IAEA Nuclear Energy Series

No. NF-T-3.6

Management of Damaged Spent Nuclear Fuel

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MANAGEMENT OF DAMAGED SPENT NUCLEAR FUEL

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA NUCLEAR ENERGY SERIES No. NF-T-3.6

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2009

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Sales and Promotion, Publishing Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
June 2009
STI/PUB/1395

IAEA Library Cataloguing in Publication Data

Management of damaged spent nuclear fuel. — Vienna : International Atomic Energy Agency, 2009.
p. ; 29 cm. — (IAEA nuclear energy series, ISSN 1995–7807 ; no. NF-T-3.6)
STI/PUB/1395
ISBN 978–92–0–103809–8
Includes bibliographical references.

1. Spent reactor fuels — Management. 2. Radioactive wastes — Management. I. International Atomic Energy Agency. II. Series.

IAEAL 09–00589

FOREWORD

Spent nuclear fuel (SNF) has been stored safely in water in approximately 30 countries for a number of decades. Dry systems are now widely used given their modular deployment and passive nature. Most IAEA Member States do not use reprocessing and have not yet decided upon the ultimate disposition of their SNF. Interim storage is the only current solution for these countries and is becoming increasingly important, particularly as storage durations extend longer than anticipated in the past. To maintain safe operations and minimize the time, dose and human resources associated with management of SNF, it is important to minimize the amount of damaged fuel. With growing interest and international cooperation in the nuclear fuel cycle, it is increasingly important to develop a consistent methodology for identifying spent fuel requiring non-standard handling as well as sharing methods for detection and handling of this fuel.

During a technical meeting on provisions for spent fuel storage organized by the IAEA in late 2004, participants recommended that the IAEA organize an activity focused on handling damaged spent fuel. The Technical Working Group (on Nuclear Fuel Cycle Options and Spent Fuel Management) responsible for reviewing the IAEA's spent fuel management activities endorsed this effort, and the IAEA held a technical meeting on this topic in December 2005 with representation from 13 Member States. Subsequent smaller meetings were held in September 2006 and December 2007 to transform the results of the technical meeting into the following publication.

The IAEA wishes to thank all meeting attendees for their participation and, in particular, R. Einziger (USA) for chairing these meetings and for coordinating the preparation of this technical publication. The IAEA also expresses thanks to the other principal contributors to this publication, including W. Goll (France), B. Carlsen (USA) and D. Haslett (United Kingdom). The IAEA officers responsible for this publication was W. Danker and X. Zhou of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

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SUMMARY

The IAEA convened a meeting in December 2005 to discuss the handling of damaged spent fuel. Representatives from over 20 countries presented their views on defining, physically detecting and/or handling damaged spent fuel. A concept was advanced that fuel should be considered damaged if it could not fulfill its intended functions. Three groups were formed to address the issues identified above. This report, which builds upon the ideas formulated at that meeting, provides a methodology for dealing with spent fuel that requires non-standard handling (damaged fuel).

Currently, most countries define fuel as damaged if it contains one or more defects from a preset list. The proposed definition would clarify that defects alone are not sufficient to conclude that a rod or assembly is damaged. Rather, the proposed definition indicates that the defect(s) must impede the fuel from performing the required safety, regulatory or operating functions.

The first part of the methodology discusses the identification of the safety, regulatory and/or operating functions[1] the fuel must satisfy. It shows how these functions will depend on the current, planned and potential future stage of the back end of the fuel cycle. These functions are then translated into characteristics which might cause the fuel to be considered to be ‘damaged’ based on potentially active degradation mechanisms and the expected behaviour of these defects. Fuel that needs non-standard handling (‘damaged fuel’) is fuel containing defects that must be accommodated to ensure it will perform its required functions.

The second part of the methodology discusses techniques that can be used to detect and evaluate fuel characteristics that may impede its ability to meet its performance requirements. In particular, available techniques for detecting various defects are presented along with their respective advantages and limitations.

Handling of damaged fuel will depend on: (i) the type of defect, (ii) the function that may be compromised and (iii) the desire to carry the damaged fuel along with the undamaged fuel (as opposed to, for example, segregating it for handling with special provisions). Non-standard handling options will depend on the remaining stages of the back end fuel cycle. Fifteen approaches are identified and discussed along with the attributes and limitations of each. Countries using the techniques are identified based on papers presented at the December 2005 meeting and related references. Charts are provided that show which different approaches are useful for a variety of defects and functional deficiencies in each stage of the back end of the fuel cycle. A short discussion is provided on points of consideration when choosing a technique to handle a particular situation.

This report is intended as a guide for countries expecting to have to deal with damaged fuel, or wanting to reconsider their current methods for dealing with damaged fuel based on the current experience of other countries and utilities. This report concludes with a number of actions that support the overall objective of providing Member States with current and relevant technical resources on this topic.

1. INTRODUCTION

1.1. BACKGROUND

Spent nuclear fuel (SNF) has been stored safely in pools or dry systems in over 30 countries for a number of decades. This international experience with storage has resulted in an extensive technical basis and an appropriate understanding of operational practices that are beneficial for spent fuel storage. The majority of Member States neither reprocess SNF nor have they decided upon and/or implemented a solution for its final

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[1] Safety requirements are those requirements that relate directly to safe operation of the system. They are a subset of the regulatory requirements. In addition to the safety requirements, at least in the USA, the regulatory requirements also include operational requirements such as retrievability.

disposition. Consequently, management of SNF during interim storage is becoming increasingly important, particularly as storage durations are extended longer than originally anticipated. During an October 2004 technical meeting on provisions for spent fuel storage organized by the IAEA, participants recommended that the IAEA organize a technical meeting focused on handling of damaged spent fuel. During the annual meeting of the Technical Working Group (on Nuclear Fuel Cycle Options and Spent Fuel Management) responsible for reviewing the IAEA's spent fuel management activities, the group endorsed the activity to produce this report.

Given current resources and the projected demands for energy, it is likely that countries currently using nuclear power will be expanding their capacity, and other countries will be establishing capabilities for generation of nuclear energy, which will result in more fuel passing through the back end of the fuel cycle. To minimize costs (i.e. time, dose and manpower) associated with management of this SNF, it is important to minimize the amount of damaged fuel consistent with the goal of having safe operations and retrievability of the fuel.

The IAEA convened a meeting to focus on the technical aspects of handling damaged spent fuel at its headquarters in Vienna on 6–9 December 2005. The workshop was attended by representatives of 13 countries who each presented short papers on addressing damaged fuel in their countries. Breakout groups were formed to address the following questions: (i) What is damaged fuel? (ii) What methods are available to detect damaged fuel? (iii) How should damaged fuel be handled? The list of participants, copies of their presentations and the chairman's summary of that workshop are given in Appendices I, II and III, respectively. Key results and conclusions from this work have been consolidated and are presented in this publication.

The term 'damaged fuel' is often used when referring to SNF that requires non-standard handling to ensure that relevant safety, regulatory and operational requirements are satisfied. Yet, the condition and properties of fuel that is considered as 'damaged fuel' is neither well nor consistently defined[2]. Historically, there has been a tendency to categorize fuels based on properties relevant to the present stage of the life cycle. For example, fuels were initially determined as failed based upon their suitability to be re-inserted into the reactor. Potential shortcomings of this approach are: (i) that it classifies fuels as damaged that may in fact be suitable for subsequent life cycle activities and (ii) that it may also fail to identify others that, while not failed with respect to reactor operational criteria, may require non-standard handling to perform designated safety, regulatory or operational functions during subsequent life cycle activities.

Without a methodology for interpreting 'damaged' or 'failed' in functional terms, the binary nature of these terms (e.g. either 'damaged' or 'undamaged') tends to obscure the fact that safety does not depend solely upon the properties of the fuel. It also depends upon other available engineered and natural barriers, the technology and the controls implemented by the host facilities, and the conditions under which the fuel must perform its designated functions.

A framework is needed that includes these considerations when identifying SNF that requires non-standard handling. With growing interest and international cooperation in the nuclear fuel cycle, it is increasingly important to develop consensus on the underlying criteria for categorizing SNF as well as consistent methodology for identifying spent fuel requiring non-standard handling.

1.2. OBJECTIVE

This report formulates a systematic methodology that will serve Member States as a tool to decide, in a technically supportable way, what fuel should be considered damaged and thus handled in a non-standard manner. It will:

- Present a methodology for identifying SNF needing non-standard handling, based on the fuel condition, its intended use, available technology and applicable regulations;
- Provide an overview of available technologies for detecting and assessing spent fuel needing non-standard handling, including the advantages and limitations associated with each method, so that an appropriate method of identifying and accommodating damaged fuel can be implemented;

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[2] Similar situations exist regarding other terms such as 'failed fuel' or 'non-standard fuel'.

— Provide guidelines for managing spent fuel needing non-standard handling;
— Provide a basis for evaluating the effects of changes in regulatory and technological constraints.

1.3. SCOPE

The scope of this report is to review part of the back end of the fuel cycle. The methodology provides a general solution that applies to all facets of the spent fuel management system. Each of the stages has its own governing regulations, safety issues and technical limitations that may be applied to determine whether fuel is to be considered as damaged during that stage. Storage (wet and dry) and transport will be considered in detail in this report[3]. The scope of the report also includes all fuel types. Due to different fuel characteristics, the same considerations during the same stage of the fuel cycle may result in some fuel types being considered as damaged while others with similar defects may be considered to be undamaged.

Methods presented for identifying damaged fuel are limited to those that can be exercised either in-reactor or in storage. Once sealed in a cask or canister, few, if any, present methods are available to reliably determine whether, and to what extent, fuel degradation occurs. Determining damage that might occur in a sealed container prior to repository emplacement (i.e. during transport or storage), without opening the container, is beyond the scope of this report.

This report focuses on identifying and addressing SNF requiring non-standard handling. The detection and handling options described in this report[4] are intended for situations where a limited number of rods or assemblies have defects that must be addressed to ensure the fuel will perform its safety, regulatory and operational functions (i.e. ‘damaged’). Two cases are considered. In the first case, the damaged rods or assemblies are intended to be handled in a special manner but carried along with the undamaged fuel. The second case is where a batch of damaged fuel is segregated for treatment using an alternative path.

Some reactor operations decades ago resulted in significant numbers of in-core rods and assemblies incurring defects that classified them as damaged, making them unsuitable for further use. Cases where large fractions of the core are damaged are not within the scope of this report. For example, this report would not apply to cases such as the Three-Mile Island and Chernobyl accidents, where damaged rods and assemblies were the norm, not the exception.

1.4. INTENDED AUDIENCE

This report provides examples of practices related to the management of spent fuel to regulators, spent fuel storage and transport managers, spent fuel storage and transport container designers, and reactor staff responsible for identifying and managing damaged fuel prior to its movement. It may be used to assess impacts and risks associated with a particular regulation or proposed regulatory change (e.g. a requirement that all fuel rods with cladding breaches cannot be put in dry storage). It provides guidance for determining whether fuel with a particular type of defect is acceptable or whether it requires non-standard handling. It facilitates evaluation of the costs and benefits of design concepts or design changes for storage or transport systems (e.g. if a change in design would increase or decrease the amount of fuel classified as damaged). It also helps in selecting appropriate methods for identifying and addressing damaged fuel.

This report is intended to be useful to regulatory bodies trying to determine whether their regulations concerning damaged fuel are technically justifiable, and to utilities trying to determine the best way to identify and handle damaged fuel.

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[3] Because the SNF is deliberately destroyed during reprocessing and allowed to undergo irreversible degradation during disposal, these stages are considered as end points in the nuclear fuel cycle and are not explicitly addressed in the scope of this report.

[4] While no particular method is recommended, readers are informed of the pros and cons of the methods that are available for use. Some of these methods are proven or approved in one country but not in another. Depending on the particular situation, any of the indicated methods may be the ‘best practice’.

2. BACKGROUND

2.1. OVERVIEW

Fuel has historically been designed for optimal performance in the reactor. Due to reactivity events, debris in the primary coolant and lack of control of primary coolant chemistry, defects can occur in the fuel rods, fuel rod cladding and assembly hardware [1]. In the early 1970s, whole cores or significant portions of cores were often affected. Due to continued improvement in fuel design and materials, the rate of defects has declined significantly. Today, 99.99% of rods typically remain unbreached [2]. Breached rods are due to a number of causes but the predominant cause of cladding breach is, currently, fretting wear. A large percentage of the breached rods are removed from the reactors by the fuel manufacturers for study with the intent of reducing subsequent breach events. Similar types of breach modes occur in other types of reactors. For example, in AGR reactors, two modes of pin breach are end cap failures due to over-pressurization and pin/brace interaction (similar to fretting wear). In addition to fuel defects caused in the reactor, faulty materials behaviour such as corrosion and hydriding or mishandling events during the transfer of fuel from the reactor core to the storage pool and within the storage pool may cause defects in the assembly hardware. The causes of fuel defects, and detailed statistics of fuel defects by year and type are given in many review articles [2].

While the defects in the rods and assemblies would preclude reinsertion of the assemblies into the reactor, these rods and hardware are not necessarily damaged for the purposes of post-reactor operations. Currently, there is no internationally accepted definition of ‘damaged fuel’. Decisions are made in each country with no uniform underlying principle for making the determination. This report proposes that the underlying principle for classifying fuel as ‘damaged’ be based on whether or not the defect limits the capability of the fuel to fulfill its function.

Once a determination is made of what constitutes damaged fuel, a variety of methods is available for detecting characteristics relevant to properly identifying damaged fuel. Cladding breaches have historically been the primary cause for classifying a fuel as damaged. These breaches are usually detected via fission product and fuel releases into the primary coolant. Subsequent reactivity pulsing and sipping can usually locate the leaking assembly. Detection of the leaking rods within an assembly is somewhat more difficult, and both false positives and negatives do occur. The variety of methods available includes visual, Eddy current, ultrasonic and gamma scanning among others. Each has its pros and cons. Operations records and visual examination are the primary methods for determining assembly hardware defects. The need to obtain good photographic records and inspection data on the damaged fuel at the earliest opportunity cannot be overemphasized.

‘Damaged’ fuel is handled differently in various countries depending on regulatory requirements, available technologies and the stage of the fuel cycle, i.e. wet storage, dry storage, transport, disposition in a repository or reprocessing. Sometimes the handling method depends on the severity of the defect. For example, in the USA, rods with small pinholes and tight cracks do not receive special treatment but larger breaches have to be put in cans for dry storage. The United Kingdom would not consider leaking fuel rods as damaged fuel unless there was gross damage to the rods. In the Ukraine, this distinction is based on whether the rod can leak gas and whether water can contact the fuel. On the other hand, in Germany, rods with any sort of cladding breach cannot be put in dry storage and are currently left in the pool in canisters.

