective use of the Minimum Burnup vs Enrichment loading limit curve.

Thermal design

- Current computational tools will benefit from additional experimental data on internal temperatures and other cask internal conditions for casks of recent design loaded with high burnup/high heat fuel assemblies. These data will support further validation studies to reduce current uncertainties in temperature and other thermal analysis results. Direct measurements of decay heat from well-characterized high-burnup fuel assemblies will also contribute to the reduction of uncertainties.

- One or more systematic non-proprietary long term programs are needed for storage performance assessments on high-burnup fuel that include periodic cask openings and direct assembly inspections. Such programs would develop the quantitative data for improving current understanding and modeling of the principal factors that influence long term cladding performance. Such long term programs would also be able to anticipate unexpected difficulties and, if appropriate, provide the basis for remedial action, well before the situation became serious.

Shielding design

Current computational tools for the analysis and design of gamma and neutron shielding can be considered state-of-the-art. They will continue to improve with time, particularly as computer processing cycles continue to shorten, and allow more and more detail to be included in shielding computations. These tools are calibrated against shielding benchmarks consisting of measured doses resulting from well-characterized spent fuel assemblies shielded by well-characterized shielding materials and dimensions. As licensing of casks for zoned loading develops, there will be a need for new shielding benchmarks to provide measured doses from one or more zone-loaded casks with well-characterized fuel assemblies.

Structural design

Current computational tools for the structural analysis and design of casks and cask containment, particularly under accident conditions, can be considered state-of-the-art. Uncertainties in the structural design are mostly related to the behavior (e.g. pin drop impact) and the margins (e.g. load level in critical locations, such as gasket path, lids, and lid bolts) in accident conditions. Other uncertainties include such aspects as brittle fracture, acceptable stress levels relative to failure, and concrete’s susceptibility to either long term or fire-induced heat loads. Uncertainties need to be reduced by component and material testing, plus the cask drop and other severe testing outlined in Annex III.

Operational factors

A quality-assured source for all of the relevant data on each fuel assembly must be available and accessible. The most important of these data items are used to plan cask loadings and to screen each assembly at the time of loading. Of particular importance are the geometry, burnup, initial enrichment, discharge date, and initial fuel mass. Burnup uncertainty is also needed because burnup uncertainty is subtracted from the Minimum Burnup vs Enrichment loading limit curve. Assembly absolute burnup is calculated as it is accumulated, from detailed in-core measurements, detailed core power distribution calculations and time integration of measured absolute plant power output. Burnup uncertainty can be calculated at the same time, but this is seldom done. It also can be calculated later if the detailed measurements and power distributions are saved. Otherwise burnup uncertainty must be estimated, in which case it will be more uncertain (ie, larger) and exclude more assemblies.

10.5 TRADE-OFFS AND INTERACTIONS

This section summarizes the principal tradeoffs within and between technical design areas and between costs and cask performance measures. The more important of these includes the tradeoff between shield material performance and cost, in which the less-effective shielding materials are typically chosen because of costs.

Cask material selection

- Early in the design process, it is necessary to select primary shielding material by making a tradeoff between shield material performance and cost. In this tradeoff, the less-effective shielding materials, concrete (for storage) and steel, are typically chosen because of costs.

- Another tradeoff that is made in the material selection area is between, on one hand: the delay and cost of material R&D and qualification programs, including more sophisticated manufacturing processes and other implementation changes; and on the other hand, the expected long term benefit in terms of cask performance increases, ease of licensing, ease of manufacturing and control, operational improvements, and overall reductions in future impacts and costs.

Criticality control

With respect to tradeoffs between the criticality, thermal, and structural areas, the space between adjacent assemblies within all casks needs to include materials that serve three functions: neutron absorption for criticality control, heat transfer for temperature control, and rigidity for structural integrity. A single material, or a two-material composite with the required properties would be ideal for this situation, and identifying existing materials, or formulating new materials is a worthy optimization activity.

Thermal design

The principal trade-off and interaction in the potential optimization of cask thermal performance takes place between the thermal and shielding areas when dealing with zoned cask loading approaches. In this case, the internal temperatures are increased by zoned loading, requiring innovation by the thermal designer to avoid imposing temperature limits on zoned loadings.

Shielding design

When dealing with zoned loading, the benefits from self-shielding are obtained by putting hotter fuel in the inner cask locations, thereby increasing temperatures and challenging the thermal designers.

Structural design

Designing structures to limit accident degradation is relevant for ensuring both sub-criticality and heat transfer. Further, the structural design of the cask has a definite impact on the thermal capacity since heat transfer through the structural members of the cask internals and wall partially determines cask thermal capacity. Selection of materials for components other than the cask body can raise questions about material compatibility. Last but not least, operational factors are widely impacted by the structural design, particularly by the cask's size, weight, and closure method.

10.6 OPEN ISSUE SUMMARY

The following_is a summary of the status of the open issues identified in Annex II. Some of the issues that address parts of an overall issue have been combined.

Long term fuel integrity, performance confirmation and retrievability
A significant goal of storage cask design is the assurance of ultimate retrievability, without significant complications at the end of the storage period, or in the case of transportable storage, after post-storage transport. Analyses and limited data give encouragement that with proper limits on the initial cladding temperature, cladding integrity will not be compromised at the time of retrieval, following extended storage periods. However, there is uncertainty in this conclusion because there is very little experience and data on the long term performance of:

- the newer Zr-Nb cladding materials,
- fuel with burnups above 45 GW.d/MTU,
- MOX fuels,
- fuel over extended storage periods.

Such data are urgently needed for the validation of computer programs, and for anticipating the need for remediation, should such prove to be required. This suggest the need for a cooperative international program that would be planned and implemented to monitor and periodically measure actual cladding and fuel assembly hardware performance over an extended period of storage.

It is expected that this issue will remain open for many years.

Burnup credit

The gradual regulatory acceptance of actinide and fission product burnup credit is expected to occur because of major international efforts to improve computational methods and data on actinide and fission product isotopes, the spatial effects of non-uniform fuel depletion, and ultimately, the substantial benefits that can be realized. Such cask performance benefits will arise from raising the maximum enrichment limits and related burnups, and from the avoidance of flux traps in PWR casks. The ability to accommodate the criticality aspects of higher burnup fuel will also necessitate advances in shielding and thermal analysis. Implementation of burnup credit will require the use of quality-assured reactor and fuel records, and the development of burnup confirmation and measurement protocols at the time of cask loading. Assemblies that do not qualify for burnup credit loading would require either different casks or, for PWR assemblies, the use of special rod cluster absorber assemblies inserted into the assembly's internal control rod holes and locked into place. Burnup credit is being implemented progressively in some regulatory jurisdictions, but is expected to remain an open issue in other jurisdictions for many years.

Zoned cask loading

Zoned cask loading is being, or can be practiced for storage casks within current regulatory practice because it provides the logistic benefit of saving cooler fuel assemblies for later cask loading, also giving them additional cooling time. With a change in regulatory practice to accept self-shielding credit, increased logistics benefits can be realized and the average burnup/age capability of casks can also be increased. Zoned loading of transportable storage casks needs to address the additional heat transfer that is required when hotter assemblies are loaded into the inner cask locations. Criticality and the adequacy of neutron shielding also need to be addressed. Zoned cask loading will remain an open issue for at least several years.

Computer code validation and validation measurements

Additional qualification of computer programmed design tools, using appropriate additional benchmarks is currently occurring with burnup credit in the criticality area, but is needed in general in the other design areas in order to execute cask designs at higher burnups and enrichments. Computer code validation will remain an open issue as long as there is additional optimization potential.

Damaged fuel

A clear definition of damaged fuel is needed. This should include a determination as to whether the following are to be included or excluded form the damaged fuel definition:

- Assemblies containing rods with pinhole leaks or hairline cracks
- Assemblies designated as “leakers” during reactor operation, but without observable damage

Regulatory conditions for storage of damaged fuel, including containment, should be established. Damaged fuel will remain an open issue until a practical definition of damaged fuel is developed, and storage regulations for damaged fuel have been established.

Life of cask components and long term maintenance

Specific cask components critical to extended storage life need to be identified, designed for minimum maintenance, but with maintenance requirements and frequencies identified. Components of interest include lifting trunnions, seals, neutron moderator and monitoring equipment. Long term maintenance of key cask components will remain an open issue.

Long term records management

Effective management and protection of fuel assembly characteristics and storage-related data is a key condition for long term spent fuel management in general and for optimization efforts in particular. As data storage technologies and media evolve, and as personnel rotate, continuity and accessibility of records and knowledge will require continuing attention.

The long term management of fuel assembly and storage records will remain an open issue.

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ANNEX I
REPORT OF 2002 CASK OPTIMIZATION MEETING

FOREWORD

Long term storage of spent fuel is a major topic within the Member States. The issues of long term storage of spent fuel have been addressed already by means of an IAEA coordinated research project (CRP), 1994–1997 (IAEA-TECDOC-1293, 2002). It was recognized as a new challenge to extend the life of existing and new storage facilities. Dry cask storage of spent fuel is of steadily increasing importance.

The Regular Advisory Group Meeting on Spent Fuel Management Status and Prospects was convened in Vienna 30 August–3 September 1999. It was concluded that the management of spent fuel would continue to have high priority in assuring the safe and sustainable use of nuclear power. Among other issues the increasing importance of away from reactor (AFR) storage systems was recognized.

Meetings were held on the application of burnup credit. Issues seem to be judged differently in different Member States. The newly merged Technical Working Group on Nuclear Fuel Cycle Options and Spent Fuel Management recognized the importance of higher initial enrichment of fuel and of extended burnup of spent fuel in the back end of the fuel cycle management (TWG NFCO held in Vienna 8–11 July 2002).

The IAEA, in cooperation with OECD NEA organized the International Conference on Storage of Spent Fuel from Power Reactors which was held in Vienna, Austria, 2–6 June 2003. It addressed issues related to extended long term storage.

In this context a consultancy on the optimization of cask/container loading for long term spent fuel storage was held 18–22 November 2002 which discussed the issues, elaborated findings and problem definitions pertaining to and in preparation for the technical meeting (TM) that took place at the end of March 2003.

The IAEA Officer presiding over the meeting was K.A. Schneider.

CONCLUSIONS

The consultancy identified and discussed the main issues regarding the optimization of cask/container assembly capacity and burnup/age capability in the design of systems for long term spent fuel storage and the related integrity of fuel. It was noted that cask designers currently face a number of new challenges including storage of high burnup fuel with correspondingly higher enrichments, the use of mixed oxide (MOX) fuel, and obtaining regulatory approval for the use of burnup credit. Consideration was given to the fact that optimization might have different meanings from the views of the cask vendor, the cask owner, the cask operators, the institution having the ultimate responsibility for the storage, the Licensing and Supervisory Authority.

Optimization is a part of the design process in which the combination of application objectives, regulatory limits and design margins are innovatively addressed and judiciously balanced in the final design. A primary result of a successful design optimization is a cask of superior assembly and burnup/age capacity that minimizes the total number of required cask loadings. An equally important and parallel benefit is that this process also results in reduced radiation exposure, thereby contributing significantly to ALARA objectives. In this sense, both cask designers and regulators have the common ultimate goal of improving cask performance, and thus of facilitating the optimization process.

The expected useful life of the fabricated materials that make up the physical cask components is generally expected to be more than 100 years, assuming reasonable monitoring, care, and maintenance. However, with regard to the spent nuclear fuel (SNF) contents of the cask, the experience with dry storage is not long but gives encouragement that extended periods of dry cask storage without loss of cladding integrity are a realistic expectation. However, considerable additional data is needed concerning cladding performance during longer storage periods and subsequent transport, particularly at higher burnups, for the new Zr-Nb cladding materials, and for MOX Fuels.