2.2. LITERATURE SURVEY

The concept of damaged fuel is rooted in reactor operations. In-reactor damage is based on the ability of the fuel to perform as desired. This same claim can also be made for defining fuel as damaged for the back end of the fuel cycle, but instead of irradiation performance, pool or system contamination, handling capabilities, pressurization of containers, criticality and other issues are the driving concerns. Below is a summary of how damaged fuel is identified and managed in various countries.

2.2.1. USA

In 1983, in the absence of design information regarding the repository concept, damaged fuel was defined in US Federal regulations [3] as:

- Visually detectable fuel that cannot be handled normally;
- Radioactive leakage;
- Assemblies that had to be encapsulated for handling purposes (containment).

The definition was vague but rooted in the concept that damage was defined by function.

In 1984, the United States Nuclear Regulatory Commission (US NRC) issued a Director's Decision (DD-84-9) defining rods with breaches greater than pinholes or hairline cracks as damaged [4]. This was in response to a shipment of fuel from the Connecticut Yankee reactor to the Battelle Columbus hot cells where rods with such defects contaminated the cask and the pool during opening due to oxidation of the fuel during transport. Although pinholes and hairline cracks were never defined, this did specify an identifiable characteristic of the fuel that could be used to define damage.

In 1993, E.R. Johnson presented a paper [5] giving a performance-based definition of damaged SNF that moved away from the reactor-based definition: "A failure should be defined with respect to its effect on spent fuel storage and transportation regardless of how the operator may have classified the assembly or rod in question for other purposes." Johnson further broadened the definition of failed assemblies to include those that were structurally deformed to the degree that they were incompatible with storage and transport vehicles.

A 1997 EPRI report [6] extended Johnson's work to distinguish between major and minor assembly and cladding damage, but gave no clear way of translating this distinction into characteristics that could be detected in order to separate damaged and undamaged fuel.

The US NRC issued Interim Staff Guidance-1 (ISG-1) Rev 1 [7] providing a definition of damaged spent fuel based on the functions in storage regulations [8] and transport regulations [9] by specifying certain characteristics of spent fuel that determined whether the fuel or assembly was damaged. There was little allowance for deviation from these defining characteristics even if the system was designed to make the function redundant. Recently, the American National Standards Institute (ANSI) issued a standard for defining damaged fuel for storage and transport [10]. For the most part, the 2005 ANSI guide paralleled ISG-1 [7], and added little new to the definition of damaged fuel.

2.2.2. Germany

In Germany [11], any rod with a cladding breach is considered damaged, as is any assembly with rods removed. In addition, fuel assemblies containing rods with a significantly reduced cladding thickness are only allowed in certain positions in a dry storage basket. This is the only situation or country where rods with potential damage receive special treatment. The damaged rods are stored in sealed capsules in a pool to minimize contamination and by regulation cannot be placed in dry storage. The reason for encapsulations in the pool is contamination control, but no reason is given for the exclusion of the breached rods from dry storage.

2.2.3. United Kingdom

The United Kingdom [12] is the only country to distinguish between failed fuel and damaged fuel. Failed fuel has a cladding breach or an end cap failure, while damaged fuel is a geometric change to the 'as-manufactured' feature that causes a safety or handling issue. This is comparable to the US definition for assembly damage and is rooted in the functionality of the fuel. The United Kingdom has both damaged LWR (structural damage) and a very small quantity of failed AGR fuel (cladding failure). Failed AGR fuel is detected at-reactor and dry packed in hot cell facilities before shipment to Sellafield for reprocessing. Prior to placement in a pond for storage, failed AGR fuel is combined with standard AGR feedstock in a slotted can that is compatible with the THORP processing plant. Additional information can be found in the appendix to this report.

There are also a number of mechanically unsound assemblies in pond storage at Sellafield which require some form of conditioning prior to reprocessing to render them safe to handle and manage through the plant process. A nuclear safety assessment is the first stage in deciding on any remediation technique to be employed and a series of additional guidelines is in use at Sellafield to ensure nuclear safety remains the paramount consideration in handling any non-standard fuel.

A specific example of this was a damaged fuel assembly received with additional structural support in place. It was capable of being handled with existing equipment but was not considered robust enough to be handled through the monitoring regime — instead, a safety case was generated to allow the assembly to bypass the monitor and the fuel was subsequently sheared and reprocessed successfully (see Example 1 in Section 4.2).

2.2.4. Ukraine

Ukraine [13] has “Requirements on Transportation of Radioactive Materials” and “Requirements on Dry Storage of SNF” that require inspection of their RBMK fuel before loading, and prohibit the loading of damaged fuel into a container. The main driver for classifying fuel rods as damaged is the possibility that the fuel will retain water under the cladding after drying and subsequently pressurize the canister and cause breach. Cladding integrity is classified into four groups depending on the ability of the cladding to retain radioisotopes and exclude water. The size of the breach in each category is specified. Mechanical defects to assemblies are categorized into 12 types such as absence of support straps or missing grid spacers. Those assemblies that cannot be handled by normal means are considered damaged. The Ukraine report makes reference to a significant accumulation of mechanically damaged assemblies requiring structural remediation for handling purposes.

2.2.5. Others

Other countries have taken a somewhat more rigid approach towards identifying damaged spent fuel. In Slovenia [13], the integrity of the fuel (PWR) is based on the radioisotope release in the reactor. There is no indication that the function of the cladding in storage is a concern. All failed elements are stored in a pool.

Bulgaria [14] considers a rod failed if it has a sipping indication. Assemblies have structural failure if there is relocation of the grid spacer or the rods are no longer fixed to the bottom end plate. The basis for this definition is not indicated. Damaged fuel is stored in a hermetically sealed pack.

A number of countries using PHWR or CANDU type systems have issues at the back end of the fuel cycle dealing with the behaviour of the fuel during the reactor on-line handling activities. Deformation of the assembly structure can result in binding during unloading. The assemblies are discharged at an elevated temperature into an air atmosphere holding tray. Breaches in the cladding can result in severe fuel oxidation and release of radioactivity. These issues are considered when defining damaged fuel for these reactors in Canada and India [15].

2.3. DEFINITIONS

spent nuclear fuel (SNF). Nuclear fuel that has been irradiated in a reactor. In this report, this term is used to refer to both fuel rods and fuel assemblies;

damaged SNF. Any SNF that requires non-standard handling to demonstrate compliance with applicable safety, regulatory or operational requirements;

defect. Any unintended change in the physical as-built condition of the SNF with the exception of normal effects of irradiation (e.g. elongation due to irradiation growth or assembly bow). Examples include missing rods, broken or missing grids or grid straps (spacers), springs, etc. and gross structural damage, such as sheared tie rods or a missing top nozzle. SNF with a defect is damaged only if it cannot fulfill its intended safety, regulatory or operational functions;

breached spent fuel rod. Spent fuel rod with cladding defects that permit the release of gas from the fuel rod. A breach may be limited to a pinhole breach or hairline crack or may be a gross breach;

pinhole leaks or hairline cracks. Minor cladding defects that will not permit significant release of particulate matter from the spent fuel rod, and therefore present a minimal concern during fuel handling and retrieval operations;

grossly breached SNF rod. A subset of breached rods. A breach in spent-fuel cladding that is larger than a pinhole leak or a hairline crack. An acceptable measure of a gross breach is the visual exposure of the fuel pellet surface through the breached portion of the cladding;

remediation. An action taken to correct a deficiency such that the SNF can be demonstrated to be compliant with requirements;

accommodation. An action taken to modify the safety case so that SNF with a defect or defects can be demonstrated to be compliant with requirements;

non-standard handling. Unique handling steps taken to segregate, remediate or otherwise accommodate fuel that may not meet relevant safety, regulatory and operational requirements if handled in the same way as undamaged fuel from that reactor or reactor site;

standard handling of damaged fuel. Handling steps taken to handle the damaged fuel in the same way as undamaged fuel from that reactor or reactor site;

damaged fuel can. A metal enclosure that is sized to confine one damaged spent fuel assembly. The can must be designed so that all of the following requirements are met: (i) the can, with its contents, is readily retrievable from the storage system using normal spent fuel handling methods (e.g. crane and grapple), (ii) the can, with its contents, is removable as a unit from a storage system, (iii) there is no potential for significant adverse chemical, galvanic or other (e.g. pyrophoric) reactions, and (iv) the can design facilitates draining, drying (if required) and filling with the desired atmosphere. Note that the can may use a mesh screen or slotted walls to achieve gross particulate confinement but still allow water drainage depending on the system related functional requirements;

debris. Any fuel rod or assembly material that cannot be retrieved as part of a fuel assembly.

3. METHODOLOGY FOR MANAGING DAMAGED SNF

This methodology identifies fuels that may require remediations or other accommodations in order to assure safe operations, storage, handling and disposition (i.e. reprocessing or disposal) without imposing unnecessary requirements on fuels that can be safely handled using standard techniques, processes and equipment. Specifically, the methodology identifies SNF with significant defects that disqualify it from being relied upon to perform required functions during the current and remaining phases of its life cycle. Required functions define those properties of the fuel that are relied upon to assure that safety, regulatory and any other operational requirements are met.

The methodology recognizes that the functions and the fuel conditions relevant to determining the fuel’s need for non-standard handling depend upon (i) the applicable regulatory requirements, (ii) the capabilities and controls in place at the host facility, (iii) the fuel’s intended use and (iv) the conditions and scenarios under which the functions must be performed. Because these may change over time, the methodology is sufficiently flexible to allow a fuel to be re-categorized when there are changes to either the fuel condition or the functions that it is being relied upon to perform. Effective implementation of this approach minimizes the quantity of SNF requiring alternative handling while assuring that applicable requirements are met.

The methodology, outlined in Fig. 1, includes three basic steps which correspond to Sections 3.1 through 3.3. Section 3.1 provides the methodology for identifying appropriate performance criteria and the associated fuel properties used for identification of fuels which may require non-standard handling. Techniques for detection and measurement of these fuel characteristics are discussed in Section 3.2. Lastly, Section 3.3 discusses available technologies for addressing these conditions.

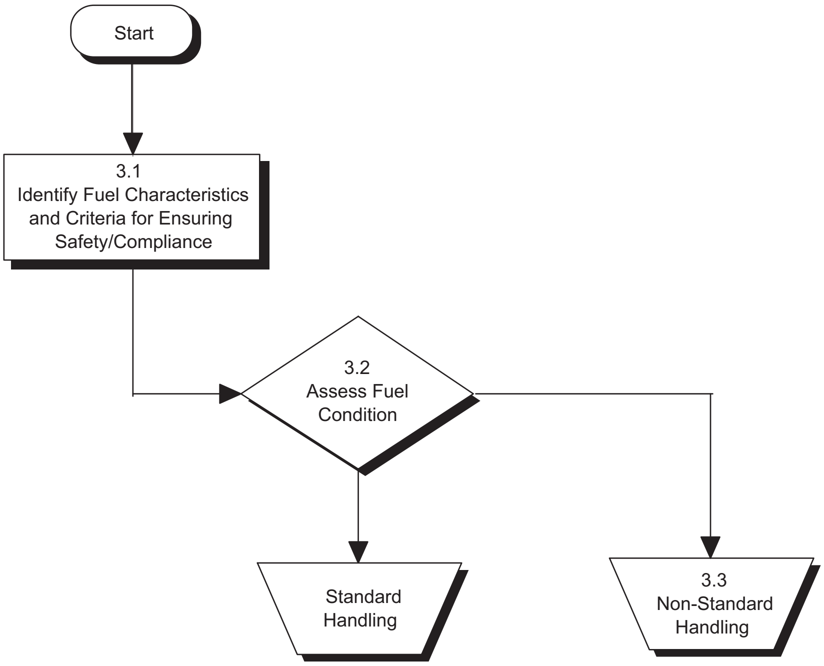

FIG. 1. Methodology for handling damaged fuel.

3.1. IDENTIFY FUEL CHARACTERISTICS AND CRITERIA FOR ENSURING SAFETY/ COMPLIANCE

While major consideration should be given to the present status and planned disposition of the fuel when determining the functions SNF will be relied upon to perform, consideration should also be given to other potential paths that may be encountered in the life cycle of the SNF. As shown in Fig. 2, the basic steps in the life cycle of the fuel include fabrication, operations, wet storage (cooling, interim and/or long term), dry storage (interim and/or long term), transport, reprocessing and disposal. SNF may be stored for various lengths of time, wet and/or dry, and may also be transported one or more times before reaching an end point (i.e. reprocessing or final disposal). The duration and conditions of this storage are relevant to identifying the safety functions allocated to the SNF as are the potential transport and fuel conditioning steps that may occur. For example, in some situations, if the fuel is destined for reprocessing, maintenance of full assembly retrievability may not be important.

Although the methodology focuses on categorizing fuel with respect to the back end of the fuel cycle (Fig. 2), the fabrication and reactor operations phases are shown due to their relevance in providing input related to predicting and evaluating subsequent failure mechanisms.

Figure 3 illustrates the process for identifying the performance criteria to be used as the basis for assuring that SNF will meet its required functions and/or for identifying SNF for which special accommodations must be made.

3.1.1. Principal SNF functions

Performance criteria are identified based on the functions that SNF must perform to meet its safety, regulatory and operational requirements. The principal functions that may be performed by the fuel assembly are:

- Preventing radiological release/exposure in excess of the allowable limit (radiological confinement);
- Maintaining sub-criticality (criticality control);

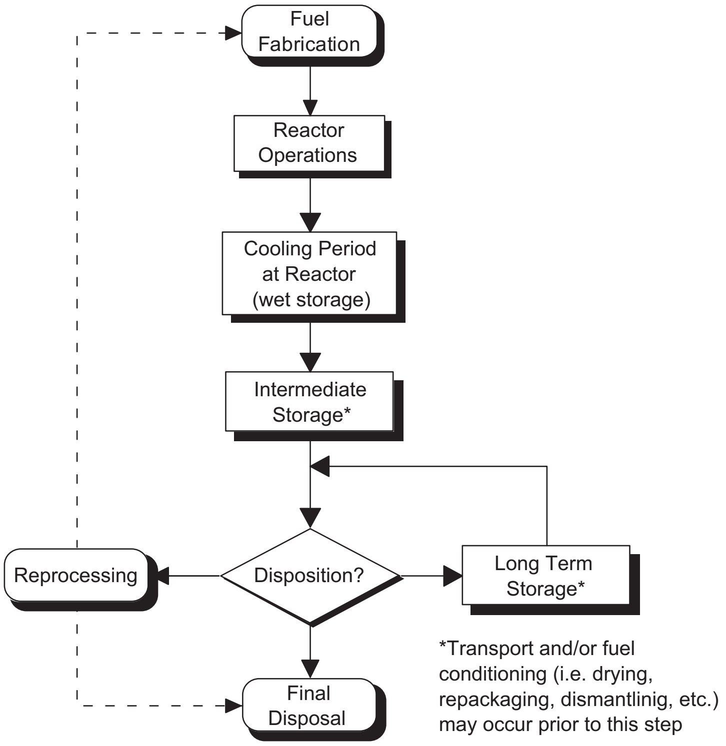

FIG. 2. Life cycle of nuclear fuel.

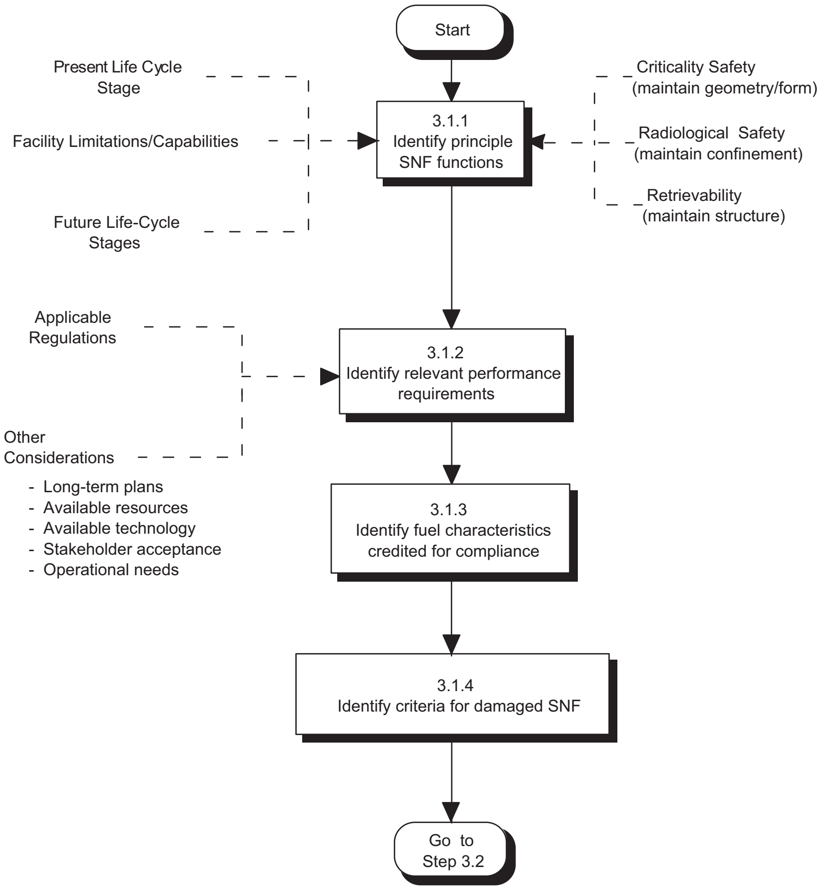

FIG. 3. Identifying criteria for segregating damaged SNF.

— Facilitating safe retrieval of the fuel using standard tools and techniques (retrievability);
— Maintaining radiological dose within analysed safety envelope (dose considerations);
— Assuring adequate rate of decay heat removal[5].

Because these functions require maintaining the structural form and/or integrity of the SNF, deficiencies can often be mitigated by reducing the demands placed upon its structural form and integrity. Similarly, deficiencies may be repaired and/or corrected by implementing appropriate design solutions that assure form and integrity are maintained (e.g. structural re-enforcement, confinement barrier, etc.).

Maintenance of radiological dose/shielding is included above as a safety function of the fuel because fuel geometry is an input to shielding calculations. However, it is not carried as a separate function throughout the remainder of this report because any shielding provided by the fuel is not typically credited for safety and also because any loss of fuel structural integrity and/or geometry will be addressed as part of the criticality safety and retrievability functions.

3.1.2. Relevant performance requirements

Specific SNF performance requirements are then identified for each of the functions identified in the previous step. These performance requirements are tailored to the relevant conditions, operational considerations and regulatory requirements applicable to the fuel being evaluated.

For identifying the SNF performance requirements, use of a table similar to Table 1 is suggested. The principal safety, regulatory and operational functions performed by the fuel form the column headers. A row is included for each of the life cycle stages within which the functions must be performed. This grid provides a framework for confirming that the fuel will perform each of its required functions during the current and remaining stages of its life cycle.

The table structure is tailored to the SNF being evaluated by adding and/or deleting rows and columns as needed to represent, respectively, the life cycle stages and the applicable functions that apply to the SNF. The table cells are then populated with the specific functions that must be performed by the fuel to assure that requirements will be met during each of the identified life cycle stages. The summation of each column provides all of the performance requirements associated with each principal function. An example of the use of this table is given in Section 4.

Although there are typically relatively few functions that must be performed by the fuel (i.e. a great deal of redundancy between the rows of the table), the table provides a rigorous and systematic method for considering fuel performance requirements. Using the table may also aid in consolidating functional requirements to the minimum set that achieves the objectives.

TABLE 1. EXAMPLE OF A TABLE FOR IDENTIFYING SNF PERFORMANCE REQUIREMENTS

	Maintain radiological confinement	Maintain structural form/integrity	
		Criticality safety	Retrievability/handling
Storage (cooling)			
Intermediate storage			
Transport			
Long term storage			
Final disposition			

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[5] While the ability to adequately remove decay heat is a requirement of the system, it is a function that is required in order to meet the other four functions of the system. It is included in this list to be consistent with IAEA Safety Standards Series No. NS-G-2.5, “Core Management and Fuel Handling for Nuclear Power Plants”. It is not a function that is analysed further in this report.

The applicable regulatory requirements form the basis of performance criteria such as radiological release limits, criticality safety margins, etc. The intended disposition path, facility capabilities and other operational considerations are the key to establishing criteria associated with equipment compatibility, facility maintenance, ALARA and other operational objectives. Uncertainty associated with each of the above should be considered when establishing the performance requirements and associated criteria.

The degree to which radiological confinement and structural integrity must be maintained by the fuel is dependent upon the engineered barriers and the capabilities of the host facility (i.e. secondary packaging, filtration systems, geological barriers, etc.) as well as the governing regulations. As a result, the specific criteria associated with satisfactorily performing these two functions can be tailored to the specific facility, the applicable phase(s) of the life cycle and the governing regulatory regime.

3.1.3. Fuel characteristics credited for compliance

The objective of this step is to translate the identified performance requirements into specific fuel properties and/or other parameters that must be verified and maintained. In order to identify those assemblies that have defects and will be categorized as damaged, the performance requirements must be translated into a concrete set of fuel characteristics. These properties are typically those associated with maintaining the mechanical and chemical stability of the fuel, the cladding or other credited barrier, and any fixtures or handling devices needed to support operations. They may also include properties such as the fissile or moderator content. Examples of fuel properties affecting handling and contamination control might be cladding breach size and fracture toughness of the cladding. Stability of the assembly might be governed by missing components, fractured rods or storage conditions. When the property cannot be sufficiently maintained or verified, it is considered to have a defect. The significance of this defect determines whether or not a non-standard handling technique is needed.

3.1.4. Rejection criteria for damaged SNF

With an understanding of the relevant degradation mechanisms, one can establish the specific characteristics and associated criteria that will assure performance requirements are met. These may include: (i) conditions on the fuel itself such as cladding integrity, decay heat, enrichment, burnup, fuel and cladding constituents, etc; and (ii) conditions relative to the storage environment such as temperature, pressure and other environmental conditions that may allow oxidation, embrittlement or other mechanisms that could adversely impact credited characteristics.

These characteristics and criteria are used to reliably identify fuels that require non-standard handling techniques in order to ensure that specified safety, operational and regulatory requirements are met.

3.2. ASSESS FUEL CONDITION/DAMAGED FUEL DETECTION

Dependent on the criteria for damaged fuel, defined in Section 3.1, detection techniques can be chosen from Table 2 below. The detection techniques have to determine the physical data to quantitatively characterize the damage and, thus, allow assessing the damage condition of the SNF. Figure 4 outlines the assessment process for identifying fuels requiring non-standard handling.

The assessment process may start with one or several detection techniques. If it turns out that the result is not conclusive, a further technique may be used to improve the data base.

The extent to which the operator pursues detection techniques and related actions is influenced by likely handling options. Site specific actions will not result from rote compliance with steps described in this report, but will depend on a sequence of decisions that depend on circumstances specific to a particular country and facility.

3.2.1. Detection techniques

Table 2 gives a summary of detection techniques that are used in LWRs, HWRs and AGRs to detect and examine fuel failures. These techniques are usually available and can be used to serve as detection techniques to assess the condition of the damaged fuel.

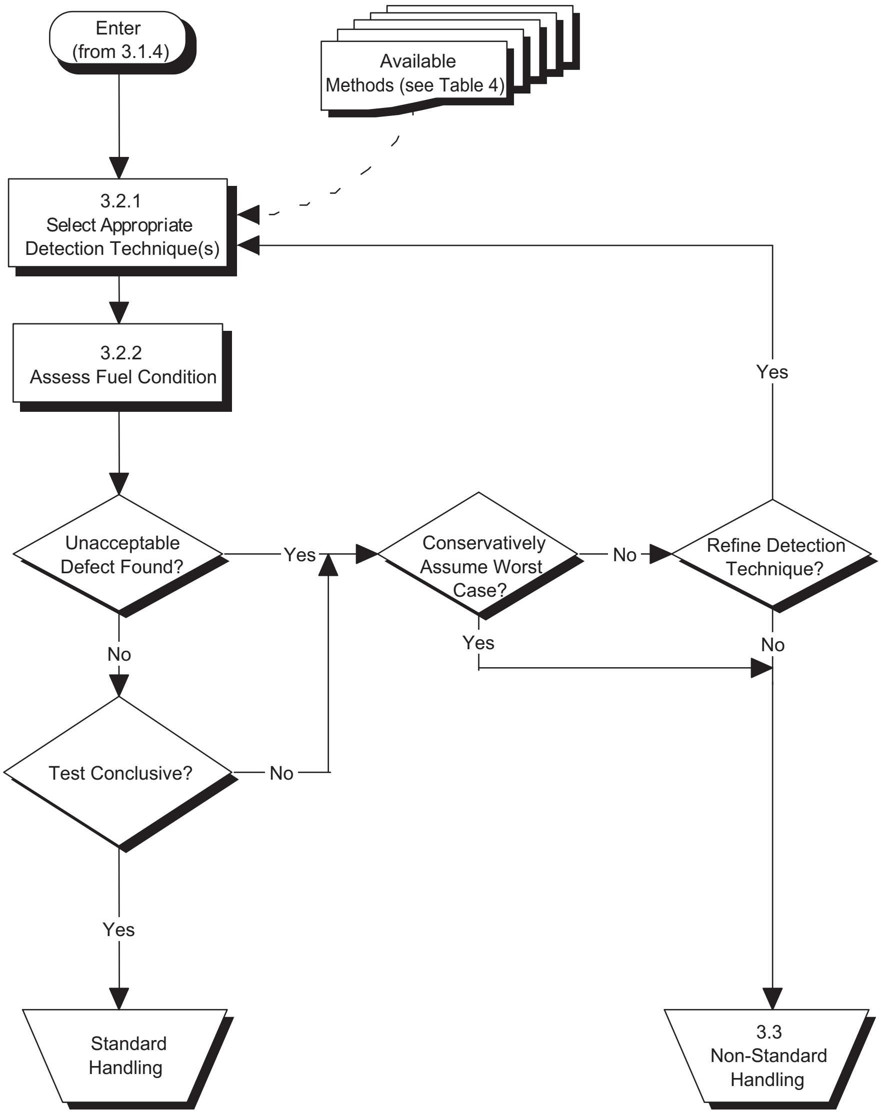


FIG. 4. Detecting damaged fuel.

The techniques were primarily devised to detect and characterize cladding failures. To detect structural damage, there are only a few techniques available, such as visual inspection or fuel assembly proof load tests with a loading machine.

3.2.1.1. Fuel rod cladding failure

Evaluation of coolant activity in operating plants, so-called on/off-line monitoring, allows leaking fuel to be detected. Monitoring the activity of selected fission product isotopes in the off-gas system or the primary coolant provides information on the onset of failure, approximate number and type of failure, and approximate burnup of failed fuel. Due to demanding operating conditions, on/off-line monitoring is a highly sensitive technique for failure detection. The downside of such a system is its limited ability to identify individual fuel assemblies with leakers. At most, a certain group or type of fuel assemblies can be identified.

In addition to the on/off-line systems, most reactors have sipping systems associated with de-fueling in the main mast of the fuel handling machine and in-pool operations to detect leaking fuel assemblies. In a PWR (including WWERs), sipping can be done routinely during unloading assembly and a qualitative test takes an additional minute or two [16]. A disadvantage is that a qualitative test takes about 30 min per assembly and 3–6 h if done in the storage pool [17]. It is very time consuming to inspect the great number of fuel assemblies that

TABLE 2. SUMMARY OF DETECTION TECHNIQUES

Detection technique	Fuel type	Measured characteristic	Location	Comments
On-line monitoring	LWR PHWR	Fission products (FP) activity	Core	Only records for cycle before fuel removal are relevant; Only useful if further examination is accessible to locate the leaking assembly; Tight or open in nature leaks; Fuel rod burnup estimation from $^{134/137}Cs$ ratio
Off-line monitoring	LWR PHWR	FP and transuranic elements	Core	Primary coolant water sampling; Lower detection limit than on-line monitoring; See on-line monitoring + serious damage of fuel rod cladding
		Sipping by AREVA NP — one fuel assembly		
On-line	LWR	On-line ^{133}Xe activity	Main mast of the fuel handling machine	Qualitative test; Change in hydrostatic pressure; Until two months after shutdown of the reactor
Off-line	LWR	On-line ^{133}Xe activity gas sample — ^{133}Xe water sample — FP	Storage pool	Qualitative test; Auxiliary heating is applied; Until two months after shutdown of the reactor
		On-line ^{85}Kr activity gas sample — ^{85}Kr water sample — FP		Qualitative test; Auxiliary heating is applied; Until ten years after unloading from the reactor
		On-line ^{133}Xe activity gas samples — ^{133}Xe water samples — FP		Quantitative test; Auxiliary heating is applied; Until two months after shutdown of the reactor
Leaching test	RBMK LWR AGR	Neptunium and caesium activity	Storage pool	
Visual inspection	LWR PHWR	Defects on visible surfaces; Gross deformation; Fuel assembly bow and twist measurements	Storage pool	1: Good for structural damage; 2: Limited use for detecting cladding breaches
Ultrasonic examination	LWR	Water in the rod	Storage pool	Proven technique; 99% effective; All rods examined at once
Eddy current testing	LWR	Cracks; Oxide layer thickness	Storage pool	Assembly must be dismantled (oxide layer — the peripheral rods can be measured without dismantling)
Eddy current testing — rod control cluster assembly	LWR	Surface defects	Storage pool	Good for control rod surface damage

TABLE 2. SUMMARY OF DETECTION TECHNIQUES (cont.)