Retrievability has to be assured. It is suggested that a long term storage monitoring program be initiated to justify either continued storage or remediation if it appears that future retrievability might be compromised.

The consultancy has identified a number of open questions whose resolution will improve future optimization of casks for long term storage of spent fuels.

1. INTRODUCTION

Long term storage of spent fuel is a major topic within the Member States. The issues of long term storage of spent fuel have been addressed already by means of an IAEA Coordinated research project. It was recognized as a new challenge to extend the life of existing and new storage facilities. Dry cask storage of spent fuel is of steadily increasing importance.

Following the IAEA Safety Requirements, International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, IAEA Safety Series No. 115 each practice should be justified according to the ALARA principle, economical and social aspects should be taken into account.

Each consultant prepared and presented a paper representing his views on the topics. The papers were discussed in detail. The main issues of optimization of cask/container loading (capacity) were identified and discussed with respect to long term storage and the related integrity of fuel. The different practices in Member States were taken into account as well as international aspects.

The following represents the report of the Consultancy elaborated on the spot. The papers presented are attached

2. THE ROLE OF OPTIMIZATION IN CASK DESIGN

The purpose of this section is to describe the optimization process within the context of cask design, in general, and storage cask design, in particular. The general objective of cask design is to provide a cask with the largest possible capacity of SNF assemblies with the largest burnups and shortest cooling times that are practicable. The cask must also meet the weight and dimensional limitations defined by the application, and must meet regulatory requirements with appropriate design margins. Optimization occurs because many of the cask safety limits such as dose and fuel temperature limits can be met only by imposing limits on the various cask performance measures such as assembly capacity or burnup/age capability. Optimization is thus the part of the design process in which the combination of application objectives, regulatory limits and design margins are innovatively addressed and judiciously balanced in the final design. A primary result of a successful design optimization is a cask of superior assembly and burnup/age capacity that minimizes the total number of required cask loadings. An equally important and parallel benefit is that this process also results in reduced overall radiation exposure, thereby contributing significantly to ALARA objectives. In this sense, both cask designers and regulators have the common ultimate goal of improving cask performance within regulatory limits, and thus of facilitating the optimization process.

There is an additional optimization consideration that is specific to storage casks: assurance of the integrity of the fuel cladding and assembly structural components that is required for assured retrievability of the fuel at the end of the storage period. In many storage applications, this issue is complicated by the uncertainty as to the duration of the storage period that will be required prior to the ultimate disposition of the stored SNF. The expected useful life of the fabricated materials that make up the physical cask components is generally expected to be more than 100 years, assuming reasonable monitoring, care, and maintenance. However, the general requirement for storage is that the SNF contents of the cask remain isolated from the environment and maintain their cladding integrity, and as a minimum be mechanically removable from storage without significant complication. In the latter regard, the experience with dry storage is not long but gives encouragement that extended periods of dry cask storage are a realistic expectation. However, extrapolation of current data on storage performance to longer storage periods and higher burnups must include an uncertainty that increases with the degree of extrapolation. In that regard, the concept of "long term storage" can be defined by the following time periods:

- Initial period with little uncertainty as to storage safety. Design basis conditions would fall within this period.
- An intermediate period during which the predictability of performance has larger, but reasonable uncertainty.
- The subsequent period during which the predictability of performance is much less certain, requiring greater analysis and more data.

It is noted that storage monitoring programs can be used in conjunction with "long term storage" to provide the basis for continued storage, or remediation, if necessary.

3. OPTIMIZATION

The purpose of this section is to describe the optimization process in more specific terms. Optimization has always been a part of the design process for storage and transport casks. However, prior designs were frequently for the storage of long-cooled, lower-burnup fuels. Test casks were also loaded with these fuels and periodically checked as a part of government-funded national programs, resulting in much of the data currently available on fuel performance. The situation is now progressively changing:

- much of the cool fuel is now in storage, leaving the hotter, shorter-cooled fuel;
- fuel burnups are steadily increasing and will continue to do so;
- storage requirements for spent MOX fuels are developing;
- the available storage performance data applies principally to the lower-burnup fuels.

All of these factors significantly increase the challenges of cask design, demanding innovation in cask technology and requiring better analytic methods and benchmarking data to justify reduced design margins as regulatory limits are approached.

The optimization process is described by first summarizing the overall requirements and constraints imposed by certain existing features of the reactor(s) requiring SNF storage, the types and characteristics of the fuel requiring storage, the safety and regulatory requirements to be satisfied, and the overriding goal of also achieving minimum life cycle unit cost of storage. Next, the design problems that result from the requirements and constraints are outlined. Then the methods for achieving optimized design solutions are described. Finally, summaries are provided of the open issues whose resolution would facilitate further optimization in future designs.

3.1 Overall requirements and constraints

(1) Individual utility circumstances:

- Prior to initiating a SNF storage project, utilities typically decide on what NPP changes are cost-effective for facilitating storage cask loading and handling. Consideration may be given to making changes to NPP equipment and structures such as transfer cranes, fuel loading machines or equipment and structures adjacent to the pathway for movement of the cask to its storage location. However, once the decisions are made to make those changes and incorporate them into the specification of storage requirements, the utilities do not want any further changes to be made. Compatibility of the cask with the resulting specification of NPP equipment and facilities is thus required with respect to weight, dimensions, and handling.
- Casks should be compatible with the existing site transportation system.
- It is required that interactions with NPP operations be minimised.
- The storage system must be compatible with the available site storage area.
- The cask must be able to accommodate most or all of the many fuel types and characteristics that are typically present in a reactor pool.
- Although some national regulations already require that storage casks be transportable, most recent commercial procurements of dry storage systems also require licensed transportability. This has the practical effect of imposing transportation cask requirements on storage cask design.

(2) Fuel characteristics:

- The burn up of some SNF assemblies is currently as high as 55 - 60 GW.d/t (assembly average). Some utilities have plans for further burnup increases.
- Initial enrichment of fuels is increasing, consistent with the achievement of higher burnups. This increases initial fuel reactivity and decreases the critical mass of fuel.
- In some cases reactor pool capacities are small, and therefore the SNF assemblies going into storage have a short cooling time.
- There are needs for storage of various type of fuels such as BWR (8x8, 9x9, 10x10), PWR (Zircaloy-4, new Zr-Nb cladding), and MOX. They have a variety of characteristics including geometry, mechanical design, burn up, heat and radiation source distribution.
- There are needs for storage of damaged SNF assemblies and possibly for SNF that is physically different from the original plant fuel design .

(3) Safety and regulatory requirements:

- The regulatory requirements in the following technical areas have to be satisfied for storage: Subcriticality; Shielding; Containment; Heat removal; and Structural Integrity.
- In some cases, transportability of storage casks is a regulatory requirement.
- Retrievability of assemblies after extended storage is typically required, either by regulations, or as a consequence of regulatory practice.
- The requirements of more accurate design analyses and calculations are constantly increasing in most areas of design. Computer code validation and benchmarking based upon qualified data is, and will continue to be required as long as there is excess conservatism in design margins.
- The requirement for security is also increasing.

(4) Reduction of storage cost per tU :

- The establishment of a free market in electricity generation is a worldwide trend. This maintains a constant pressure on utilities to reduce and minimize all costs. Thus the life cycle unit costs of cask procurement and usage must be addressed and minimised by the utility. Because of the competitive market in cask supply, the composite unit costs of cask design, licensing, manufacturing, loading and storage must be addressed by cask suppliers and minimised using the optimization process.

3.2 Identification of problems raised by analysis of requirements

(1) Limits on cask dimensions and weight for casks loaded at the NPP

The design of buildings and equipment at NPPs defines some boundary conditions that are essential limits for the cask design. In order to transfer the cask from the fuel pool to the storage location, all restrictions concerning dimensions and weight have to be satisfied. As a result the smallest dimensional clearance and the weakest building structure or crane on the path to storage location may limit the diameter and/or the total weight of a cask.

(2) Increase in the source term

Due to increasing burnup and increasing use of MOX, the source terms of the cask inventories increase correspondingly. Both higher burnup and the use of MOX have a strong impact on neutron source terms. This results in relatively higher neutron dose rates in the longer term, due to the slower reduction of the neutron source term relative to the gamma source term.

(3) Increased initial enrichment

In order to reach higher burnup, an increase of the initial enrichment of U or Pu_{fiss} is necessary. Criticality design must assure that the reactivity of stored spent fuel is controlled to maintain required subcriticality margins.

(4) Increased thermal power

Thermal power of cask inventories increases with storage of higher burnup and MOX fuels. Limitations on maximum temperatures for cladding, for accessible surfaces and, in some cases, for specific materials must be met. In order to stay within all limits, more effective heat transfer from the fuel elements to the environment is essential.

(5) The impact of high burnup and long term storage on fuel integrity

Higher burnup will lead to increased load and stress on fuel cladding. Fuel design margins are established to assure safe and reliable in-core operation during the 5 or more years required to reach high burnup. From the viewpoint of cladding performance during storage, the degradation mechanisms leading to cladding deterioration are expected to be different, and include hydride effects on cladding, build up of He, and α-decay damage in MOX fuel.

(6) Consideration of new materials for cladding

Development of new fuel cladding materials has focused mainly on safe and reliable reactor operation. Considerations unique to long term dry storage have not yet been integrated into the fuel design and material selection process. There is little data on the storage performance of the newer Zr-Nb clad materials for PWRs. As such data becomes available, requirements affecting cladding material performance during long term storage will need to be addressed during fuel design and fabrication. Therefore the cask design has to provide margins to cope with uncertainties related to long term cladding behaviour, until the cladding can be designed to include features favourable to performance during long term dry storage.

(7) Potential regulatory requirements for decreased cladding temperature

Cladding design does not yet address integrity issues that are unique to long term storage, nor is there significant long term storage cladding performance data, particularly at higher burnups and for the newer clad materials. Due to the resultant uncertainties in the projection of fuel cladding behaviour during long term dry storage, a decrease in the maximum cladding temperature may be required to provide margins against cladding degradation. With respect to the increase of thermal power due to higher burn up, the use of MOX fuel and/or more dense packing of the fuel elements in the cask, a requirement to maintain or decrease the current maximum fuel temperature will strongly influence the cask design.

(8) Immediate transportability required for storage

In some countries the license for storage also requires a transport license. Therefore the cask has to fulfil both storage and transport requirements. Also, because the transport license assumes immediate transportability, the fuel limits are based on immediate transportability, and the cask capability limits may be significantly determined by the transport requirement. In these cases, the required assumption of immediate transportability ignores the substantial thermal and source term decays that occur during storage, and thus imposes an unrealistic and unnecessary extra margin of safety in the ultimate transport. Significant benefits via improved storage cask capability and ALARA appear to be available if regulatory practice can be changed so as to license storage-transport casks for transport conditions that occur at the end of a specified storage period.

(9) Increasing complexity of the fuel inventory list

Competition in the fuel supply market leads to a large variety of fuel designs serving the individual needs of the utilities. Together with the already existing fuel element designs, particularly for BWRs, the potential inventory of the cask is broad and complex. Cask design and capability limits are then determined by optimizing the design, after identifying and then using the most limiting of the fuel designs within the total inventory. The safety margins will then be greater when the cask is loaded with any of the other fuels in the inventory list, and in that sense, the loading of the overall inventory is not fully optimized. However, the optimization process also needs to consider the issue of how best to cover the whole spectrum of fuel characteristics within the total inventory list, using the minimum number of different cask designs. Thus, when considering the complete fuel inventory list, the extent of overall optimization is limited by the trade off between the optimization gains from having larger numbers of cask designs, and the increased costs and operational complexity of having to design, license and operate with larger numbers of different cask designs.