Detection technique	Fuel type	Measured characteristic	Location	Comments
Profilometry	LWR	Diameter changes due to local corrosion or hydration; Oxide layer thickness	Storage pool	Assembly must be dismantled
F/A proof load test	LWR	Structural integrity	Storage pool	To exert a force at a lifting rate and a total force greater than expected in handling to see whether the F/A stays intact
Electrostatic precipitator, also known as Burst Cartridge Detection (BCD)	AGR	β activity arising from daughter products of Kr and Xe electrostatically precipitated from gas samples from each reactor fuel channel	Core	If the general activity in the circuit is found to be high, a search is made channel by channel using a trolley mounted precipitator
Gamma spectrometry of (GAM)	AGR	Gas composition	Core	Provides sensitive detection of fuel failure but not location

are stored in such a system. In BWRs, partial sipping is common, especially in combination with a previous flux-tilt to define a narrow area in the core where the leaking fuel is located. Fuel failure detection by sipping is based on the release of gaseous fission products from the leaking rod. A finite amount of gas is released from the pellets to the rod plenum during irradiation. Most of this gas is released when breach occurs. The remaining gas will slowly diffuse from the rod. The longer the duration between rod break and sipping, the less gas is available for detection and the less accurate the method. A ‘sipping in pool’ system by AREVA NP is designed with electrical heaters to open the breach and stimulate the fission product release of cooled-down fuel stored for several years [16]. An improved sipping device called NIFSIL makes use of the caesium absorption properties of potassium nickel ferrocyanide incorporated in a water insoluble gel. To survey all fuel assemblies in a container, sorbent containing detectors can be placed on top of every fuel assembly in the pool and analysed for caesium by gamma spectroscopy. The system accelerates the detection of leakers. Additional information on sipping can be found in Ref. [16].

In the United Kingdom, any cracks or pinholes in the cladding material of the uranium metal rod must be detected at an early stage so that the fuel element may be removed and prevent contamination of the gas circuit by fission products. A range of equipment is provided for detecting, locating and monitoring failed fuel. The main systems provided for this function are:

- The electrostatic precipitator system: Makes use of the fact that a high proportion of fission products are gaseous isotopes of the noble gases krypton and xenon which in time decay to active solid daughter products. The system works by sampling gas from each fuel channel outlet and precipitating the daughters onto an electrode which is then moved to a scintillation counter to measure the beta activity on the wire. In AGR reactors, if the general activity in the circuit is found to be high, a search is made channel by channel using a trolley mounted precipitator;
- The reactor gas activity monitoring system: Uses a gamma spectrometer sample reactor gas selected from any one quadrant outlet for each reactor. The flow of gas is monitored and deviations alarmed. It provides a sensitive detection of fuel failure but does not locate the failure.

Visual inspection of the fuel assembly may be used to assess its degree of damage in more detail. If the damage is located inside the fuel assembly, the assembly may be disassembled to inspect single fuel rods. If fuel assemblies cannot be dismantled, the amount of damage can only be analysed indirectly, for instance, by leaching tests. Visual inspection is a technique for detecting the presence of gross defects on the outside of the cladding on outer row rods (for a 17 × 17 PWR assembly, this is ~18% of the rod surface) or on structural parts of the fuel assembly. Very small defects cannot be easily detected with this technique. Defects in modern fuel tend to occur by fretting wear and occur near or under the grid spacers where they are difficult to detect visually. Visual examination of the outer surface of an assembly is insufficient to determine whether an assembly contains cladding breaches.

Further details on the location of damaged fuel rods can be obtained by ultrasonic inspection (UT), which detects liquid water in a fuel rod. While not foolproof, the technique tends to give few false readings and will not indicate an unbreached rod as breached. Errors are usually caused by closure of the breach site as the internal rod gas pressure is vented prior to the ingress of water. Advantages of this technique are that the assembly does not have to be dismantled, individual breached rods can be detected and whole rows of fuel rods can be examined simultaneously. This method will not locate a breach site on a rod.

Eddy current (EC) techniques allow the axial location of a defect to be determined. The technique is very sensitive and can also be used to detect non-penetrating cracks. Oxide thickness measurements determine the thickness of the oxide on cladding as well as on structural parts, such as spacer grids or guide tubes.

Profilometry measures the axial diameter profile of a rod in order to check for volumetric effects due to fuel oxidation or hydrating of the Zircaloy cladding. Only gross defects can be detected and the assembly may have to be disassembled. Defect testing, oxide layer determination and profilometry are techniques that allow assessing the operational behaviour of the material and, thus, its degradation.

On/off-line monitoring, sipping, leaching tests and ultrasonic testing are tests that detect the confinement of the fuel. The tests are performed on whole fuel elements and can be used to pre-select fuel for further examination. To obtain information on single fuel rods or on the condition of the fuel structure inside the fuel assembly, the element has to be opened and then the rods can be examined in detail by EC testing or visual inspection.

It has to be noted that all techniques are primarily suited to detecting and describing the current condition of a fuel assembly and whether it fulfills current safety aspects. The amount of work to measure its condition can be very high, especially, if it has to be opened and single rods measured. More details on variations of these breach identification techniques can be found in Refs [16, 18].

3.2.1.2. Fuel assembly mechanical damage

Fuel assemblies may have mechanical damage of individual structural components, such as spacer grids, tie plates or guide tubes, up to gross geometrical deformations including bow or twist of the whole assembly structure. Structural damage can be mostly detected by visual examination or by geometrical constraints occurring during handling of the fuel assemblies. Any damage occurring during handling activities should have associated documentary and/or photographic records associated with the event.

PWR top nozzle stress corrosion cracking susceptibility is one form of assembly defect. The issue of PWR top nozzle susceptibility to corrosion was first raised in 1981 during fuel handling operations in the Prairie Island Unit 1 fuel pond when a PWR top nozzle became detached from the remainder of the assembly resulting in the fuel being dropped. The event was attributed to inter-granular stress corrosion cracking at the site of the nozzle to guide tube joint. PWR fuel of similar design (i.e. with stainless steel bulge joint) stored at Sellafield was thus monitored for corrosion at regular intervals until the time of reprocessing. Three schemes were developed for dealing with the following potential scenarios: reinforcement of suspect top nozzles; recovery of an assembly with a detached nozzle; recovery of a dropped assembly following nozzle separation. However, as repeated visual inspection did not indicate a corrosion problem, the fuel was reprocessed without the need for any intervention or recovery. The French have also had experience with this issue and opted to structurally reinforce the assemblies.

3.2.2. Fuel condition assessment

Using an appropriate detection technique, the fuel characteristics of interest are measured against the criteria identified in Section 3.1. If no unacceptable defects are found and the test is considered sufficiently accurate to be conclusive, the fuel may be considered as undamaged. If unacceptable defects are found, one may conservatively assume worst case conditions and proceed with selection of an appropriate technique to remedy the condition. This is illustrated in Example 3 (Section 4.2.3). Alternatively, one may refine the detection technique in order to better inform the selection.

3.3. NON-STANDARD HANDLING

Once the criteria for defining damaged fuel have been established for a particular fuel type and/or reactor and/or storage regime using the guidance in Section 3.1, and any damaged fuel has been identified using one of the methods described in Section 3.2, an appropriate handling method must be identified and implemented. The handling method will depend on the safety or operational function that is, or has the potential to be, compromised by the defect in the fuel or assembly and the severity of the defect.

The back end of the open fuel cycle has any or all of the four components: wet storage, dry storage, transport and disposal. For example, the Swedish concept does not include dry storage. The first three components will be considered; disposal is outside the scope of this study. Steps to handle the damaged spent fuel during storage and transport are still needed.

Although applicable regulations vary from country to country, they are typically derived from either safety or operational functions. As noted previously, the principal functions are:

- Preventing radiological release/exposure in excess of allowable limit (radiological confinement);
- Maintaining sub-criticality (criticality control);
- Retrievability (operations);
- Maintaining radiological dose with safety envelope (dose considerations).

These functions are also used in the selection of non-standard handling techniques.

The characteristics of the defects will be identified when the fuel is examined to isolate the defective fuel (see Section 3.2). There can be defects in the fuel cladding and/or the fuel assembly structure. The defects will be dependent upon the specific characteristics of the fuel but can generally be classified into the two broad groups given below:

- Rod/plate cladding defects:

    - Unconfirmed material properties or conditions;
    - Debris;
    - Missing rods or pieces of rods;
    - Gross breaches;
    - Small holes.

- Fuel assembly structure defects:

    - Unconfirmed material properties or condition;
    - Debris;
    - Missing components;
    - Gross deformation.

‘Unconfirmed materials properties or condition’ means that the materials properties or the condition of some component such as the cladding ductility or nozzle corrosion are not available to enable the calculations necessary to determine whether functions can be met. Although this in itself is not a defect, the availability of necessary data and baseline conditions must be considered when choosing a handling technique. ‘Debris’ is defined as all fuel rod or assembly material that cannot be retrieved as part of a fuel assembly. This may be rod parts, fuel particulate, hardware parts, etc. The debris in itself will cause problems that must be addressed, usually with respect to retrievability. It may also cause other issues to arise due to the fact that it may create a weakness in the assembly. The other types of defects are self explanatory.

There are two situations to consider when selecting the path forward. The first is when there is a damaged fuel that one would like to handle, with some accommodation or remediation, along with the remainder of the undamaged assemblies (e.g. a single breached rod in one assembly out of many assemblies to be loaded into the storage facility). The second occurs when damaged fuel elements and/or assemblies have been accumulated over time, and the need arises to handle this damaged fuel as a batch. An example would be when isolated breached rods have been replaced with dummy rods in an assembly and the breached rods have been collected in a storage can.

3.3.1. Methods for non-standard handling

Proven methods in this text are related to several methods used in non-standard handling. A number of methods have been suggested to accommodate damaged fuel at the back end of the fuel cycle. Some are proven and in use today; others are obvious but have not been put into practice. In the following sections, each method will be discussed, addressing, where applicable, to what types of defects, how it solves the problem, advantages and disadvantages, and examples of current use. Relevant appendix references include papers given at the 2005 IAEA technical meeting on this topic. Shortened references to these methods are shown in parentheses in the following section titles for subsequent use (i.e. in Tables 4–7).

3.3.1.1. Change storage conditions (SC)

Storage parameters are controlled and associated limits are set for each stage of the fuel cycle. These include pond water quality, maximum and minimum temperature, gaseous atmosphere composition and pressure, radiation field, fuel cooling time and humidity. In addition, facility modifications can include modifications to tools and handling fixtures. Fuel and assembly components would be considered damaged if they are unable to meet, or unable to confirm that they will meet, their required safety and operational functions in the applicable storage environment. However, the storage environment can be altered to accommodate fuel conditions. For example, a fuel rod that has a very small hole that might oxidize and disperse particulate in a high temperature oxidizing atmosphere would be classified as damaged. Yet it might be considered undamaged if the maximum temperature limit was lowered or an inert atmosphere was used.

Modifying the environmental conditions may not make sense when there are only a few rods identified as damaged. On the other hand, if many fuel elements were segregated because the standard environmental conditions resulted in their being classified as damaged, a change in environmental conditions for these segregated rods may allow them to be treated by normal methods as undamaged. This methodology is particularly useful during the dry storage stage when fuel cladding may be breached or split.

3.3.1.2. Moderator exclusion (ModEx)

Moderator exclusion prevents criticality by excluding moderator from a potentially critical fuel array configuration. It is a method for accommodating fuels during storage or transport when there is the potential for criticality if moderated, or when the absence of this potential cannot be confirmed.

Cask systems are usually designed to assure criticality safety even under fully flooded conditions. Transport regulations (e.g. in the USA) require consideration of moderation to the most reactive credible extent for criticality safety. Under normal conditions of transport, a single package must be critically safe with water in the containment system. For accident conditions, a single package must be critically safe in its most reactive credible configuration and with moderation by water to the most reactive credible extent. Criticality safety can be difficult to assess for fuel with certain defects, especially if they can lead to an uncertain fuel reconfiguration after an accident. Although the non-mechanistic assumption of flooding assures a margin of safety if a cask containing undamaged fuel were to flood during an accident, it may not be the case when fuel structural integrity is not credited for maintaining geometry. By physically precluding the possibility of moderator intrusion into the package, relief from the assumption of flooding may be available. For example, Ref. [19] states:

> “For a package in isolation, it shall be assumed that water can leak into or out of all void spaces of the package, including those within the containment system. However, if the design incorporates special

features to prevent such leakage of water into or out of certain void spaces, even as a result of error, absence of leakage may be assumed in respect of those void spaces."

Assemblies may have defects that cause them to be in a configuration that could become critical if water entered the cask. In this case, these assemblies would be considered damaged. Such defects might be a grossly deformed assembly, an assembly with missing components, or assemblies that have had rods removed due to a breach in the reactor or some other cause. Exclusion of moderator might allow these assembly and rod conditions to remain subcritical and thus be considered undamaged for storage and shipment.

Currently, moderator exclusion is not a licensed method in the USA, although at least one applicant has indicated that they intend to submit an application for a design that credits moderator exclusion for assuring criticality safety during transport. The authors are unaware of moderator exclusion being used anywhere in the world. The acceptability of moderator exclusion is based largely on the ability to demonstrate that water is precluded from the fuel cavity under all credible scenarios.

3.3.1.3. Poison addition (Poison)

When the defect jeopardizes the ability to assure subcriticality, adding poisons to the system is another method for addressing criticality safety. This might be the situation with rods missing from the lattice, deformation of the assembly structure, missing assembly parts that could jeopardize assembly configuration during an accident or the inability to analyse the expected behaviour of an assembly with a defect due to the unavailability of required materials data.

Poisons can be in the form of rods within the guide tubes, walls in the basket, a higher density of ^{10}B within the basket structure or the addition of soluble poison that goes into solution when a moderator is put in the system. The solid absorbers have the advantage of being easy to emplace but the disadvantage of not mixing uniformly with the damaged fuel in the case of an accident. Since most fuel loading is done underwater, soluble poisons have an emplacement problem. To date, no country has used the addition of poisons as a means to assure criticality safety of damaged fuel.

3.3.1.4. Rod replacement (RodRep)

Defects in fuel assemblies can include fuel rods with cladding breaches as well as fuel rods that have fallen or been removed from the assembly. A number of countries would classify these assemblies as damaged due to contamination control (e.g. Germany) or potential criticality issues (e.g. USA). A plant safety assessment produced at Sellafield demonstrates that assemblies that have had rods removed can be considered bounded by the reactivity of a complete assembly and will not pose a criticality hazard.