(10) Retrievability after long term storage

In order to keep all disposal options open, fuel elements must be retrievable after long term dry storage, i.e. degradation that compromises retrievability is not acceptable. Due to the lack of long term storage experience and the current situation in which storage issues are not addressed in fuel design, restrictions on cask design could be imposed.

(11) Efficiency of control during storage

During long term storage the tightness of each of the barriers has to be ensured. Furthermore any precursor of degradation of the cask must be identified before the safety function is affected. Monitoring the proper functioning of the casks is necessary.

(12) Specific management of the storage site

Due to high thermal power at the beginning of the storage, casks may have to be stored with separations not compatible with the long term storage capacity of the site.

(13) Requested solution for damage fuel storage

Cask loadings with previously damaged fuel have to be considered even with respect to storage. Important issues to be properly addressed in the design are water inside the damaged fuel and criticality.

(14) Cost reduction

In a competitive market, reduction of at least unit costs is always an issue. But component cost reductions without a change in the cask technology are almost impossible. Options for changing the cask technology are very limited and include potential risks on cask performance and even costs.

A sound cask design approach has to balance the increased costs of sophisticated design, materials and methodologies against the reductions in unit costs achieved by reducing assembly spacing and other measures that result in increased cask capacity and/or improved burnup/age capability.

3.3 Methods for achieving optimized design solutions

Taking into account the storage cask design issues and the sometimes-conflicting requirements raised by the above analysis of the cask design requirements, it becomes evident that there is both a strong need and a significant benefit to be realized by designing to achieve improvements in cask performance.

These improvements could be realised in different ways:

- **improvement in terms of assembly capacity** of the cask (meeting all weight and interface requirements for loading at the NPP). This could result from reduced assembly spacing within the cask basket, and/or improved burnup/age capability
- **increased material performance** of the cask or use of new package materials (shielding, structural, thermal…), including the qualification of these materials at high ranges of temperature and radiation.

An approach to reach these goals may consist of the **identification and reduction of design margins,** using more calculations of greater precision. This would take advantage of additional benchmarking performed so as to improve the qualification of codes and calculation methodology.

Once identified, the design margin reductions can be achieved via increased sophistication of both cask design and content definition (inventory list) in the areas of shielding, structural, thermal and criticality design. This increased sophistication can occur in both the software and hardware areas, with software referring to the methodology of analysis (assumptions, definition of the content, scheme of calculation …) and hardware referring to the tangible design itself (physical properties of the design).

From the cost point of view, there is a tradeoff between reductions in unit hardware costs and increases in software costs. The closer spacing of fuel elements, with higher demands on heat removal, shielding, sub-criticality etc., the need to reduce design margins, and the effort of meeting increasing licensing requirements are additional software costs that must be incurred in order to realise unit cost reductions in hardware.

Several of the design methods that illustrate the increased level of design sophistication are discussed in the following paragraphs.

The first method could be called the '**zoning approach**', in which defined zones of the cask radial cross section are loaded with spent fuel of different characteristics, with the objective of increasing the burnup/age capability of the cask. It could be implemented by the definition of loading patterns in the design license that contain fuel of defined characteristics, achieved and verified during the loading of the fuel elements into the cask. This approach could be simultaneously used for:

- increasing shielding effectiveness, with fuel elements with higher source term in the central area of the cavity so as to use the self shielding properties of fuel elements
- for criticality analysis
- for thermal analysis

In implementing the zoning approach, a balance should be made between the advantages (in term of capacity) given by the zoned loading pattern and the flexibility needed by utilities for loading the cask with a large variety of fuel elements. The difficulties raised by a potential lack of flexibility are avoided in the case of a fuel inventory that is known and fixed prior to cask design. Cask optimization in this particular case could be very efficient in term of an increase of cask capacity.

With regard to thermal optimization of the cask, a primary goal is to improve heat transfer so as to decrease the temperature of the cladding as much as possible, thereby avoiding or reducing the risk of cladding degradation due to high temperature. Particular attention should be paid to :

- the reduction of gaps and interfaces in heat conduction
- the choice of adequate material
- the adaptation of the external shape of the cask for thermal control

For thermal optimization of the cask, full advantage should be taken of all cask material properties without regard for their alternative functions. For example, take advantage of thermal and mechanical benefits by including material designed for criticality control.

The concept of loading patterns could be extended to storage site management. A dynamic site emplacement pattern for cask storage could be developed to maximize heat removal from recently-loaded casks, with subsequent repositioning of casks so as to maximise site cask storage capability within thermal and radiation dose limits.

A second general optimization method is the '**improvement of regulatory practice'**. The primary goal is to neutralize the impacts of the fuel initial enrichment increase by:

- reducing the stack-up of conservative assumptions in the analysis,
- validating and implementing burnup credit in a qualitative way,
- validating and implementing burnup credit in a quantitative way (such as actinide and fission product approach). The individual fuel assembly characteristics must be confirmed within the established utility QA

system, with the possibility of additional controls at the time of loading (i.e. confirmatory burnup measurement).

Current regulatory practice for cask storage does not generally acknowledge the reality that transport will occur many years into the future, and that heat and source term decay could be significant. There are potential benefits from optimization of cask performance that can be realized by including such decay in the design concept, and requesting regulatory review. This approach has the potential for justifying changes in the current regulatory practice in this area, so as to better reflect the actual situation of long term storage and decay of heat output and source terms, followed by transport of fuel that is now much cooler than at the time of loading into the cask.

Improvements of regulatory practice can also result in realistic long term dose rate management on the site. Source term decay during the storage period needs to have regulatory acknowledgement. Furthermore, if there is a deliberate bias in favour of neutron shielding relative to gamma shielding in the original design, the subsequent slower decrease of neutron sources relative to gamma sources will result in lower total long term doses than if the normal neutron/gamma shielding tradeoff had been made in the original design. Ultimately, the foregoing approaches open the possibility, over the storage period, to admit more casks without increasing dose rates or total thermal power allowed in the facility.

Additional possible solutions in particular circumstances are:

- Any physical limits on the cask (overall dimensions and weight) that are imposed by the required compatibility with NPP interfaces could be bypassed by not loading the cask in the NPP. A dedicated smaller cask and additional cask handling operations could be used to transfer the fuel from the NPP pool to the storage cask in a controlled loading area.
- The use of qualified internal criticality control material in PWR fuel elements might be the most cost-effective way to accommodate outlier assemblies with insufficient burnup relative to initial enrichment.
- Typical approaches for dealing with damaged fuel are the use of a sealed bottle, or the use of a vented canister. These choices may affect the cask design with respect to heat transfer and mechanical design, as well as the handling and drying procedures. Since experience with storage of damaged fuel is limited, the need to store damaged fuel elements could have an impact on cask and basket design and on loading patterns.
- There are tradeoffs to be made in selecting between welded and bolted lid systems for long term containment. In the case of welded lid system, more initial effort has to be spent on quality control during welding and periodic inspection of weld integrity is needed. In the case of bolted lid systems, specific monitoring systems and operational monitoring programs are needed to ensure uninterrupted control of the tightness of containment barrier.

It is clear from the foregoing that the cask design optimization process requires increased sophistication in both the software and hardware aspects of design. Because the potential benefits from design margin reductions on material performance are not unlimited, the current primary focus of optimization is on software developments. The ultimate limit on design optimization may be reached at the point that maximum cask assembly capacities and burnup/age capabilities have been realized. This is likely to have been achieved by reducing design margins to the point beyond which there are increased operational controls at loading, and increased restrictions on utility flexibility with respect to the selection of assemblies for cask loading.

4. OPEN ISSUES

(1) *Cladding:* there is a need for data such as creep, ductility etc. during long term storage, particularly on the new cladding materials (Zr-Nb alloy) and high burnup cladding. Validation of codes based upon such qualified data is needed. Since the requirements for cladding features for long term dry storage are not well defined, cladding features unique to long term storage are not yet included in fuel design, and the predictions of the long term behaviour of cladding have significant uncertainties. From a viewpoint of rod integrity, the hydride affect on cladding, and built up He and Alfa decay damage on MOX fuel must be considered. For transportation and retrieval after extended storage, it might be necessary to consider the possibility of brittle fragmentation of fuel rods as a result of the postulated cask drop accident, and the consequences of such an accident, including criticality analysis.

(2) *Retrievability of fuel following long term storage and transport is essential:* the period of assured retrievability depends significantly on resolution of the issues discussed in Point (1), above.

(3) *Zoning:* the potential benefits of zoned cask loading need to be investigated with respect to criticality, shielding and heat removal.

(4) *Burnup credit, QA and burnup measurement:* Burnup credit has to be developed to its full extent if the full potential of optimization is to be realised. The issues of quality assurance have to be resolved accordingly. In parallel the methodology for the measurement and confirmation of assembly burnup has to be developed.

(5) *Storage of damaged fuel:* regulatory conditions for storage of damaged fuel, including containment, have to be established.

(6) *Internal criticality control material in PWR spent fuel elements:* technical feasibility and regulatory requirements need to be investigated

(7) *Computer codes:* additional qualification of codes is needed in all design areas, with significant increases in detail and precision based on appropriate additional benchmarks. As an example, improved data for source term definition is needed for use at higher burnups and enrichments.

ANNEX II
REPORT OF THE 2003 CASK OPTIMIZATION MEETING

Long term storage of spent fuel from power reactors remains a major topic with IAEA member states, who have concluded that this topic must continue to have high priority to assure the safe and sustainable use of nuclear power. As a part of its efforts to further understanding of spent fuel management, the IAEA has organized meetings to develop issues related to optimizing the loading of spent fuel into casks and containers. The IAEA held a consultants' meeting 18–22 November 2002 to discuss issues and define problems and findings on this topic. The working materials from that consultants' meeting formed the technical basis for a technical meeting held 24–27 March 2003 to obtain country-specific views from both regulators and implementers.

"Optimization" might have different meanings to cask vendors, owners, operators, and regulators. But in many regards, all have a common goal of safe, efficient cask performance. Open issues identified in the November 2002 consultants meeting fit under the following headings:

- Fuel integrity
- Retrievability
- Zoning
- Burnup credit
- Damaged fuel
- Internal moderator
- Computer code verification

During the March technical meeting, the IAEA scientific secretariat summarized results from the November 2002 consultants meeting. National representatives followed with country-specific perspectives on this topic, which stimulated discussion and questions from the other participants. Thereafter, meeting participants formed into two working groups to expand on the above open issues. One group represented the views of a regulator, while a second group represented the views of the implementers of these optimization efforts (e.g. designers, operators). The following discussion identifies conclusions and candidates for follow-on actions developed by these working groups. Reports from each working group are attached to this summary. Report, Copies of Presentations at this Technical Meeting or the November 2002 Consultants' Meeting are available from the Secretariat on request.

(1) Fuel integrity

Implementer: As the design/manufacturing of fuel assemblies (and in-reactor conditions they experience) evolve, the implementers identified the need for further research and development to assure fuel integrity during storage, specifically dry storage. For example, work related to the following parameters is required…creep, cladding absorption of hydrogen, stress corrosion cracking, oxidation, internal gas pressure (helium build up).