Rod replacement can be used if single rods of a fuel assembly are damaged and, hence, violate safety functions. Such a technique can be applied to all fuel assembly types that can be repaired by removing the top or bottom tie plate. It allows handling a wide spectrum of rod defects. Many facilities have the capability to remove selected rods from assemblies.

Removal of the damaged rods for treatment by a different handling method and replacement of the damaged rods by steel rods would render the assembly undamaged. Rod replacement is a means to separate spent fuel into fuel assemblies that can be classified intact and rods or pieces of rods that are clearly defect. The unirradiated steel rods would not affect the structural stability of a PWR assembly and would improve the structural stability of the BWR assembly if the defective rods scheduled for replacement are in the tie-rod positions. Both radiation and thermal loads in the cask would be lessened.

Considerations when choosing this handling technique would be the time required in the pool and dose taken by personnel due to the reconstitution, as well as the remaining need to deal with the breached or fractured rods by another handling means. Whereas rods with small breaches can be easily removed as one unit, broken rods require more elaborate techniques for rod fragment retrieval. Earlier PWR assembly designs practically precluded this handling method since the end bells were welded to the guide tubes. Newer assembly designs are bolted and more amenable to the technique. An important premise for rod replacement is that the storage situation after such an action is better than before. For instance, if all damaged rods have to be removed from a fuel assembly for storage and if handling options are available for those rod remnants, rod replacement can be a viable option. If low defect levels can be classified intact or if fuel assembly canning (see below) can be generally applied, rod replacement becomes unattractive.

3.3.1.5. Canning (Can)

Canning is the most widely accepted means of handling damaged fuel. It can be used for SNF that has difficulty meeting criticality, confinement and operational functions. When an assembly is placed in a can, one or more of the above functions (depending on the type of can) is assumed by the can instead of the assembly. The can confines the fuel to a known volume within the storage or transport cask. In accordance with its design, it may provide a barrier to limit and/or prevent radiological release and/or moderator intrusion. Use of a standardized can may also simplify required tools and procedures, and facilitate handling operations. Canning is also used to isolate and handle fuel that has incurred structural damage due to a drop event.

The can should be designed with the necessary fixtures so that the can, with the damaged assembly inside, could be easily retrieved using normal means (e.g. grapple and crane). Cans may be constructed in many sizes to contain anywhere from a fuel assembly to a number of damaged rods removed from a fuel assembly. If a can is used for a single rod, it can assume the functions of the cladding. Canning can have drawbacks. Cans used to hold a full fuel assembly may require modification of the basket to accommodate the can. Canned fuel is often only allowed in a limited number of basket sites in a cask.

Canning in some form is used by many countries for accommodating damaged fuel. Canning is used in India for CANDU type fuel [16]. Failed but mechanically intact WWER fuel is stored in hermetically sealed containers in Bulgaria until it is sent for processing [15]. Hungary stores its damaged fuel in unsealed canisters in a pool to allow for the venting of radiolytic gases (Cserhati, Appendix II). Damaged fuel is stored in vented cans in Lithuania prior to storage and transport (Poskas, Appendix II). In the United Kingdom, AGR failed fuel is put in a dry bottle prior to being stored in a pool [12] (Callaghan, Appendix II). In the USA, canning is the suggested remediation for damaged fuel [7] and utilities are allowed to load canned assemblies in specified and limited slots in a cask. In some countries, such as Germany, canning of damaged fuel is currently a regulatory requirement (Hoffmann, Appendix II).

Cans may be either hermetically sealed or welded to contain all radioactive material or open but capped in a manner to contain most of the fuel particulate. Depending on the type of can used, confinement can also be achieved. In addition to the functions that the can is to perform, the choice of a vented versus a sealed canister should consider the time, dose and expense of vacuum drying, and the additional time, cost and space requirements of a sealed can. The issues associated with sealed and vented cans are summarized below. These cans should have lifting features that can be handled with existing grabs, grapples, etc., unless future handling at another facility is anticipated.

Sealed can

As indicated above, many countries require that their damaged fuel and assemblies be placed in hermetically sealed canisters either individually or several together. The sealed cans are usually used when contamination control in the pool or cask is desired. The design must provide mechanisms to seal the can, evacuate the can and dry the fuel in the can to prevent the generation of radiolytically generated gases. Design features to seal and drain the cans typically require additional space and possibly new racks in the pool or baskets in the cask. Long term issues with the use of sealed cans include the failure of weld or seals requiring either re-packaging or dealing with the effects of either water or air in the can. This can result in potential new safety issues that must be considered such as fuel oxidation or corrosion and build up of radiolytically generated gases.

Since the criteria for drying a cask were developed with pressure buildup and gas generation in mind, the same criteria for drying a cask should hold for drying a can. The can is drained, allowed to heat up to evaporate the water, and then vacuum dried to remove the water vapor. When the specified pressure in the can is held for the specified time limit with the pump isolated, the drying is done. In the USA, dryness of vacuum-dried LWR fuel is demonstrated by maintaining 4×10^{-4} MPa for 30 min with the vacuum pump isolated [20].

Normally, vacuum drying of a canister is conducted using the decay heat from the contents of the canister. In a can holding a small quantity of fuel or a fuel with a low decay heat output, supplemental heating may need to be applied. Additionally, factors such as the fuel configuration and the potential for water or other sources of hydrogen gas to be entrained with the canister contents should be considered when establishing drying times and temperatures as well as test times and pressures for acceptance criteria.

Open or vented can

Some countries, such as Hungary, allow or even require vented canisters to be used in order to release any radiolytic gases that are generated. In other countries, where confinement of the fuel to a known location for criticality control or for operational handling purposes are the only concerns, a vented can is allowed. This can be as simple as a mesh screen fastened over the top and bottom of the can. An advantage of a vented can is that it allows easy draining of any water and eliminates the need for a canister vacuum drying system. In the United Kingdom, these are called slotted cans and are configured to be compatible with handling at the reprocessing facility.

3.3.1.6. Water filtration (Water)

Filtration is the process of removing radioisotopes from the wet storage facility water before they can provide a dose to the workers or come to the water surface where they can be released to the atmosphere and, thus, become uncontained. It is only applicable to wet storage where there is a medium to filter. It can be used to reduce the impact for any type of defect in the rods or cladding that allows radioisotopes to enter the water (crud is not a defect so there is no reason to exclude it) to an acceptable level.

Types of defects that might release radioisotopes into the water are debris, missing rod pieces, gross breaches, and small pinhole leaks and tight cracks. Although rare (failure rates of 0.01% in LWR fuel), small pinhole breaches and tight cracks do occur in-reactor. Sometimes the assembly containing the leaking rod is identified and sometimes it is not. If an assembly containing this type of defect is placed in wet storage, the majority of the isotopes released will be soluble iodine, caesium, etc., along with some fission gas. Since this type of defect does not release fuel to the system, actinides are not an issue. However, designing a system with sufficient capacity to handle a large quantity of radioisotopes, especially actinides released from the debris, missing rods or gross breaches may present engineering challenges that need to be assessed, especially if a large quantity of fuel is expected to have this type of damage.

3.3.1.7. Off-gas filtration (Gas)

Ventilation is used in parallel to water filtration but is used for the filtration of a gaseous medium. Ventilation systems are routinely put on large hot vaults to maintain radiological confinement, such as the hot fuel examination facility in Idaho. The filters are intended to trap respirable particulate and certain volatiles such as iodine, etc. Damaged fuel might tax the capacity of these systems if not specifically designed for the applicable service conditions. It would not be a good solution for either dry storage or transport casks where most countries require a sealed container. It might be useful in a vault type storage unit where the ventilation system could be installed on the complete vault air system.

3.3.1.8. Tailored cask shielding (Shield)

Tailored shielding is a method to accommodate fuel during storage and transport that has damage from debris, gross rod breaches, gross assembly deformation or unconfirmed properties. Most systems are built with shielding designed to hold intact fuel and assemblies. When there are defects that result in the relocation of the fuel, there is the potential that the shielding will be locally inadequate within a cask. As a result, the addition of locally placed shielding might be required to meet the radiological dose considerations. When additional shielding is contemplated, factors such as attachment to the cask, additional weight, positioning of the shielding (inside or outside) and type of radiation (usually neutrons or gamma) to be shielded must be considered. To date, no country indicates use of tailored shielding as a remediation method for handling damaged fuel.

3.3.1.9. Replace and/or repair damaged structural fuel assembly components (StrucRep)

The ability of a fuel assembly to meet its functional requirements can be enhanced by replacing the components that contain defects. Germany [11] (Goll, Appendix II) considers damaged grid spacers, spacer springs, vanes on grid spacers and tie-plates to be replaceable parts. This is a viable solution when the damaged part jeopardizes the stability of the assembly, such as its ability to maintain configuration for criticality control or continue to be retrievable by normal means (grapple and crane). The cost in time, money and dose must be considered in relation to other potential handling solutions when deciding to replace assembly parts with defects. After remediation, the damaged parts that are removed must still be dealt with. In many instances, these parts are not fueled and can be dealt with by simpler means. This technique for dismantling LWR fuel could also be used to remove damaged parts of a fuel assembly.

3.3.1.10. Hydrogen getters (Hget)

Spent fuel that is retrieved from basin storage may contain residual amounts of water unless dried rigorously. The residual water might be physically adsorbed (as layers of molecular water) to the exposed surfaces of the fuel assemblies and structural components, or might exist as chemisorbed water in the oxides at the surfaces of exposed metal, crud or exposed fuel.

When thorough dehydration of the fuel is not feasible (either by using the intrinsic decay heat of the fuel or by application of an external heat source) or cannot be verified, the use of hydrogen scavengers may be an option. Several types of hydrogen scavengers are obtainable (e.g. hydrogen recombination agents, organic hydrogen getters, metal alloys), each with unique advantages and disadvantages.

The United Kingdom has extensive experience using re-combiners for transport and storage of intact fuel where, due to the large quantities of water present in the containers, there is a risk of significant and hazardous accumulation of hydrogen and oxygen [21].

3.3.1.11. Supplemental structural support (StrucSup)

Supplemental structural support is the addition of mechanical strengthening to the assembly to make up for the loss of capability of the damaged part. Unlike the option of replacing the damaged parts having the defect, as described earlier, this option adds new components without removing the damaged structure from the assembly. This type of structural modification has been carried out on several occasions by overseas operators prior to shipment of the damaged fuel to the United Kingdom for reprocessing (Callaghan, Appendix II). For example, structural support was added to an assembly that was severely bowed and had a loose end fitting. In another instance, wiring was used to provide support and maintain structural integrity of a mechanically damaged fuel assembly. One utility in the USA has proposed additional structural support to some assemblies to remedy a stress corrosion cracking issue in the top end nozzle of their assemblies. Additional structural support may require a modification of the cask (flask) or basket, as the additional support may make it difficult to place the assembly in the basket in the cask. Structural modification to support damaged assemblies is a remediation technique that has historically been routinely employed by reactor operators. An example of this technique is given in Section 4.

3.3.1.12. Modification of regulations (Reg)

In addition to the inability to meet safety functions, inability to meet regulatory requirements is another reason for classifying fuel as damaged. For example, in the USA, regulations [8] specifically indicate that fuel with a gross breach is considered damaged during storage and must be canned or treated in a manner to ensure retrievability. Similar regulations in Germany require fuel that has cladding breaches developed in-reactor to be segregated and placed in sealed containers for wet storage.

Under current German regulations, these rods are considered damaged and cannot be put in dry storage without being canned. If it can be shown that a requirement does not affect a safety function, then the possibility exists that the regulation can be modified or withdrawn. This may well depend on the size of the defect and the stage of the back end of the fuel cycle. It has been shown in the USA and Germany that LWR rods with small defects can be adequately dried to allow them to be stored and transported in an inert atmosphere without propagation and safety consequences. If canning is necessary for radiological dose control, then these rods could possibly be considered undamaged for the purpose of dry storage and be loaded into a cask as undamaged after removal from the can. If canning is not required for dose control, these rods may never have to be classified as damaged in the first place and can either be left in their original assemblies and eventually loaded into a dry storage cask after drying or placed back into the pool.

3.3.1.13. Burnup credit (BUC)

Implementation of burnup credit is a potential remedial action if criticality is an issue when trying to transport a batch of fuel that has structural damage, missing assembly components or missing rod pieces. It is also a potential action if the materials properties of the assembly components or fuel rods are either unknown or cannot be sufficiently confirmed for the behaviour of the assembly or rods during a potential accident to be adequately assessed. Burnup credit should be implemented on a case by case basis.

One of the fundamental safety considerations during the back end of the fuel cycle is preventing the array of assemblies from becoming a critical mass, especially during an accident event. The ability of an array of fuel to become critical depends on the presence of moderator, the configuration of the material and the fissile content of the fuel. Some countries require that the presence of complete moderation be assumed during any criticality calculation. These calculations are usually made with the assumption that the fuel assemblies are intact with all the components present and that the fuel contains all its original fissile material. Should the accident cause the fuel to change configuration or if the materials properties are unknown to the extent that a change in configuration cannot be assessed, then criticality may be calculated to occur. Criticality safety might nonetheless be demonstrated by modifying the calculations to account for the facts that: (i) during irradiation some of the fissile material is burned so the fuel is less reactive and (ii) some of the isotopes produced are actually poisons.

Burnup credit is not universally accepted. Burnup credit ranges from only the reduction in the ^{235}U and ^{238}U to complete credit for neutron absorbing actinides, fission products and burnable absorbers. The most common use is the reduction in the uranium isotopes and presence of the neutron absorbing actinides [22]. Some of the problems facing the use of burnup credit are the uncertainty in the isotopic composition of the fuel due to the complexity of the fuel design, non-uniformity of the fuel and its dependence on the axial burnup profile [23]. Few measurements have been made on the isotopic composition of WWER fuel and more are needed [23–26]. The situation with burnup credit for LWR fuel varies from country to country. In the USA, burnup credit is only allowed for actinides for high burnup LWR fuel due to the lack of benchmark measurements for the fission products in high burnup fuel. On the other hand, Germany has concluded that there are adequate measurements and code benchmarking to take full burnup credit [22]. Additional information on the current world attitude towards burnup credit is given in the proceedings of the IAEA's latest technical meeting on burnup credit.

The use of burnup credit might allow criticality safety to be demonstrated for a particular fuel configuration without the need for crediting the fuel for maintaining its geometry, thus allowing the fuel to be reclassified as undamaged with respect to the criticality safety function. A compilation of countries using burnup credit for wet and dry storage, and transport for different types of fuels can be found in Ref. [21].