Regulator: This group divided the fuel integrity topic into cladding issues and mechanical damage, and concluded that the November 2002 consultants' report was fairly complete regarding cladding. Regarding mechanical damage, the group noted that "tightness" of potentially damaged fuel rods required definition, and that fuel pellet contact with water would require moisture absorbers in dry storage. Fuel Integrity is closely related to retrievability,(topic 2) and damaged fuel storage (topic 5).

(2) Retrievability

Implementer: "Retrievability" requirements must be defined in national contexts and specific requirements as early as possible in any project. Depending on national policy, retrievability requirements could vary significantly.

Regulator: This group clarified definitions and noted that requirements would vary depending on cask purpose (e.g. dual purpose).

(3) Zoning

Implementer: While clarifying definitions, this group noted that there needs to be a balance between the potential advantages of zoning and operator flexibility in dealing with a large variety of fuel assembly characteristics.

Regulator: Zoning must consider the total cask system and related requirements (e.g. both storage and transport if dual-purpose).

(4) Burnup credit

Implementer: In order to pursue the storage-related advantages of burnup credit, it is necessary to have good knowledge of spent nuclear fuel characteristics, from both measurement and calculations.

Regulator: This group confirmed the need for both high quality computer evaluations and measurements, and noted that special attention needs to be paid to MOX fuel applications.

(5) Damaged fuel

Implementer: It was pointed out that no universal definition of damaged fuel exists. Damaged fuel has to be canned for dry storage or some special measures have to be taken.

Regulator: Guidance should be elaborated to ensure that optimization efforts do not impact protection goals.

(6) Internal moderator

Both groups concluded that further development of this topic should be in the context of specific concepts. Implementers noted that technical feasibility and regulatory requirements need more investigation.

(7) Computer code verification

Implementer: Additional code qualification may be needed for specific storage cask designs. The group also noted that careful definition of source terms will continue to be important.

Regulator: This group referenced discussions developed under the topic of burnup credit.

In addition to the above topics, technical meeting participants identified the following additional topics for further consideration.

(8) Life of cask components

Implementer: Specific cask components critical to extended storage life should be identified, with a view to reducing needed maintenance.

Regulator: Consideration should be given to the useful life of selected components (e.g. lifting trunnions, seals, moderator) of the cask to ensure safe operation. A regulatory framework should be developed for re-licensing or re-certification of casks.

(9) Long term maintenance of the storage cask

It is necessary to evaluate cask design implications to ensure appropriate maintenance during the storage period.

(10) Long term performance confirmation

To assure that facilities and components operate as expected, monitoring programs for radiation, temperature, etc. may be carried out.

(11) Long term records management

Long term management of storage-related data must be ensured for future spent fuel management.

The March 2003 technical meeting of national representatives served as a key step toward developing the knowledge base available to IAEA Member States on this subject. Follow-on actions recommended during the meeting will be developed in a subsequent meeting. A consultants' meeting in the coming year is planned for development of an IAEA TECDOC on optimization of cask/container loading.

Attachment A: Working Group Report – Views of the implementers

Attachment B: Working Group Report – Views of the regulators

ATTACHMENT A

VIEWS OF THE IMPLEMENTERS

(1) Fuel integrity

What are the important and necessary points to define about the integrity of the fuel? The fuel integrity depends mainly on the cladding integrity. It is necessary to distinguish between:

(a) Manufacturing and reactor conditions

- Fuel characteristics: initial composition, physical properties of pellet
- Cladding properties
- History: power cycling, specific power, operational transients (number versus type)
- Water chemistry during reactor operation and pool storage

(b) Integrity during dry storage

- Creep
- Hydrogen absorbed in cladding
- Stress corrosion cracking
- Oxidation
- Build up He and Alfa decay occur in reactor and storage cask
- Internal pressure of rod
- Acceptance criterion (Strain)

For the present fuel and the advanced fuel under design there is a need of further R/D of the above parameters (calculations, measures, tests…) in order to predetermine the integrity evolution.

How to check the integrity of the fuel during cask storage? A closure monitoring system could only check the tightness of the cask.

(2) Retrievability

Retrievability should depend on the national policy and it should be defined at the beginning stages of any project (what components must be retrieved?)

Definition of the conditions of the retrievability: either normal transfer of SNF to another cask/container or after an assembly failure incident

During storage, degradation of the fuel assembly might occur. To prevent any degradation of the fuel assembly, the cavities of casks are dried and filled with an inert gas and the casks are closed with lids sealed with gaskets or welded. The confinement boundary is designed to ensure that the inert fill gas does not leak or diffuse through the sealing system. A closure monitoring system could also verify the tightness of the casks. Therefore, it is a mean to avoid a risk of corrosion of the cladding and so a release of radioactive material.

Therefore, the integrity of the fuel elements after long term storage should allow reloading of the cask in a wet pool or in a hot cell without release activity or dispersion of fissile material.

(3) Zoning

For the majority of the storage casks an uniform loading pattern is carried out. All the SNF loaded in casks have the same characteristics: maximal burnup and minimum cooling time to meet the design specifications and regulatory requirements. These assumptions limit the shielding and thermal performances of the cask. Nevertheless the management of the SNF assemblies for the storage is easier for the utilities in terms of flexibility.

The zoning approach defines different radial zones of the cask where spent fuels of different characteristics are loaded, with the objective of increasing the burnup/age capability of the cask. This approach concerns two aspects:

- increasing shielding effectiveness, with fuel elements with higher source term in the central area of the cavity so as to use the self shielding properties of peripheral fuel elements
- thermal analysis performed to verify the thermal heat transfer in the cask, due to the hottest SNF assemblies in the centre increasing the temperature while the coldest SNF assemblies in the outer region decrease the temperature inside the cask.

In implementing the zoning approach, a balance should be made between the advantages (in terms of capacity) given by the zoned loading pattern and the flexibility needed by utilities for loading the cask with a large variety of fuel elements. Self-shielding properties of the SNF assemblies inside the cask need also be balanced with the requirements regarding the temperatures of the SNF elements.

The difficulties raised by a potential lack of flexibility are avoided in the case of a fuel inventory that is known and fixed prior to cask design.

(4) Burnup credit

Until recently, criticality safety analysis performed to demonstrate subcriticality under storage conditions assumed that the SNF were in their most reactive state, i.e. the SNF were assumed unburned or fresh. The advantage of this fresh fuel assumption is simplicity and the disadvantage is an overestimation of the cask content reactivity that results in additional shipments, worker and public exposure and also expensive costs.

The use of burnup credit in criticality analysis is a mean to:

- Increase the cask capacity
- Accommodate the use of higher initial enrichment fuel with higher burnup
- Reduce some costs (fixed poison, number of shipments, radiological protection)

France has been using the burnup credit for SNF transport and reprocessing activities in La Hague since the late 1980s. Germany allows for burnup credit in the existing safety guidelines.

As an example, France has been using an actinide-only approach: this approach is conservative, but completely serves their initial need which is to continue the use of existing casks at full capacity or the use of the existing reprocessing plants, even as initial enrichment of new fuel design increases. The significant conservatism of this approach rests in the assignment of assembly burnup, which uses the average burnup of the first 50 cm for the assembly.

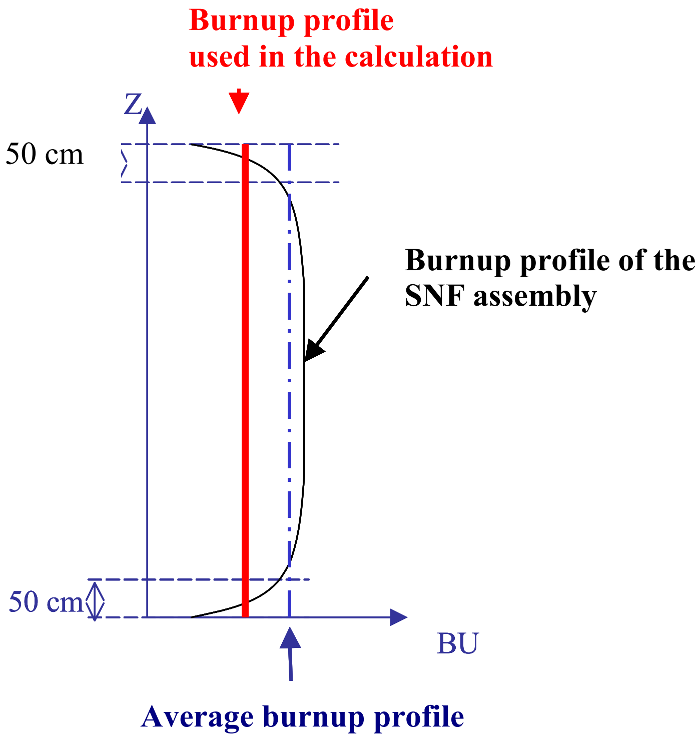


Figure II.1. Model of the axial burnup profile used in the actinide-only approach.

In that respect, it is necessary to have a good knowledge of the composition of the SNF, i.e. the radioactive source term, which depends on the recording of the fuel history in reactor and on the validation of the calculation tools and data for the simulation of the irradiation. Moreover the use of the burnup credit in the criticality safety analysis requires the measurement of the burnup of some SNF before the loading in the cask.

Consequently, many studies are underway to investigate the physics aspects of burnup credit. For instance the REBUS International Programme has been introduced to answer directly on the loss of total reactivity between burnt and fresh rod bundles, which are well characterised.

(5) Damaged fuel

When speaking of damaged fuel, it is necessary to distinguish individual phases of the fresh fuel lifetime from fuel fabrication until its loading into the reactor core. The quality control system for the previous steps is implemented in order to avoid the loading of damaged fuel in the reactor.

There is no universal definition of damaged fuel. Damage can occur in a number of ways, and almost each utility has its own criteria. But damaged fuel is generally regarded as having cladding defects, since severe structural damage is very unlikely.

The way to proceed for taking the damaged fuel out of reactor and putting it in a special can is relatively well known for wet storage pool, but going from wet pool to dry storage cask needs broader investigations. Damaged fuel has to be canned for dry storage or some special measures have to be taken.

The purpose of a damaged fuel can or container is to confine gross fuel particles, debris or damaged assemblies to a known volume within the cask to facilitate criticality, shielding and thermal requirements and permit normal handling and retrieval from the cask. For instance, damaged fuel container may need to contain neutron absorbing materials to prevent criticality if many damaged assemblies are collocated in a single cask.

(6) Internal criticality control material in PWR spent fuel elements

Technical feasibility and regulatory requirements need more investigation. The use of neutron absorber material inside the control rod guide of assembly has been applied for in Germany but it is not yet licensed.

(7) Computer codes

Computer codes are dedicated for the evaluation of shielding analysis, criticality analysis and thermal behaviour. However additional qualification of these codes are needed in the specific design of storage cask.

The prediction of the source term of actinides, fission products and activation products is a major importance for the shielding evaluation, criticality evaluation and thermal evaluation. As an example the experimental program of radiochemistry analysis ARIANE was carried out on MOX and UO2 fuels irradiated in PWR and BWR conditions reaching burnup of 35 to 55 GW.d/tM.

A more elaborated shielding analysis may lead to a better exploitation under safety conditions of the storage casks and can increase their performances. To achieve credible shielding analysis methods, advanced computational analysis techniques and data are used, such as three-dimensional Monte Carlo codes and/or recent evaluations of nuclear data with more evaluated treatment of cross sections.

The benchmark analysis concerning different radiation sources shows that the three-dimensional Monte Carlo (e.g. using codes TRIPOLI-3.4, MCBEND, MCNP…) calculations are in good agreement with the measurements.

The qualification of criticality codes (for instance CRISTAL or WIMS8a and KENO for the predetermination in the REBUS program) takes into account a lot of criticality experiments; some of the benchmarks concern different fuels in different configurations some of which being representative of fuels loaded inside different casks. Bias and uncertainties associated with the calculation of k-effective derive from benchmark experiments that closely represent the important features of the cask design and spent fuel contents.

(8) Other topics

- Useful life of cask components

  At present time the useful life of cask components is foreseen to be 40–50 years but it is possible that the storage period could be longer. Is it necessary to qualify the cask components for more than 50 years or to consider some other measures?

- Long term maintenance of the storage cask

  It is necessary to evaluate the design implications to reduce the maintenance requirements during the storage period.

ATTACHMENT B

VIEWS OF THE REGULATORS

The report of the Consultancy on Optimization of Spent Fuel Cask Loading (18-22 November 2002) included a list of topics to be considered for inclusion in a TECDOC to be developed subsequently. Participants in the 23–27 March 2003 Technical Meeting on Optimization of Cask Loading considered this list of topics and added several additional topics. Discussed below are the views of several members of the regulatory community taking part in this March 2003 Technical Meeting regarding approaches for further development of the list of topics into the future TECDOC.

The goal of optimization of cask loading must not be met at the expense of nuclear safety or radiation protection goals. These nuclear safety and radiation protection goals include:

- Safe enclosure
- Ensurance of heat removal
- Ensurance of subcriticality and
- Radiation protection requirements in agreement with the ALARA principle.

Appropriate implementation of the measures discussed below is dependent upon the storage period anticipated in national programs. Financial considerations associated with decisions regarding optimization very often are important factors, but were considered to be beyond the scope of this document.

(1) Fuel integrity

It is recommended that this topic be divided into separate sections related to the issues of cladding and mechanical damage.

- Cladding

  Report of Consultancy (18–22 November, 2002) is fairly complete as far as cladding material is addressed.

- Mechanical damage of fuel assemblies as a result of improper loading, handling, and storage of fuel rods and assemblies.

  As in the case of cladding defects, one issue of concern in regard to mechanical damage is the question of “tightness” of damaged fuel rods. In this context, tightness has to be defined. One specific criterion is whether water can or cannot be in direct contact with fuel pellets. Contact with water would cause the need for moisture absorbers in dry cask interim storage.

Fuel integrity is closely related to retrievability, which is discussed below, in Topic 2 and damaged fuel storage which is discussed, below, in Topic 5.

(2) Retrievability

For long term storage, retrievability refers to:

- Retrievability of fuel assemblies from loaded casks for the purpose of disposal of the fuel in a repository, for reprocessing, or as a result of damage or malfunction of seals or other components.

- Retrievability of the cask itself for transportation, service purposes, etc.

Requirements for retrievability will depend on the type of cask used (e.g. dual purpose or multi-purpose casks).

(3) Zoning

Zoning of fuel elements must be considered in terms of the total cask system. Consideration must be given, at a minimum, to the thermal, shielding, and criticality design and operation of the cask. Zoning needs to consider the requirements associated with both storage and transportation configurations of the cask (and in the case of multi-purpose casks, disposal would also have to be considered). In the case of national programs where long term storage is of sufficient length to allow for significant additional decay to occur during the storage term, these programs may not require the cask to fulfil the transportation requirements at the time of emplacement into the interim storage facility.

(4) Application of Burnup Credit (BUC) by means of calculation and measurement

- Burnup Credit needs to be considered in terms of the cost and benefit of the approach. Individual States may develop standards for the application of burnup credit, based upon the national spent fuel program, particularly as it applies to final disposal options available.

- Computer codes used for criticality evaluation of stored fuel assemblies must be verified and validated according to the highest available standards of reliability and quality. Such standards of reliability and quality assurance are normally a basic component of national nuclear regulatory programs. The particular concerns that are associated with the codes that would be used for such evaluations include concerns about biases and uncertainties of calculated $k_{eff.}$

- Special attention needs to be paid to proposals to grant burnup credit to Mixed Oxide (Mox) Fuels because the nuclide composition is more complex.

- Should burnup credit be used in dry cask storage, calculated and measurement-based burnup values have to be available for all spent fuel assemblies loaded into these casks to assure the subcriticality of the cask content during the entire storage period. In this regard, existing guidance in some countries (USA, Germany) consistently requires measurement of each fuel assembly prior to loading casks, confirming the reactor records and calculated k_{eff} values.

(5) Damaged fuel storage

Damaged fuel, in the context of this report, is defined as fuel which:

- is mechanically damaged, as discussed in Topic 1, above, or
- which is untight due to cladding defects. Such defects may result in:
  - water contact or penetration into the fuel matrix, or
  - release of volatile radionuclides or gas from the fuel matrix into the cask.
- Damaged fuel may also exhibit any other condition that is judged to be adverse to the criteria of confining radioactive material, controlling criticality, maintaining shielding, dose or thermal limits or is adverse to the design conditions of the cask.

In terms of optimization of cask loading, guidance should be elaborated to ensure that optimization does not contradict the fulfilment of all protection goals.

(6) Internal Criticality Material in PWR Spent Fuel Elements

Further development depends on the specific concepts applied for. We note, however, that some national programs currently contain guidance on acceptable contents of non-spent fuel elements in storage and transportation casks. As this topic is further developed, such information (e.g. U.S. and German guidance documents) might be consulted in this regard.

(7) Verification and Validation of Computer Codes

At least four groups of computer codes are usually used in the safety evaluation of storage casks: criticality codes, shielding codes, mechanical stress codes, and thermal load codes. As discussed with regard, specifically to criticality codes, in Topic 4 above, these computer codes must be verified and validated according to the highest available standards of reliability and quality. This statement is also true for the three remaining categories of computer codes mentioned above, as well as any other computer tools used in safety applications.

(8) Others

Useful life of cask components

Consideration should be given to expected lifetime of selected components of the cask in order to ensure their proper function over the required period of time. A regulatory framework should be developed to provide for relicensing and/or re-certification of casks. Among the significant components expected to require attention are: sealing system, transportation interfaces (e.g. trunnions), neutron moderator, monitoring equipment. Welding should also be considered in cases where welded components are integral to cask performance. For casks constructed with concrete as a significant component, aging of concrete needs to be carefully considered.

Long term record keeping and monitoring

In order for zoning and/or other techniques for optimization of cask loading to be carried out in a safe and secure manner, it is important that relevant information and records are kept for the entire life of the nuclear facilities operation. as prescribed by national authorities. As recognized by previous IAEA studies, such spent fuel data will also be essential for future transportation, spent fuel management, and for the design and operation of future facilities to which the spent fuel will be delivered (disposal facilities, reprocessing facilities, etc.). This data can also be used in the optimization of these facilities as well.

To assure that facilities and components operate as expected, monitoring programs for radiation, temperature, etc. may be carried out.

ANNEX III
EXPERIMENTAL INVESTIGATIONS RELEVANT FOR THE ASSESSMENT OF EXTREME MECHANICAL AND THERMAL LOADS

In the following, the most important experimental investigations that are relevant for the assessment of extreme mechanical and thermal loads acting on the casks are listed.

Drop tests

Apart from the drop tests within the framework of cask licensing, a range of drop tests was also performed from greater heights or under more severe conditions. These include among others:

- Multiple dropping of various different Type-B packages, such as a 1:2-scale model of a TN 8/9 fuel assembly transport cask (mass approx. 4 Mg) fitted with shock absorbers from a height of 200 m onto different soft soil types and onto a concrete slab (1977),
- Drop test of an original CASTOR® Ic cask in side-on-orientation from 19.5 m height onto the foundation of a road suitable for heavy vehicles (1980),
- 9 m drop tests with CASTOR® Ia, Ic and TN 900 prototypes without shock absorbers in side-on-orientation onto the lifting trunnions, in some cases cooled down to –40 °C (1978 – 1985),
- 14 m drop tests with CASTOR® VHLW cask onto steel roller pedestals mounted on the unyielding surface; without shock absorbers, but with an artificially applied 120 mm deep notch in the highest-loaded area (1991),
- 9 m drop tests of a hollow-cylinder 1:2.5-scale CASTOR® V model onto steel roller pedestals, without shock absorbers but with large artificially applied faults in the highest-loaded area; no fracture despite several times increased loading compared with the use of shock absorbers (1988),
- Drop of a C30 cask from 25.5. m height onto a foundation simulating the track corridor surface of the Greifswald NPP,
- 9 m drop test at the CRIEPI test institute (Japan) using an original fuel assembly cask that is very similar to the large German CASTOR® V casks, having a mass of approx. 110 tons, at a temperature of – 40°C onto an unyielding surface (1988 – 1989),
- 17 m drop test (vertical and oblique orientation) at the CRIEPI test institute with two monolithic test casks made of ductile cast iron in storage configuration onto a reinforced-concrete slab,
- Drop tests from 9 m and 18 m height with a super cooled MOSAIK® cask with artificially applied crack-like incipient damage onto a steel roller pedestal mounted on an unyielding surface, SANDIA National Laboratories,
- Drop tests performed by the GNS company with MOSAIK® casks from 800 m height (400 km/h) onto a concrete runway.

In all these experiments with increased mechanical load impacts going beyond IAEA design requirements the casks showed no loss of integrity.

Other extreme mechanical loads

Other experiments included above all some high-speed crash tests were carried out. In the USA, GB and Japan experiments to study of fuel assembly transport casks were performed:

- After two tests involving the crash — at 97 km/h and 135 km/h, respectively — of a 20.5 Mg cask mounted on a road vehicle into a massive concrete wall (mass 626 Mg backed up with 1580 Mg of soil), the cask showed no sever damage. Although a fuel element bundle (Savannah core II) inside the cask suffered clearly visible deformation, the fuel rod cladding nevertheless remained intact,
- A diesel locomotive (109 Mg) traveling at 131 km/h impacted the broadside of a 22.7 Mg transport cask. With the exception of two 26-mm-deep depressions, the cask as well as the fuel assemblies inside remained undamaged,
- A fuel assembly transport cask weighing 61.8 Mg on a railcar was launched at 131 km/h at a massive concrete wall; both cask and fuel assemblies only showed elastic deformation,
- Two tests were carried out involving reinforced-concrete slabs and a ductile-cast-iron transport and storage cask (mass 107.9 Mg), with the slab being dropped from a height of 5 m and 17.1 m, respectively. While the concrete slab was smashed to smithereens, the cask's integrity and leak tightness was maintained in the tests,
- Experiments with an original specimen cask were concluded with a crash in which a locomotive (mass 140 Mg) and three wagons (Mass 35 Mg each) crashed at 160 km/h into a horizontal fuel assembly transport cask (mass 48 Mg).

Aircraft crash

The basis for the assessment of the safety margins of the casks to withstand the mechanical loads of an aircraft crash its formed by a number of experimental investigations performed in Germany and France.

In Germany, initial experiments were performed between 1978 and 1980 at the German Federal Armed Forces' test site at Meppen. These experiments involved shortened CASTOR® casks of the types Ia and IIa, retaining their original cross-section. Later, three further tests were carried out at Meppen, this time using a full-scale TN 1300 cask. In all German experiments, a heavy hollow cylindrical projectile was fired from a special gun at near sonic velocity at the shell or lid side of the test cask.