3.3.1.14. Reprocessing (Repro)

Reprocessing is an option for remediation of damaged fuel assemblies that (alongside repository disposal) provides the ultimate solution. The option is only directly available to those countries that either have reprocessing capability (e.g. France, United Kingdom, Russian Federation, India and Japan) or those countries that have reprocessing contracts in place. Additional countries using the services of these facilities include Spain, Italy, Germany, Switzerland and Bulgaria. Reprocessing is an option for dealing with both standard and damaged fuel. The option, however, may also be available to others who have historically used this route or those to whom the route is new. The UK/BNFL has had specific requests to accept damaged, failed and 'PIE'd' fuel for reprocessing as a mechanism for conditioning the fuel.

The cost of providing new reprocessing capability is likely to be prohibitive for small quantities of damaged fuel and, therefore, it would not be a viable domestic option for many countries. However, these countries may consider contracting to those countries that do have the capability.

Although reprocessing provides an ‘end solution’, the requirement placed on a utility to prepare, package and transport the damaged fuel cannot be avoided and, therefore, reprocessing must be combined with one or more of the previous steps to enable the option to be delivered.

It may be that cooperation by Member States in consolidating their damaged fuels with others for treatment of the fuel by reprocessing is an option that could be employed. This would require inter-governmental and, likely, IAEA/WANO assistance to enable the option, and to deal with the issues of title to the products and wastes generated.

3.3.1.15. Refine analysis (RefAn)

To simplify the safety case and associated data needs, calculations are often based on parameters intended to conservatively represent uncertainties. These simplified analyses are not representative of actual fuel properties or conditions and are often needlessly conservative. Hence, a more thorough analysis, based on additional fuel data and/or calculational precision, is often sufficient to confirm that SNF will meet its requirements without additional action. Advances or improvements in measuring techniques may provide bases for reducing uncertainties. When reducing conservatisms, care must be taken to ensure that a valid technical basis exists and is applicable under all relevant conditions.

3.3.2. Potential handling methods as a function of activity and type of damage

Some of these 15 methods for addressing fuel that needs non-standard handling are more appropriate when there are only a few rods or assemblies that are damaged, and others are better suited to the batch case where an accumulation of damaged fuel is to be handled. In some situations, both may apply. For example, fuel assemblies with damaged rods may be accommodated by replacing the damaged rod(s) with a surrogate, and then canning and storing the damaged rod(s) in wet storage. The accumulated damaged rods can then be handled later as a batch by some other means. The applicability of the 15 methods for addressing isolated damage and batch situations are shown in Table 3.

Each method may be more appropriate for a particular type of assembly or rod defect or to remedy the inability of SNF to meet a particular function or regulation. Once the user has determined what requirement is not satisfied, and the type of defect in the SNF, the user can go to the appropriate table (Tables 4–7) to determine the applicable non-standard handling option for the particular phase of the back end of the fuel cycle concerned. An example showing the use of these tables is given with Table 4. ‘NA’ entries in the following tables mean ‘not applicable’. Table 6 only addresses wet storage since damaged fuel will always be able to meet the radiological shielding function due to the self shielding qualities of uranium.

Example: To determine appropriate non-standard handling techniques for criticality control, go to the column for the relevant phase(s) of the back end of the fuel cycle (e.g. dry storage) and then scan down to the row for the defect causing the problem (e.g. fuel assembly structural damage, missing components identified). As seen in Table 4, canning, structural support and BUC are remedial techniques that can be used for dry storage facilities.

3.3.3. Select handling method

Several considerations apply when selecting appropriate methods for accommodating or remediating damaged fuel. In addition to the efficacy of resolving the identified safety or operational deficiency, these considerations also include the applicable regulatory requirements, the maturity and availability of the necessary technology, and the time and resources available to address the concern.

As noted above, many of the methods presented, although technically feasible, have little or no precedent for regulatory acceptance. Much of the regulatory framework within the nuclear industry is based on rigid adherence to accepted practices that have been demonstrated to ensure adequate safety. Hence, regulatory acceptance and compliance with the ‘safety case’ are necessary considerations when selecting a methodology for accommodating damaged SNF.

As existing regulatory regimes evolve to meet needs associated with both long term management of spent fuel and closure of the fuel cycle, it is expected that new technologies and approaches for accommodating

TABLE 3. METHODS FOR HANDLING DAMAGED FUEL

Methods	Criticality safety	Radiological confinement	Rad. dose	Retrievability and operations	Isolated damage[a]	Batch[b]
Modification of storage conditions (SC)	X	X			X	X
Moderator exclusion (ModEx)	X					X
Poison addition (Poison)	X				X	X
Rod replacement (Rod/Rep)	X	X	X	X	X	
Canning (Can)	X	X		X	X	X
Filtration (Water)		X	X			X
Ventilation (Gas)		X	X			X
Tailored shielded (Shield)			X		X	X
Replace and/or repair damaged structural F/A components (StrucRep)	X			X	X	X
Catalytic re-combiners and/or hydrogen getters (Hget)		X			X	X
Supplemental structural support (StrucSup)	X				X	
Modification of regulatory conditions (Reg)	X	X	X	X	X	X
Burnup credit (BUC)	X					X
Reprocessing (Repro)	X	X	X	X	X	X
Refine analyses (RefAn)	X	X	X	X	X	X

[a] Fuel with defects that can be accommodated to enable it to will be handled with the remainder of the undamaged fuel.

[b] Damaged fuel that has been accumulated to be handled as a batch — anomalies or one-time event, sufficient to justify separate design solution.

existing and future needs will be adopted into the regulatory framework. The US NRC is currently migrating from its traditional deterministically-based regulations toward a more risk-informed framework. This shift will present opportunities to tailor compliance approaches to the applicable risks and thus better focus resources on areas of higher risk. This shift in regulatory basis will provide opportunities for performance-based solutions to existing and future needs relative to accommodating damaged SNF.

The preferred handling method should be chosen from those that are applicable to the defect that must be mitigated so that functionality and safety of the fuel can be restored. In some situations, there is the luxury of a long timeframe and ample funds to provide a remedy. In other situations, this is not the case. The handling method, chosen from the list of potential technologically suitable methods, should meet financial and temporal constraints as well as possible. It should be remembered that if a method is chosen that is not currently licensed in a country, the licensing and tailored process can be quite lengthy and costly. As a result, evolutionary rather than revolutionary change is normally preferred.

TABLE 4. CRITICALITY CONTROL

	Methods to remedy criticality control deficiency		
Damage type \ Fuel cycle phase	Wet storage	Dry storage	Transport
Fuel assembly structure			
Debris	Can, BUC	Can, BUC	BUC
Gross deformation	Can, BUC, StrucSup	Can, BUC, StrucSup	ModEx, Poison, Can, Reg, BUC, StrucRep, BUC
Missing components	Can, BUC, StrucSup	Can, BUC, StrucSup	ModEx, Poison, Can, Reg, BUC, StrucRep
Unconfirmed properties	Can, BUC	Can, BUC, StrucSup	ModEx, Poison, Can, Reg, BUC , StrucRep, BUC
Rod/cladding			
Unconfirmed properties	Can, BUC	Can, BUC	ModEx, Poison, Can, Reg, BUC
Debris	Can, BUC	Can, BUC	BUC
Missing rod pieces	Can, BUC, RodRep	Can, BUC, RodRep	ModEx, Poison, RodRep, Can, Reg, BUC
Gross breaches	Can, BUC	Can, BUC	BUC
Small holes	Can, BUC	Can, BUC	BUC

TABLE 5. RADIOLOGICAL CONFINEMENT

	Methods to remedy radiological confinement deficiency		
Damage type \ Fuel cycle phase	Wet storage	Dry storage*	Transport
Fuel assembly structure			
Debris	NA	NA	NA
Gross deformation	NA	NA	StrucSup, can, StrucRep
Missing components	NA	NA	StrucSup, can, StrucRep,
Unconfirmed properties	NA	NA	NA
Rod/cladding			
Unconfirmed properties	RodRep, Can, StrucSup, Water	NA	Can
Debris	RodRep, Can, StrucSup, Water	NA	Can
Missing rod pieces	RodRep, Can, StrucSup, Water	NA	RodRep, Can
Gross breaches	RodRep, Can, StrucSup, Water	NA	RodRep, Can
Small holes	RodRep, Can, StrucSup, Water	NA	NA

* Presumes storage container integrity.

TABLE 6. RADIOLOGICAL DOSE

Methods to remedy radiological dose deficiency	
Fuel cycle phase / Damage type	Wet storage
Fuel assembly structure	
Debris	gas
Gross deformation	NA
Missing components	NA
Unconfirmed properties	water
Rod/cladding	
Unconfirmed properties	water
Debris	water
Missing rod pieces	water
Gross breaches	water
Small holes	water

TABLE 7. OPERATIONS

Methods to remedy operations deficiency			
Fuel cycle phase / Damage type	Wet storage	Dry storage	Transport
Fuel assembly structure			
Debris	Can	Can	Can
Gross deformation	SC, Can	SC, Can	SC, Can
Missing components	StrucRep[a]	can, StrucRep	can, StrucRep
Unconfirmed properties	Can	Can	Can
Rod/cladding			
Unconfirmed properties	Can	Can	Can
Debris	Can	Can	Can
Missing rod pieces	Can, StrucRep	NA	NA
Gross breaches	Can	Can	Can
Small holes	Can[b]	NA	NA

[a] This fix is dependent on the type of missing component and degree of damage.
[b] Even small holes are a concern if there are water chemistry issues.

4. EXAMPLES

4.1. APPLICATION OF METHODOLOGY

This example is based on a typical but theoretical scenario that serves to illustrate the application of the methodology provided in this report for assessing whether SNF is damaged. This example then describes the selection of an appropriate SNF handling method.

Scenario

During normal reactor discharge operations (at a reactor in the USA), SNF was identified as potentially leaking. During transfer of the fuel assembly to the storage rack, the transfer machine over-ran and the SNF collided with the wet storage wall but remained secured to the handling machine grapple. No obvious damage was visible following the collision event.

Base conditions

- Reactor records indicate the fuel assembly is potentially leaking gas;
- The fuel assembly hits the side of the wet storage facility during mechanical handling (no apparent reconfiguration);
- The materials of construction indicate the potential for stress corrosion cracking in the top nozzle of the fuel assembly;
- The fuel assembly has been in wet storage for approximately eight years and needs to be transferred given limited wet storage capacity;
- The fuel cycle strategy for this Member State is based on placing intact SNF in dry storage casks;
- Relevant safety and operational criteria have been defined and are available.

Questions

- Is the fuel assembly damaged?
- What fuel assembly characteristics indicate damage?
- What are the relevant accept/reject criteria?
- What options are there for remediation of the fuel?

For this example, the principal functions from Section 3.1.1 are identified in the header row of the following table (e.g. criticality safety) and then used to develop the criteria to identify damaged fuel as described in Sections 3.1.2, 3.1.3 and 3.1.4. This table (Table 8) then addresses assessment results and recommended actions.

The detection of defects and selection of an appropriate handling method is often an iterative process as illustrated in the flow chart shown in Fig. 5.

Radiological confinement relates to the containment of nuclear material or fission products within the SNF and means that no fuel or material above a certain activity level will be released from the SNF.

The following paragraphs show how the entries for one of the principal functions **'radiological confinement'** were obtained:

- The **performance requirement** is that there will be no radiological releases within the allowed limits for the particular reactor station;
- The **fuel characteristics** that need to be verified are the presence of any breaches in the fuel rod cladding and the size of these breaches;
- The **rejection criterion** is that any breaches are less than 1 mm in effective diameter;

TABLE 8. APPLICATION OF METHODOLOGY

Step 3.1.1 Principal SNF functions during dry storage	Radiological confinement	Criticality safety	Retrievability/handling	Radiological dose
Step 3.1.2 Performance requirements	Radiological material released < allowable limits	Maintain subcriticality	Maintain structural integrity; Handle by normal methods; No cladding breach	Less than regulatory requirements
Step 3.1.3 Fuel characteristics*	Presence of clad breaches; Size of breach	Assembly deformation	Top nozzle weld; Breaches and breach size; Physical deformation	Geometry
Step 3.1.4 Rejection criteria	Breaches with effective diameter >1 mm (in Germany, any breaches would lead to rejection)	No visible deformation or pin misalignment (beyond normal bow)	Top nozzle weld fails proof load test; Breaches <X	None applicable
Recommended actions	Detect breaches; Measure breach size	Determine any misalignment/ deformation; Measure and record any abnormalities	Analyse stability of top end nozzle	None
Step 3.2.1 Applicable detection techniques from Table 2	Sipping with heaters; External visual inspection of rods; UT of internal areas; Eddy current	Visual inspection of fuel assembly	Visual inspection of top nozzle; Proof test	None required
		Results of assessment		
Step 3.2.2 Fuel condition assessment	Visual external inspection of SNF revealed no breaches of rods; Further UT examination identified two breached rods within SNF, dimensions unknown	Visual inspection revealed no gross deformation or rod misalignment	Visual inspection revealed some minor corrosion but obvious cracking; Proof load test indicated SNFG suitable for normal handling	No issues
Step 3.3 Non-standard handling options	Rod replacement — dismantle assembly and remove breached rods or canning — place assembly in a can which should be sealed to contain both soluble and solid activity release from breached rods	Ensure compliance with safety case during remediation procedure (whether RodRep or Canning)	RodRep — consider whether breached rods removed need to be replaced to maintain structural integrity; Canning — ensure can has similar lifting feature to assembly or other cans for ease of retrieval/handling	Ensure compliance with safety case during remediation procedure (whether RodRep or Canning)
Step 3.3 Decision	Rather than dismantling the assembly to remove breached fuel rods, the operator canned the SNF; In the USA, this would allow the SNF to be dry stored in a cask alongside undamaged fuel, while in Germany this would require the canned fuel to be wet stored pending further remediation	No action required	No action required	No action required