The results of the German experiments relating to the aircraft crash scenario were confirmed by a further experimental study carried out by the French company COGEMA LOGISTICS. COGEMA LOGISTICS also performed aircraft crash simulation experiments using scale model so as to simulate:

- the crash of a F16 type of aircraft (velocity of 150m/s, weight of 15 000 kg) at the lid area of a TN 24 D transport and storage cask, using a projectile with a diameter of 270 mm and a 1/3 scale model of the cask,
- the crash of a F18 type of aircraft (velocity of 215m/s, weight of 20 500 kg) at the lid area of a TN 24 G transport and storage cask, using a projectile with a diameter of 270 mm and a 1/3 scale model of the cask,

Tank wagon explosion

In Germany the responsible authority performed a fire experiment involving a 45 m^3 tank wagon filled with 10 m^3 (5.1 t) of propane gas. This experiment was to provide insights for the assessment of the thermal behavior of liquid-gas tanks in an accident fire and yield indications as to which disaster control measures might be derived. The failure of a propane gas tank goes in hand with the consequential effects of a boiling liquid expanding vapor explosion, i.e. with an expanding fireball, blast wave and flying debris. Events like these involving the bursting of a tank holding flammable gases that have been liquefied under pressure belong to the most severe accidents in industrial history.

The test bed was composed of steel troughs filled with fuel oil, set up within a U-shaped sand embankment, to provide the fuel for the fire to engulf the tank wagon and the CASTOR® cask arranged at a right angle to it. The lid end was not, however, additionally protected by a shock absorber (as in the case of a road transport), nor by a cover plate (as used in storage configuration).

A few minutes after the ignition of the fire the propane gas tank burst with a subsequent abrupt release, expansion and ignition of the propane gas. The propane gas tank ruptured at first in the axial direction on the side not facing the CASTOR® cask. The abrupt gas release and explosion on the side not facing the CASTOR® cask caused a rocket-like acceleration of the entire tank wagon in the direction of the CASTOR® cask. The long side of the tank wagon hit the upper half of the lid side of the CASTOR® cask. An inspection and leak test of the CASTOR® cask after it was dug out showed that the lid had suffered no lasting deformation and that the effectiveness of the lid bolts and the leak tightness remained unchanged.

Fire

In the past, numerous fire experiments involving transport casks for radioactive materials have been performed world-wide, above all in order to demonstrate compliance with IAEA test requirements. In recent years, fire experiments involving large pool fires have been carried out above all at the Sandia National Laboratories in the USA. They serve for a better understanding of the phenomenology of large and turbulent hydrocarbon fires with regard to the development of advanced fire models and the measurement of the heat radiation transfer to large metallic bodies.

ANNEX IV
THE TECHNICAL AND LOGISTIC BENEFITS OF NON-UNIFORM, ZONED CASK LOADING

The purpose of this appendix is to describe the benefits of licensing and using non-uniform, zoned loading of casks, including the physical nature of the phenomena that underlie those benefits. Based on the systematics of the zoned loading analysis sequence, this appendix also outlines a regulatory approach for licensing and specifying the range of couplings of the outer and inner zone fuel characteristics that result in total external dose rates being at the regulatory limit.

I.1. Summary

The two general benefits are broadly categorized as:

(1) A Technical Benefit. Cask radiological capability improvements are obtained by using a non-uniform, zoned loading of the cask, in which cooler fuel assemblies are loaded into the outermost locations in the cask basket, and hotter assemblies are loaded into the inner locations. The benefit arises because the assemblies in the outer zone provide additional shielding of the inner assemblies. Thus a small decrease in the outer region source term relative to uniform loading permits a larger increase in the source term of the inner region, enabling a net increase in the cask-average source term at the same external dose level. The outer and inner zones have approximately equal numbers of assemblies.

(2) A Logistic Benefit. The use of non-uniform zoned loading in conjunction with a well-conceived long term cask loading strategy enables much longer usage of the same cask than can be obtained with any strategy used with uniform cask loading, in the typical long term situation in which fuel burnups are continually increasing. The details of the zoned loading strategy for specific fuel pool inventories would reflect the current and projected future characteristics of the fuel inventory being managed, and the characteristics of the casks being used. The basic nature of the cask loading strategy is to conceptually separate the fuel assembly inventory into an older, cooler portion, with the remaining assemblies being in the hotter portion. The outer zone of the cask is always loaded with the remaining oldest/coldest assemblies (oldest/coldest first), and the inner zone is loaded with the hottest assemblies that are acceptable within the cask's overall licensed loading limit. The logistic benefit of this basic loading strategy arises because, over the long term, the average age of the selected assemblies in both zones increases at a rate that effectively cancels the source term increases caused by increasing burnups. This enables the use of the same cask for an extended period that ends when all of the older/colder assemblies have been loaded. This extended period of usage considerably defers the time at which higher-burnup/age casks with lower assembly capacity must be used. This directly contributes to one of the principal goals of optimization: a reduction in the total number of required cask loadings.

There are two potential limitations on the foregoing practices:

(1) A potential thermal limitation, which limits the technical and logistic benefits of zoned loading to the benefits realized up to a defined thermal limit. Beyond the thermal limit, there may be benefits from external doses that are below the regulatory limit,

(2) A too-small pool storage capacity, which could limit or eliminate the ability to practice the long term logistic strategy, and

With regard to the thermal issue, placing the hotter assemblies in the inner zone adversely affects the internal cask and fuel temperatures, relative to uniform cask loading. However, it has also been observed that addressing thermal limits in cask design is typically less challenging than addressing dose limits in shielding design. A key assumption of the foregoing strategy is that thermal design can successfully address the challenge of hotter fuel in the inner zone, it being recognized that at some level of difference between the inner and outer zones, thermal limits will be encountered on inner zone loadings, and from that point, will begin to limit the benefits from zoned loading.

With regard to pool storage capacity, the reactor pool's assembly capacity needs to be sufficient to hold about 23 years or more, of discharges, in order that a meaningful pool inventory of older/colder fuel be available for loading into the cask outer zone over an extended period. With pool capacities progressively less than about 23 years of discharges, the benefits decrease progressively to the zero-benefit point: uniform, oldest-first loading of the same cask.

The remainder of this appendix describes an approximate method of evaluating the technical benefits of non-uniform, zoned cask loading, and uses that method to quantify the benefits of zoned loading in a typical from-reactor transport situation, using an appropriate long term fuel selection strategy for loading the cask's cold and hot zones.

I.2. Physical analysis of zoned loading

Cask designers are only just now moving beyond uniform cask loading. Understanding the simplest of zoned loadings, that of a cool outer, and a hotter inner zone, each zone being uniform within itself, is the natural initial step. Furthermore, the approach can be structured using the data on uniformly loaded casks as the natural point of departure. The analysis and results of two-zone cask loading will illustrate the level of benefits that are obtainable with zoned loadings in general, and will provide a relatively simple structure for understanding the source of those benefits.

The purpose of the following discussion is to provide a simplified quantitative description of the processes by which the cask loading benefits of two-zoned cask loading can be estimated. The simplified representation is an approximation to the complex shielding analysis process that actually occurs in design, but it is useful in understanding the overall behavior of zoned loading at a simplified physical level. This conceptual approach is also useful for developing a potential licensing approach for specifying the series of compatible pairs of outer and inner zone fuel characteristics.

The point of departure is a licensed cask with its established uniform loading limits, including its design limit curve of maximum-burnup vs age, with all points on the limit curve being at the applicable external dose rate regulatory limit. For most cask designs, the most limiting regulatory dose limit is the external dose rate limit at 2 meters from the cask surface. Consider the simplest zone loading patterns consisting of an outer zone of the assemblies on the periphery of the cask, and an inner zone consisting of the remaining assemblies, which are in the central locations of the cask. Typical patterns are shown in Figure IV-1, for a 24-assembly cask. In one pattern, there are an equal number of assemblies, 12, in each of the outer and inner zones. The second pattern shows an alternative pattern in which there are fewer assemblies (10) in the outer zone than in the inner zone (14). The physical rationale for zoned loading then proceeds as follows:

- With the cask uniformly loaded at the regulatory external dose limit, the radiation source terms are equal in all assemblies. Assuming that the outer and inner regions have equal numbers of assemblies, the outer region and the inner region radiation sources are equal. However because of the shielding of the inner assemblies by the outer assemblies, the fraction of the total external dose from the outer assemblies is much greater than the dose fraction from the inner assemblies. The actual outer region dose fraction for uniform cask loading would have to be determined as part of the design process, by calculating the external doses for the outer and inner zones when uniformly loaded, using shielding/dose analysis computer programs.
- The second step is to consider what happens if the previously uniform source term is decreased in the outer zone. The external dose due to the outer zone, and thus the total dose, will drop. This outer zone dose reduction can then be utilized by the inner zone, by increasing the inner zone source term and the resultant dose from the inner zone so that the total external dose returns to the regulatory limit. However, because of the additional shielding by the outer zone, and the much greater dose sensitivity to the outer zone source term as compared to the inner zone source term, the source term in the inner zone can increase much more than the source term decrease in the outer zone, both relative to uniform loading. The magnitude of this increase is the ratio of the outer zone dose sensitivity to the inner zone dose sensitivity, a ratio that can be used directly as a source term multiplier. The allowable inner zone source term increase is the outer zone source term reduction times this multiplier. The incremental multiplying factor, IM, is given by:

$$IM = F/(1 - F) \qquad \text{(Eq. 1)}$$

Where: F = original dose fraction from the outer zone
1 – F = original dose fraction from the inner zone

The above term is called an incremental multiplier because, as can be noted, the very process of progressively reducing the outer dose fraction, F, also progressively reduces the multiplier. This fact requires that, for significant changes in the outer dose fraction, an average multiplier be used. By integrating Eq.1 over the range of the change, and dividing by that range, the average multiplier, M, is:

$$M = LN((1-FF)/(1-FI))/(FI - FF) - 1 \qquad \text{(Eq. 2)}$$

Where: FI = initial dose fraction of the outer zone when uniformly loaded
FF = final dose fraction of the outer zone, after reducing the outer zone source term

In physical terms, the external dose is “M” times more sensitive to changes in the outer zone than to changes in the inner zone. Alternatively, the source term in the inner zone can be increased “M” times a source term decrease in the inner zone, at equal total external dose levels.

As a numeric example, if the initial outer zone dose fraction is 0.8, the apparent multiplier, MA, is 4.0. Thus, a 5% reduction in the outer zone source term would enable a 20% increase in the inner zone source term, at equal total external dose. However, when the average multiplier, M, is calculated with a 5% reduction in the outer zone source term (a 0.04 reduction in the outer zone dose fraction, with FI = 0.8 and FF = 0.76), the average multiplier, M, is 3.56. This result shows that the multiplier-averaging process reduces the initial multiplier and needs to be used, even for small changes. Thus a 5% reduction in the outer zone source term would enable a 17.8% increase in the inner zone source term.

- The third step is to estimate the benefit of zoned loading in terms of the increased average source term that can be accommodated, relative to uniform loading. In zoned loading, the original, uniform source term, S, is reduced by a fraction in the outer zone, and increased by M times that fraction in the inner zone, maintaining the external dose at the regulatory limit. Assuming that the outer and inner zones are of equal assembly capacity, the cask-average source term, SAV, is given by:

$$\begin{aligned} SAV &= 0.5S(1-(FI-FF)/FI) + 0.5S(1 + M(FI-FF)/FI) \\ &= S(1 + ((FI-FF)/FI) \times 0.5 \times (M-1)) \qquad \text{(Eq.3)} \end{aligned}$$

In summary, the percentage increase in the inner zone source term is M times the percentage reduction in the outer zone source term, and the percenatge increase in the cask-average source term is (M – 1)/2 times the percentage decrease in the outer zone source term.