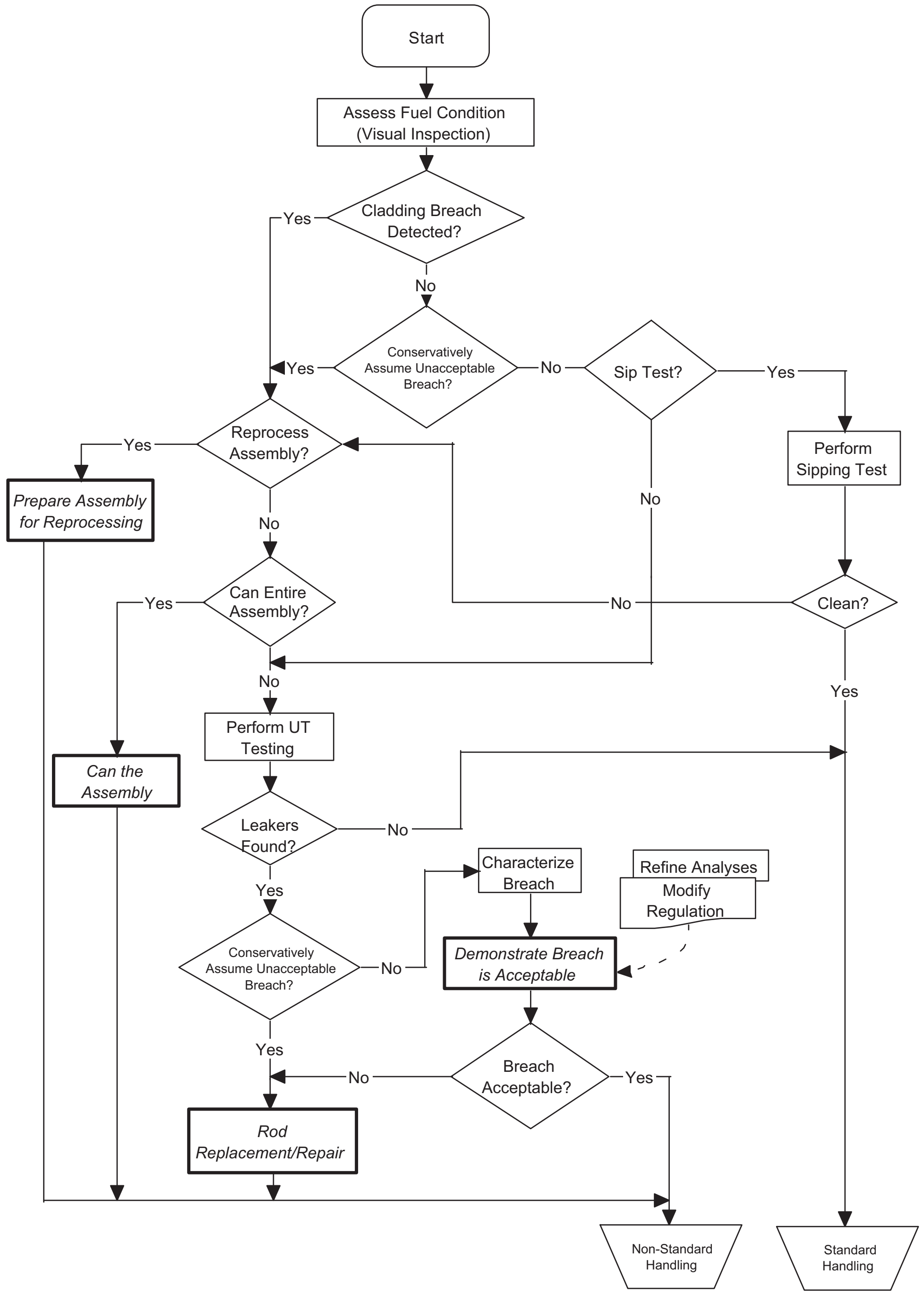


FIG. 5. Flow chart showing the interaction of the steps in detecting the defect and choosing a handling technique.

- The **recommended actions** were therefore to examine the fuel for breaches and establish the type and size of the breach;
- The **applicable methods** selected from Table 2 that could be used to detect the breaches were sipping tests, external visual inspection, ultrasonic testing and Eddy current;
- The **fuel condition assessment** identified two breached fuel rods within the assembly but the size of the breach could not be established without dismantling the fuel assembly;
- The flowchart below was used to **identify potential non-standard handling options** such as rod replacement and canning to remedy the problem.

The operator concluded that it was more cost effective to conservatively assume the breaches were significant and to can the assemblies rather than to invest in dismantling the assemblies for further evaluation. Once canned, all required safety functions were restored and the SNF could be transferred to storage in a cask alongside undamaged fuel in accordance with local regulations.

4.2. ADDITIONAL EXAMPLES

There are varied examples of damaged fuel assemblies within Member States (see 2005 technical meeting papers in Appendix II). Two actual examples are presented below and assessed using the process demonstrated in Section 4.1 above: (i) a BWR assembly that required supplemental structural support at the reactor to enable future handling and transport, (ii) a PWR assembly that required an external open can (or sheath) to retain the broken/dislodged fuel rods, thus enabling the fuel to be safely handled prior to reprocessing, and (iii) handling a variety of different configurations of spent fuel that have varying defects.

4.2.1. Example 1: Supplemental structural support

During fuel transfer operations, a BWR fuel assembly (7 × 7 design) was dropped into the fuel storage rack due to failure of the fuel handling machine.

Examination of the fuel for damage required removal of the water channel and revealed several broken tie rods and pins in the region of the bottom nozzle. The fuel assembly was fitted with a support jig at the reactor station, consisting of a bottom support ring with four wire cables linked to an additional upper tie plate. This enabled future handling of the assembly with the standard re-fuelling equipment. A reprocessing contract was in place and further assessment concluded that the original remediation work rendered the SNF acceptable for transport and interim storage at the reprocessing plant.

Further assessment at the reprocessing plant concluded that additional remediation of the fuel assembly was necessary to enable the fuel to be fed for reprocessing. The proposed method involves over-canning the fuel with a bespoke can to allow removal of the wire cables (as these items are incompatible with the fuel shearing route). The over-can contains the fuel rods within the assembly structure and provides a revised lifting feature to enable fuel handling once the original support jig has been removed (see Fig. 6).

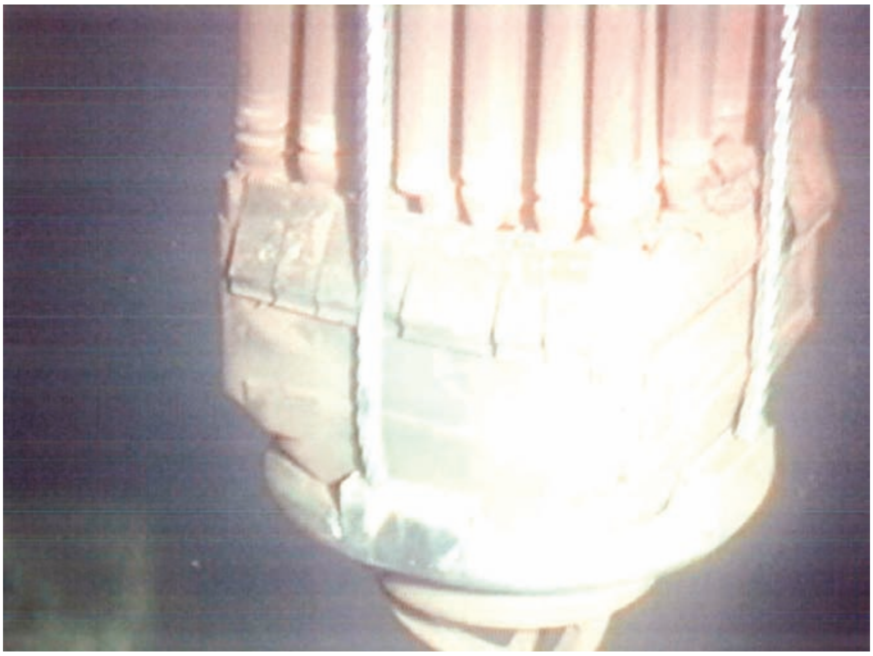


FIG. 6. Example 1: Bottom of BWR assembly fitted with securing ring and four wires (two shown) which run the full length of the assembly and are secured to an additional tie plate at the top of the assembly.

In a similar manner to the prior example, Table 9 summarizes the process of assessing the fuel damage and selecting the appropriate handling techniques. In this case, the starting point was a known damaged fuel assembly that had already been provided with additional structural support to allow safe storage within the reactor pool and the assessment focused on future handling, transport and reprocessing issues.

4.2.2. Example 2: Canning (open canning or sheathing)

A top nozzle of a long stored PWR fuel assembly at ‘away from reactor’ interim wet storage was being examined for corrosion of the top nozzle attachment and during this examination other fuel damage was evident. Detailed examination revealed damage to a number of fuel rods at the upper end of the assembly with several of the rods fractured and some rods protruding from the assembly (see Fig. 7). This damage was determined to have initially occurred during reactor operations and to have been exacerbated during subsequent fuel handling operations.

Nuclear safety and operational assessments determined that the fuel assembly could be fitted with a sheath or over-can located on the outside of the assembly to contain the stray rods/debris but allow handling by standard methods.

The fuel was successfully remediated and subsequently transported and reprocessed alongside standard assemblies.

In a similar manner to the prior example, Table 10 summarizes the process of assessing the fuel damage and selecting the appropriate handling techniques.

4.2.3. Example 3: Canning (standardized canister)

An SNF custodian has several different types of SNF composed of various fuel compounds, geometries, cladding types and enrichments from a variety of research, experimental and production reactors. Many have unconfirmed mechanical/structural properties and radiological content. Transport and disposal regulations require safety analyses to be based on confirmed data.

Disposal in a geologic repository is the designated end point for these fuels but a repository is not yet available. As a result, the duration of the interim storage period is not known and, due to political uncertainties regarding the repository, it is desirable to preserve the option for reprocessing or other fuel treatment/conditioning steps that may occur prior to geologic disposal.

Over the next several years, fuels will be consolidated from ageing wet and dry storage facilities into newer dry storage facilities. During this consolidation, fuels are to be packaged for final disposition such that there will not be a need for additional characterization or repackaging to meet requirements associated with future storage, transport or disposal.

Following the methodology outlined, the principal functions performed by the fuel are identified (see Section 3.1.1). These functions are to maintain radiological confinement and to maintain structural form/integrity. The radiological confinement function mitigates any radiological release while the structural form/integrity function is relied upon to maintain geometry which serves as the basis for criticality, shielding and thermal calculations, and also maintains the structural integrity needed for retrievability and handling.

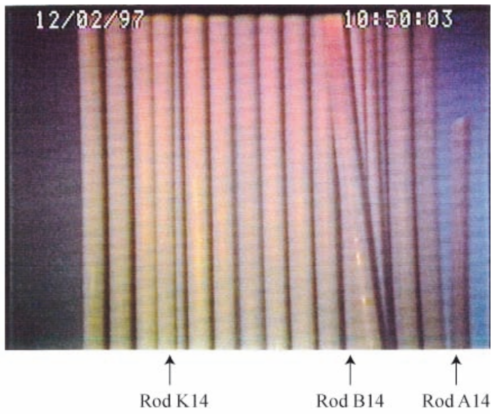
Next, specific performance requirements are identified for each of the SNF functions identified in the previous step (see Section 3.1.2). To ensure that performance requirements are identified to address the current and each of the remaining phases of the fuel’s life cycle, a table is created that includes a column for each of the functions to be performed by the fuel and a row for each of the remaining phases of the fuel’s life cycle. Cells of the table are then populated with the specific requirements that ensure the functions are satisfied for each of the phases of the fuel life cycle (see Table 11). As illustrated in Table 11, different regulations may govern the same safety function during different phases of the life cycle (i.e. storage, transport and disposal). Also, because performance requirements are primarily based on regulatory considerations, they are likely to be ‘country specific’.

The performance requirements identified in Table 11 are then collapsed into a single row and additional rows are created for each of the remaining steps of the process (see Table 12).

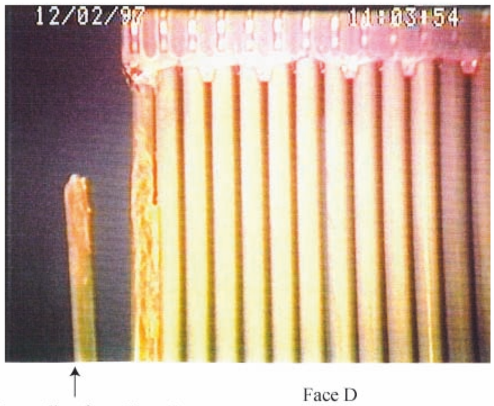
As discussed in Section 3.1.3, the SNF characteristics relied upon to achieve the specified performance requirements are identified. For this example, the characteristics include: (i) the radionuclide inventory and

TABLE 9. EXAMPLE 1

Principal SNF functions (3.1.1)	Radiological confinement	Criticality safety	Retrievability/handling	Radiological dose
Performance requirements (3.1.2)	No release of fissile material (fuel pellets or fragments) to pool	Subcriticality assured	Able to be placed into and retrieved from storage rack and transport package; Able to be sheared in a reprocessing plant	To be maintained within regulatory requirements during storage and transport
Fuel characteristics (3.1.3)	Breaches to fuel rods and size of breach	Structural integrity/deformation; Fuel rod misalignment	All SNF structural components; Top nozzle weld; Rod breaches and breach size; Rod alignment	Revised fuel assembly geometry
Reject criteria (3.1.4)	Fuel breaches that would allow escape of pellets/pellet fragments; Activity leakage to pool/transport flask exceeding allowable levels	fuel assembly geometry grossly deformed or stability of fuel rods may be suspect during fuel handling and transport such that K-eff. value may exceed 0.95	Proof load test fails; Fuel rods cannot be maintained with fuel assembly external geometry	No increase in external dose
Recommended actions	Conduct detailed visual examination of fuel assembly; Identify and record extent of damage to fuel rods; Measure activity leakage from assembly	Conduct detailed examination of fuel assembly; Identify and measure any geometric changes from standard SNF; Consider supplemental structural support to maintain fuel geometry	Analyse stability of assembly structure and top nozzle; Consider need for supplemental structural support to enable fuel handling; Demonstrate fuel safe to be handled and transported and reprocessed	Assess impact of any deformation
Applicable detection techniques from Table 2 (3.2.1)	Visual inspection of whole assembly structure and individual rods	Visual inspection of whole assembly structure and individual rods	Visual inspection of whole assembly structure and individual rods; Inspection of lifting features; Proof load test	None applicable
		Result of assessment		
Fuel condition assessment (3.2.2)	Visual inspection of assembly confirmed a number of fractured rods and some activity leakage; The activity leakage was assessed as acceptable for transport and storage in a sealed container pending reprocessing	Visual inspection of whole assembly structure indicated several rods broken and out of alignment, otherwise structure intact; Criticality safety assessed as within bounds	Supplementary structural support (fitted at reactor station) intact; Proof load test acceptable; Removal of wire support cables deemed necessary for reprocessing	No dose or shielding variations over standard SNF; No special measures/ shielding required
Decision	Extensive damage to fuel assembly confirmed, fuel contained within assembly but some pins displaced; Fuel to be sent for reprocessing; Supplemental structural support confirmed as suitable for transport and wet storage of fuel; Over canning (open sheath) proposed to enable support cables to be removed and allow fuel to be reprocessed			



(a) Continuing down Span 1, views of damaged rods.



(b) Rod B14 Protruding from Face C

FIG. 7. Damaged fuel assembly used in Example 2.

associated airborne and respirable release fractions used to calculate a radiological release; (ii) the fuel geometry and its fissile loading; (iii) the physical condition of the cladding; and (iv) the structural form and stability of the SNF and its lifting/grappling features.