Continuing with the previous numeric example, a 5% decrease in the outer zone source term would enable a 17.8% increase in the inner zone source term. The cask-average source term is increased by half of the 12.8% net increase, which is 6.4%.

If Equation 3 is rewritten to generalize the assembly fraction of the outer zone from 0.5 to a generalized assembly fraction, AF, the following equation results:

$$\begin{aligned} SAV/S &= AF(1-(FI-FF)/FI) + (1-AF)(1 + M((FI-FF)/FI) \\ &= 1 + (M(1-AF)-AF)(FI-FF)/FI \qquad \text{(Eq. 4)} \end{aligned}$$

The outer source term decrease that results in the maximum value of the SAV can be determined by setting the differential of Eq. 4 equal to zero. When that is done, the result is:

For maximum loading, $FF = AF$ (Eq. 5)

This is an extremely useful result: since the designation “outer” for the outer region is for conceptual convenience and is not actually location-specific, the above result can be applied to any, and hence to all individual assemblies. This says, in effect, that the maximum source term loading occurs when the dose contribution from every assembly has been adjusted so that its final dose fraction at the dose measurement point, FF, equals its assembly fraction, AF, which is the same fraction as every other assembly. Thus the dose contributions of all assemblies are equal at the measurement point, and the source term of each assembly has been individually adjusted to make such equal dose contributions. This is the same result that is obtained by applying matix theory to the same question regarding theoretical maximum cask loadings. As a generalization, this is a useful result because it indicates the direction in which assembly selection should proceed for zoned loadings, even when dealing with such practical issues as possible thermal limits, and the available assembly inventory and its spectrum of assembly characteristics.

The foregoing approach for structuring the analysis and quantifying the benefits of two-zoned loading has, as its starting point, the established analysis methods and the resulting maximum-burnup-vs-age loading limit curve for a cask that is uniformly loaded. Such a cask is uniformly loaded at its external dose rate regulatory limit, but has defined outer and inner zones, loaded with the same fuel, but with calculable different dose fractions from each zone. This provides the value for FI, the outer region dose fraction in the above equations. Using the uniformly loaded cask with equally loaded outer and inner zones as the point of departure, the above equations quantify the acceptable increase in the inner zone source term as a calculable multiple of a given reduction in the outer zone source term. The multiplier (Eq. 1) is large when the outer dose fraction in uniform loading is also large, and the multiplier decreases (Eq.2) as the size of the outer zone decrease gets larger. The result is that there is a continuum of compatible pairs of inner and outer zone loadings, starting from equality at zero outer zone reduction, and with progressively increasing disparity as the outer zone source term reduction increases. Thus, for any reduced loading condition of the outer zone, there is a compatible limit loading for the inner zone. As a practical matter, compatible pairs would be identified at a relatively few points, with each point having progressively greater reductions in the outer zone loading. Interpolation would be used for loadings between the evaluated points.

With regard to the regulatory approach for licensing and specifying compatible pairs of inner and outer zone loadings, the foregoing indicates the possibility that this could be done simply as an extension of current analysis, licensing and specification procedures. The burnup/age limit loading curves for uniform loading are the identical outer and inner curves for zero outer zone reduction. The series of outer zone reductions could be specified as a series of progressively larger burnup reductions from the zero-reduction, uniform loading curve. And the compatible inner-zone loading curve for each outer-zone burnup reduction point would be determined using the same iterative analysis process that results in the burnup/age for uniform loading.

With regard to applying the foregoing simplified analysis method to estimate the benefits and logistics of zoned loading, the principal challenge for making the informed simplifications that are required, is how best to represent and quantify the generalized "source term" used in the conceptual development. The complicating factor is that source terms and external doses include both gamma and neutron components, plus secondary gammas resulting from neutron absorptions in the neutron shield. Further, the inner zone neutron source term does not benefit nearly as much from self-shielding as the gamma source term, and the neutron source term has a greater sensitivity to burnup than the near-linear burnup sensitivity of gamma source terms. These complications are partly normalized out by using the burnup/age loading curve for uniform loading as the point of departure. However, the qualitative effect of the differing behaviours and dose contributions of gammas and neutrons is that the outer dose fraction has some dependence on burnup, and thus there may be some total dose mismatches when assemblies in the two zones have different average burnups. The antidote to these shortcomings in applying this simplified methodology is to be conservative by using lower-than expected multipliers.

In the interest of simplicity in the representation and quantification of "source terms", it is desirable to use a characteristic that is related to one of the readily available characteristics, such as burnup, age and/or decay heat output. These three can be related via fuel-design-specific fuel depletion calculations, such that any two of them yields the third. The actual source terms used in detailed shielding design are a mixture of gamma ray photons of various energies and neutrons of various energies. However, because each fission product or actinide decay releases heat, the decay heat level is related to a composite of gamma and neutron decay rates (source terms) and therefore appears to be the simplest single surrogate for the "source term". In fact, if the source term were only gammas, decay heat would be a very good surrogate for the "source term". Provided the gamma dose dominates, which it normally does for at least 50 years, decay heat should be the most reasonable simplified surrogate for the source term.

Based on the foregoing, a simplified method for evaluating zoned cask loading consists of the following steps:

(1) The cask's maximum-burnup vs age curve for uniform loading is converted to a maximum w/assembly vs age Loading Curve for uniform loading. The outer zone dose fraction of the total external dose is determined at one or more points along this Loading Curve,
(2) The outer zone is loaded with cool assemblies having w/assembly less than the Loading Curve value at the assembly's age. The loaded outer-zone-average of the w/assembly reduction below the Loading Curve is determined. The dose sensitivity multiplying factor is calculated based on the initial outer zone dose fraction at the average age of the loaded fuel, and the *fractional* size of the outer zone loading reduction, but reduced for conservatism.
(3) The inner zone is loaded assembly-by-assembly. The hottest assemblies that still meet the loading limit are loaded. The inner-zone w/assembly loading limit is the w/assembly Loading Curve value for uniform loading at the assembly's age, plus the average outer zone w/assembly loading reduction, multiplied by the dose sensitivity multiplier.

I.3. The logistic benefits from planned fuel selection in conjunction with the use of zoned cask loading

As noted at the beginning of this Appendix, when a cask is loaded in approximately equal outer and inner zones, there is a long term fuel selection and cask loading strategy that results in a much longer utilization period for that cask, relative to using any uniform loading strategy. That selection strategy is as follows:

> Casks are zone-loaded with approximately equal numbers of assemblies of cold fuel in the outer zone and hot fuel in the inner zone. The fuel pool inventory can be conceptually divided into two inventories, a cold inventory, and the remaining hot inventory. The conceptual dividing line between these two inventories is defined when the outer zone of the first cask has been loaded with the coldest assemblies, and the first inner zone hot fuel is being selected. The selected hot assemblies will be those that will result in just using the remaining fraction of the total dose that was not used by the outer zone assemblies, with the resulting overall loading being as close as possible to the regulatory dose limit. In general, subsequent inner zone loadings will be the coldest first from the remaining inventory that is currently hotter than the just-loaded first inner zone assemblies. The hottest of the cold inventory will be the assemblies that are just slightly cooler than the assemblies used in the first inner zone loading. Thereafter, oldest/coldest-first selection from each of the cold and hot inventories will be used for subsequent outer and inner zone cask loadings, until all of the cold inventory has been removed, and only the residual hot inventory remains. Beyond that point, a higher-burnup, lower-assembly-capacity cask would have to be used.

By way of illustration, a simulation of zoned cask loading logistics was done for a large 2-unit PWR plant in offsite shipments to a postulated repository, with a removal rate of about 1.3 times the discharge rate. The reactor pool capacity was about 25 years of discharges, so that the oldest fuel in the pool was about 25 years of age. Discharge burnups were increasing at about 1%per year. This analysis used the simplified, multiplier-based methodology described above for estimating the loading limit of the inner zone of the cask, once the characteristics of the outer zone loading had been determined. The same 24 PWR assembly cask (Figure IV-1) is used in all cases. When uniformly loaded, the cask's radiological limits are at 35 GW.d/MTU and 10 years, and 45 GW.d/MTU at 15 years. The cask's burnup/age radiological limits for uniform loading were converted to decay heat (watts/assembly) as a function of age.

The loadings were done oldest-first, for both uniform loading and zoned loading in each zone, and were continued until the cask's radiological limit was exceeded. The pool inventory was conceptually divided into cool and hot inventories to support the fuel selection strategy described above. Some iteration on the size of the cold inventory with the zoned loadings was required to establish the cases in which the cold inventory was depleted and the cask loading limits were reached at the same time. The initial pickups for the inner zone were 7-years cooled for the 12/12 outer/inner cask loading, and 9 years cooled for the 10/14 outer/inner loading.

The multipliers that were selected were based on limited data on individual assembly contributions to external dose, with an estimated 0.90 and 0.87 outer zone dose fractions, FI, for the uniform loading of the 12/12 and 10/14 loading patterns, respectively. Using the maximum loading assumption (Eq. 4) for the final dose fractions, average multipliers of 3.0 and 2.3 were calculated using Eq. 2. The values actually used to check the limiting cask doses were 2.2 and 1.9, for the 12/12 and 10/14 loading patterns, respectively. However, because the fuel pickup logic for the inner zone was oldest-first, rather than "hottest available at the dose limit", the actual simulated cask loadings were typically well below the calculated dose limit, and the equivalent average multiplier was about 1.6 for the 12/12 loading pattern. Based on the foregoing, it is believed that a rigorous shielding analysis would show at least the benefits of zoned loading indicated using the approximate estimating method used in this analysis.

The results of this simulation are shown in Figures IV-2 (assembly average decay heat) and IV-3 (age at pickup), as a function of time from the start of pickup. The 4 cases shown, and observations on each are as follows:

(1) Uniform Cask Loading can be pursued for 16 years, until none of the remaining fuel can be loaded without exceeding the cask's radiological limit. Starting at about 520 w/assembly, the decay heat progressively increases to about 670 w/assembly. The average loading was about 580 w/assembly. After starting at 24 years, the age at pickup decreased to 20 years. With 16 years of oldest-first pickup with uniform loading, the increasing burnup and decreasing age act together to increase the decay heat to the level beyond which the external dose limit is exceeded.

(2) Zoned Loading Without Self-shielding Credit can be pursued for 20 years, 4 years more than with uniform loading. The average decay heat is relatively stable, at about 630 w/assembly. Thus, even without self-shielding credit, the use of zoned loading extends cask usability by 4 years (25%) and delivers spent fuel of relatively stable characteristics to the repository. This result confirms that even without credit for self-shielding, the ability to implement zoned loading allows the cask loading strategy to operate and generate meaningful logistic benefits, relative to uniform cask loading. The multiplier used to identify the w/assembly loading limit for the inner zone was 1.0, which is the appropriate multiplier to use without self-shielding credit.

(3) Zoned Loading With Equal Zones (12 assemblies outer and inner) can be pursued for 26 years, 10 years (63%) more than with uniform loading. The average decay heat is relatively stable, averaging about 690 w/assembly. Starting at 25 years, the age of the

outer zone fuel increases to 34 years. The hotter inner zone age starts at 7 years and increases to 15 years. These data confirm that the progressively increasing age in both zones effectively cancels the adverse effect of increasing discharge burnups. The multiplier used to identify the w/assembly loading limit increase for the inner zone was 2.2 (times the decrease in the outer assembly loading).

(4) Zoned Loading With Smaller Outer and Larger Inner Zones (10 assemblies outer and 14 inner) can be pursued for 28 years, 12 years (75%) more than with uniform loading. The average decay heat is relatively stable, averaging about 720 w/assembly. Starting at 25 years, the age of the outer zone fuel increases to 38 years. The hotter inner zone age starts at 9 years and increases to 13 years. These data also confirm that the progressively increasing age in both zones effectively cancels the adverse effect of increasing discharge burnups. Reducing the size of the cask's outer zone enables the cold fraction of the pool that is reserved for the outer zone to last longer in time, even though the number of reserved assemblies may actually decrease in size, which it did in this example. The multiplier used to identify the w/assembly loading limit increase for the inner zone was 1.9.

The key observation concerning the 2-zone fuel selection and cask loading strategy is that the average age at pickup increases, substantially cancelling the otherwise adverse effects of steadily increasing discharge burnups. The reason for this can be seen by using the following relationship between the rate of age change, the original discharge rate into the pool inventory (D, MTU or assemblies/yr), and the removal rate from the pool (R):

$$\Delta Age/\Delta time = 1 - R/D \quad \text{(years per year)} \qquad \text{(Eq. 4)}$$

For the uniform loading case, and the removal rate of 1.3 times the discharge rate, the above equation shows that the average age should *decrease* at 0.3 yr/year, as generally confirmed by Figure IV-3. However, because of splitting the pickups equally between the hot and cold inventories in the 12/12 zone-loaded case, the removals from each inventory are only half of the total removals, or 0.65 of the pickup rate, and the average age should *increase* by 0.35 yr/year, which is confirmed by Figure IV-3. For the 10/14 outer/inner pattern, the removal rates are 0.54/0.76 times the discharge rate, and the corresponding average ages increase at 0.46yr/year for the outer and 0.24 yr/year for the inner zone, again generally confirmed by Figure IV-3.

It should be noted that in storage situations, the discharge rate determines the storage rate, so the ratio of removal rate, R, to discharge rate, D, is 1.0. The benefits of zoned loading in storage would be even larger rates of age increase than shown in the above example. However, clad temperature limits in zoned loading are more likely to be encountered in storage than in transportation.

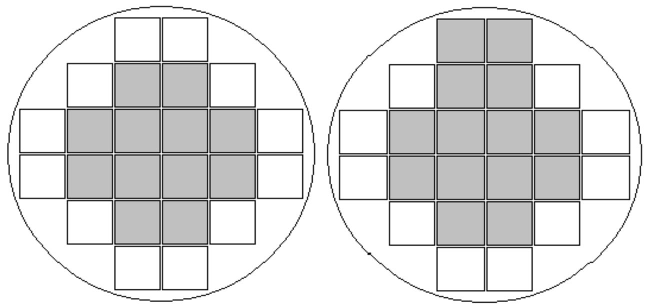
I.4. Summary and conclusions

This Appendix has outlined an approximate method for evaluating the capability of zone-loaded casks, and has used that method to evaluate zoned loading in a typical long term shipping situation. The results of the evaluation indicate that there are two types of benefit arising from the use of zoned cask loading when coupled with an optimised long term plan for fuel selection to accomplish the loadings.

- A technical benefit in which the radioactivity content of a cask is increased without an increase in the external dose rate, and

- A logistic benefit, realised through the use of an appropriate long term fuel selection and cask-loading plan, that significantly extends the usability of a cask design, delivers shipments with characteristics that are fairly stable over time, and is consistently loaded close to its license limit.

Non-Uniform Zoned Loading Patterns for a 24-PWR Cask



24 PWR, 12 Inner, 12 Outer

24 PWR, 14 Inner, 10 Outer

Figure IV.1. Non-uniform zoned loading patterns for a 24-PWR cask.

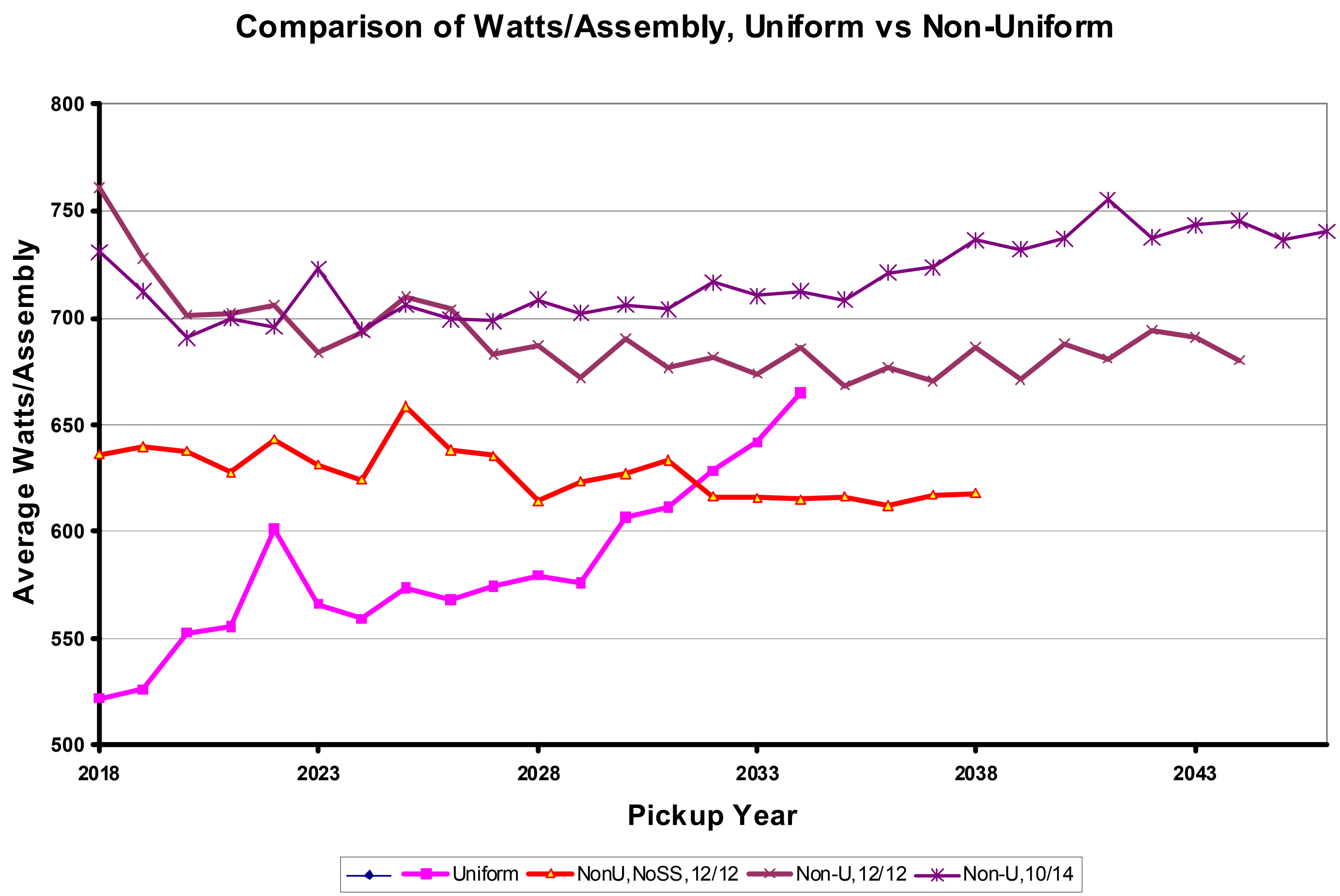


Figure IV.2. Comparison of watts/assembly, uniform vs non-uniform.

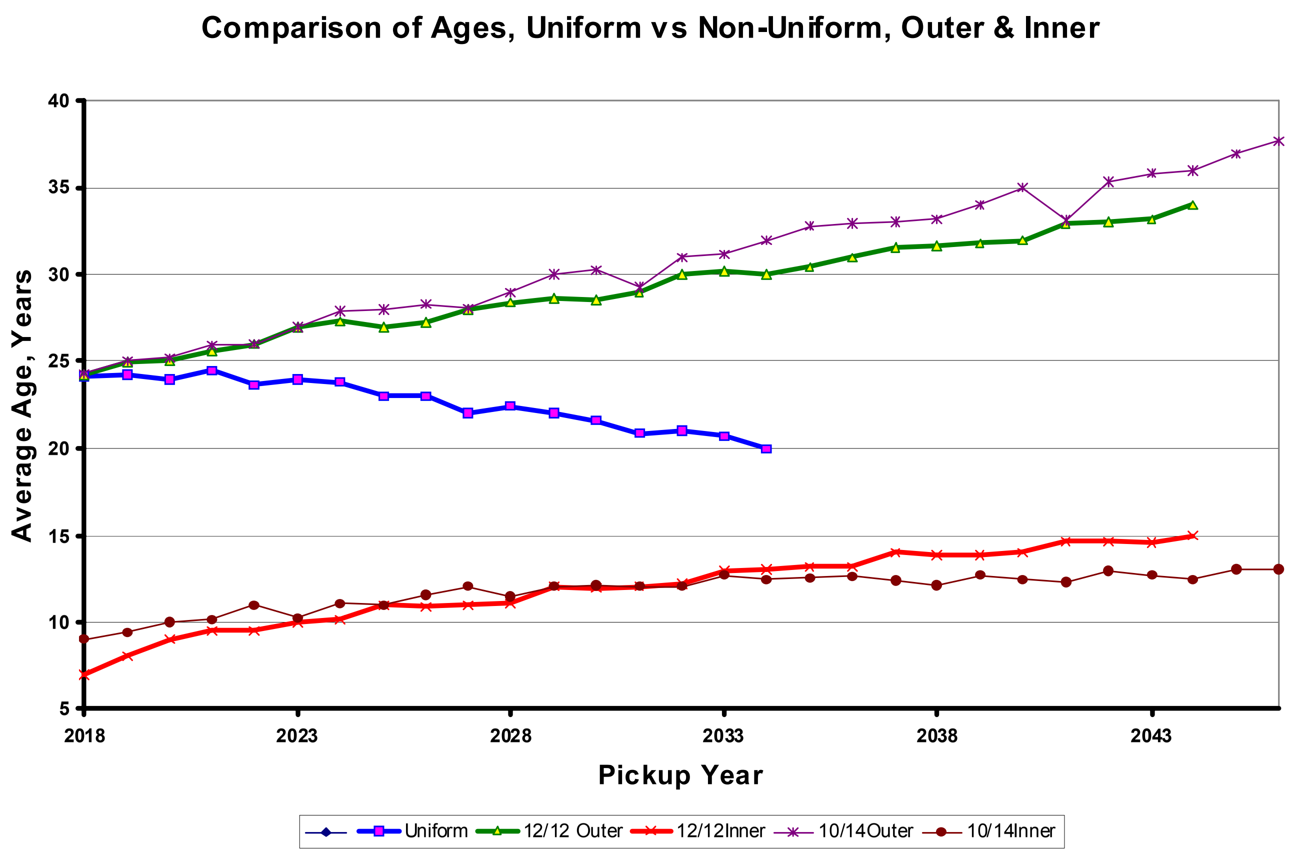


Figure IV.3 Comparison of ages, uniform vs. non-uniform, outer and inner.

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Meetings

Technical Meeting
Vienna, Austria: 24–27 March 2003

Consultancy Meeting
Vienna, Austria: 18–22 November 2002, 14–17 June 2004