As discussed in Section 3.1.4, the acceptance criteria associated with each of these characteristics are identified. Recall that the SNF, in this example, is composed of many different SNF types, many with unconfirmed radionuclide inventories and mechanical properties. Consequently, in order to demonstrate conformance with any established acceptance criteria, the radionuclide inventories and the condition of the cladding and fuel must be confirmed. Additionally, the mechanical properties must be known sufficiently to reliably predict the physical configuration of the fuel and/or fuel material following hypothetical accident conditions. Lastly, the materials interaction and fuel degradation mechanisms that may affect the SNF during the time of the interim storage period must be sufficiently understood to demonstrate that performance requirements will be satisfied following a period of interim storage that may last several years.

The next steps are to select (see Section 3.2.1) an appropriate method for measurement and detection of the credited fuel properties and to assess the fuel condition (see Section 3.2.2). Because of the many types (and relatively small quantities of each) of fuels in this example, it is not considered effective to obtain the data needed to assess the performance of each of the fuels against the relevant criteria. The personnel exposure, waste generation and other costs of characterizing each of the SNFs to obtain the necessary data are considered prohibitive. Hence, a safety strategy that accommodates these unconfirmed properties is sought.

A variety of techniques are available from Section 3.3. The management strategy selected is based on canning the fuel in a standardized canister that is sufficiently robust to assume the safety functions normally performed by the SNF. This strategy effectively shifts the safety basis to reliance on performance of the canister

TABLE 10. EXAMPLE 2

Principal SNF functions (3.1.1)	Radiological confinement	Criticality safety	Retrievability/handling	Radiological dose
Performance requirements (3.1.2)	No release of fissile material (fuel pellets or fragments) to pool	Maintain fuel assembly geometry during fuel transfer in pool and transport	Able to be placed into and retrieved from storage rack and transport package; Able to be sheared in a reprocessing plant	To be maintained within regulatory requirements during storage and transport
Fuel characteristics* (3.1.3)	Breaches to fuel rods and size of breach	Structural integrity/deformation; Fuel rod misalignment	All fuel assembly structural components; Top nozzle weld; Rod breaches and breach size	Revised fuel assembly geometry
Rejection criteria (3.1.4)	Fuel breaches that would allow escape of pellets/pellet fragments; Activity leakage to pool exceeding allowable levels	fuel assembly geometry grossly deformed or stability of fuel rods may be suspect during fuel handling and transport such that K-eff. value may exceed 0.95	Proof load test fails; Fuel rods cannot be maintained with fuel assembly external geometry	No increase in external dose
Recommended actions	Conduct detailed examination of fuel assembly; Identify extent of damage to fuel rods; Consider supplemental structural support to enable fuel handling	Conduct detailed examination of fuel assembly; Identify/measure geometric changes; Consider supplemental structural support to maintain revised fuel geometry	Analyse stability of assembly structure and top nozzle; Assess fuel condition for future handling operations	Assess impact of any deformation
Applicable detection techniques from Table 2 (3.2.1)	Visual inspection of whole assembly structure and individual rods	Visual inspection of whole assembly structure and individual rods	Visual inspection of whole assembly structure and individual rods; Inspection of lifting features; Proof load test	None applicable
		Result of assessment		
Fuel condition assessment (3.2.2)	Visual inspection of assembly confirmed a number of fractured and displaced rods and some activity leakage; The activity leakage was assessed as acceptable for transport and storage in a sealed container pending reprocessing	Visual inspection of whole assembly structure indicated several rods broken and out of alignment, otherwise structure intact; Criticality safety assessed as within bounds	Open can (sheath) secured over outside of assembly to contain stray rods; Proof load test acceptable; Fuel can be handled in standard manner and stored alongside standard fuel	No dose or shielding variations over standard SNF; No special measures/shielding required
Decision	Fuel leaking but leaching of activity from fuel can be controlled by placing in a sealed container alongside standard fuel; Over-canning (sheathing) of the fuel assembly required to contain the damaged fuel pins within the confines of the assembly structure; Assembly determined to be capable of being safely handled using standard lifting features and suitable for transport, interim wet storage and reprocessing			

TABLE 11. PERFORMANCE REQUIREMENTS FOR SNF IN EXAMPLE 3

	Maintain radiological confinement	Maintain structural form/integrity			
		Criticality safety	Retrievability/handling	Radiological dose/shielding	Thermal distribution
Intermediate storage	Confine releases from normal and accident conditions per 10CFR72 requirements	Maintain geometry/form to ensure criticality safety per 10CFR72 requirements	Maintain structural integrity to ensure retrievability per 10CFR72 requirements; Standardize handling equipment and operations	Maintain geometry/form to ensure radiological doses satisfy 10CFR72 requirements	Maintain geometry/form consistent with analysed thermal distribution
Transport	Confine releases from normal and accident conditions per 10CFR71 requirements	Maintain geometry/form to ensure criticality safety per 10CFR71 requirements	Maintain structural integrity to ensure retrievability; Standardize handling equipment and operations	Maintain geometry/form to ensure radiological doses satisfy 10CFR71 requirements	Maintain geometry/form consistent with analysed thermal distribution
Geologic disposal (pre-closure*)	Confine releases from normal and accident conditions per 10CFR63 requirements	Maintain geometry/form to ensure criticality safety per 10CFR63 requirements	Maintain structural integrity to ensure retrievability per 10CFR63 requirements; Standardize handling equipment and operations	Maintain geometry/form to ensure radiological doses satisfy 10CFR63 requirements	Maintain geometry/form consistent with analysed thermal distribution

Note: The SNF performance requirements identified using this table are consolidated into a single row of the summary table shown at the end of this example.
* For the post-closure period of disposal, there are no performance requirements on the fuel as no fuel properties are credited for safety.

TABLE 12. EXAMPLE 3

Step 3.1.1 Principal safety functions	Maintain radiological confinement	Maintain structural form/integrity			
		Criticality safety	Retrievability/handling	Radiological dose/shielding	Thermal distribution
Step 3.1.2 Performance requirements	Confine releases from normal and accident conditions per 10CFR71, 72 and 63 requirements	Maintain geometry/form to ensure criticality safety per 10CFR71, 72 and 63 requirements	Maintain structural integrity to ensure retrievability per 10CFR71, 72 and 63 requirements; Standardize handling equipment and operations	Maintain geometry/form to ensure radiological doses satisfy 10CFR71, 72 and 63 requirements	Maintain geometry/form consistent with analysed thermal distribution
Step 3.1.3 Credited fuel characteristics	Cladding integrity; Radionuclide inventory and associated release and respirable fractions	Cladding integrity; Mechanical/ chemical stability of fuel; Fissile loadings	Cladding integrity: Mechanical/ chemical stability of fuel and fuel hardware; Lifting/grappling features	Cladding integrity; Mechanical/chemical stability of fuel; Radionuclide inventory	Cladding integrity; Mechanical/ chemical stability of fuel and fuel hardware

TABLE 12. EXAMPLE 3 (cont.)

Step 3.1.1 Principal safety functions	Maintain radiological confinement	Maintain structural form/integrity			
		Criticality safety	Retrievability/handling	Radiological dose/shielding	Thermal distribution
Step 3.1.4 Acceptance criteria	Validated radionuclide inventory and associated release and respirable fractions; Basis of assurance that degradation during storage period will not adversely impact mechanical or radiological properties of cladding or fuel (i.e. likelihood or severity of breach)	Validated fissile inventory and geometry; Mechanical properties of cladding and fuel known sufficiently to reliably determine fuel configuration under normal and accident conditions; Basis of assurance that degradation during storage period will not adversely impact mechanical properties of cladding, fuel or structural components	Standardized lifting and handling equipment and operations; Mechanical properties of cladding and fuel known sufficiently to reliably determine fuel configuration under normal and accident conditions; Basis of assurance that degradation during storage period will not adversely impact mechanical properties of cladding, fuel or structural components	Validated radionuclide inventory and geometry; Mechanical properties of cladding and fuel known sufficiently to reliably determine fuel configuration under normal and accident conditions; Basis of assurance that degradation during storage period will not adversely impact mechanical properties of cladding, fuel or structural components	Validated thermal output and geometry; Mechanical properties of cladding and fuel known sufficiently to reliably determine fuel configuration under normal and accident conditions; Basis of assurance that degradation during storage period will not adversely impact mechanical properties of cladding, fuel or structural components
Step 3.2.1 Select applicable measurement & detection technique(s)	Because it is desired to avoid personnel exposure, waste generation and other costs associated with the scientific investigation needed to develop the data needed to confirm the criteria are satisfied, the fuel custodian has elected to develop a safety strategy that does not credit the fuel for performing these functions;				
Step 3.2.2 Assess fuel condition	Because the fuel characteristics will remain unconfirmed, the approach for assuring safe management of these fuels must be chosen such that it does not rely upon the SNF to perform the identified safety functions				
Step 3.3 Select approach for management of damaged SNF	Canning (i.e. a leak-tight canister performs the radiological confinement function formerly performed by the cladding)	Moderator exclusion in conjunction with bounding analyses (i.e. demonstrate that canisters remain leak-tight under all credible conditions, that canisters remain subcritical with their contents fully degraded and in their most reactive configuration and that applicable regulations are satisfied)	Supplemental structural support (i.e. canister provides all structural features relied upon for safe handling, including standardization of tools and equipment)	Bounding analyses (i.e. design cask and storage facility to ensure that dose limits are satisfied even with fuel fully degraded and reconfigured into the worst case scenario)	Bounding analyses (i.e. design cask and storage facility to ensure that temperature limits are satisfied even with fuel fully degraded and reconfigured into the worst case scenario)

rather than the fuel. Because the canister will be demonstrated to remain leak-tight during normal and hypothetical accident conditions, the radiological confinement function may be transferred from the SNF to the canister and an argument may be made for crediting the canister for preventing the intrusion of moderator. Criticality safety can be demonstrated using moderator exclusion, in conjunction with use of bounding analyses, by showing that subcriticality is assured in a leak-tight canister even with the SNF in its fully degraded state and in its most reactive configuration. Retrievability and standardization of equipment and operations are achieved by use of standardized canister handling features. Shielding and thermal considerations are addressed by ensuring that the designs of the storage facility and transport cask provide adequate shielding and heat removal under the assumption that the fuel reconfigures into the worst case scenario.

In this example, a number of different issues, related to unconfirmed data, were addressed by shifting the safety basis from reliance on fuel-specific information with relatively large uncertainties to reliance on an engineered solution (i.e. a standardized canister) that is designed and tested to meet the specified performance requirements. The entire process can be concisely documented as shown in Table 12.

5. CONCLUSIONS

It is concluded that SNF rods and assemblies should be categorized as either damaged or not based upon their ability to perform their designated functions without requiring the fuel to be handled in a non-standard manner. The chief functions performed by SNF are related to ability to maintain radiological confinement, to remain subcritical and to maintain structural integrity. The criteria for satisfactory performance of these functions may vary as the fuels progress through their life cycle and also by the characteristics and capabilities specific to the facilities where they reside.

This approach provides a consistent framework for identifying fuels with special needs, accounts for the fact that effective fuel categorization is not solely based on the properties of the fuel, and allows for fuels to be categorized within the context of the specific technical and regulatory requirements that apply. More importantly, by methodically ensuring a focus on the relevant performance requirements, management of SNF becomes more risk-informed and, thus, resources can be more effectively applied to assure continued safety.

This report is intended to be a guide for countries or utilities that either want to consider changing the way they classify and handle damaged spent fuel or countries that are initially facing issues of dealing with damaged spent fuel. A number of recommendations have emerged during the development of this report.

The basis of this report is the experience with handling damaged fuel in the various Member States. This experience was shared at the December 2005 meeting but not all countries that have spent fuel were represented. In addition, as time passes, countries will develop new techniques and gain more experience in all aspects of damaged fuel handling. A request for updated information, circulated on a triennial basis would capture this experience for all Member States to share.

Of particular interest would be information on advances in methods for detection and handling of damaged SNF. Updates should include types of damage, choosing detection (e.g. sensitivity) and handling methods, and positive and negative aspects of the techniques. Sources of this information should include regulatory bodies, utilities and fuel vendors.

Every effort should be made to set temperatures and atmospheres inside casks so that additional damage does not occur to the fuel or assembly, once a cask is sealed, which would preclude further disposition or processing of the fuel without opening the cask and repackaging or increase the hazard to workers. Currently though, there are no techniques available to determine damage occurring in a cask after it is sealed. Cask modifications or development of portable techniques that could be taken from cask to cask to determine cladding breach (gas release), fuel relocation and significant change in the strength of assembly materials might preclude unnecessary future handling of the fuel.

This report is intended to help countries facing issues with damaged fuel to proceed. While guides are helpful, direct assistance from personnel who have faced the issues themselves is a valuable time saver that prevents costly mistakes. These countries should have access to contact information for experienced personnel in all phases of ‘damaged’ fuel management (e.g. through the IAEA). In select cases, technical assistance could be made available to eligible countries to develop plans to handle damaged fuel.

An updated report on this topic should be periodically (e.g. 3–5 years) developed in consultation with knowledgeable Member State representatives.

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Appendix I

LIST OF PARTICIPANTS IN THE IAEA MEETINGS

Workshop on Handling Damaged Fuel

Vienna, Austria

December 2005

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An asterisk denotes a member of the drafting committee (D. Haslett, UK/BNG represented WG 3 and A. Callaghan in 2007)

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Appendix II

PRESENTATIONS FROM THE 2005 TECHNICAL MEETING

MELE, I., Experience with Damaged Spent Fuel in Slovenia.

BEKRIEV, D., Failed and Damaged Spent Fuel Issue at Kozloduy NPP, Current Status.

GOLL, W., HUMMEL, W., Issues in Handling Damaged Fuel in Germany.

CALLAGHAN, A.H.C., STANDRING, P.N., PRESTWOOD, J., MAKIN, D.G., The Management of Non-Standard, Failed and Damaged Oxide Fuels at Sellafield.

DVOEGLASOV, A., GRYSHEHENKO, V., NOVIKOV, A., Characterization and Selection of Irradiated Nuclear Fuel of ChNPP for the Purposes of Storage in the Dry Storage Facility.

VEDAMOORTHY, S., Experiences in Handling of Damaged Spent Fuel in PHWRs.

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CSERHÁTI, A., Monitoring and Removal of the Damaged Fuel at Paks-2, Failed Fuel Assembly Handling.

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CARLSEN, B., FILLMORE, D., MCCORMACK, R., SINDELAR, R., SPIEKER, T., WOOLSTENHULME, E., Damaged Spent Nuclear Fuel at U.S. DOE Facilities, Experience and Lessons Learned.

KUBA, S., Operational Rational Monitoring and Handling of Damaged Spent Fuel.

DAIE, J., Spent Fuel Inspections.

HOFFMANN, D., Experience with the Handling of Damaged Spent Fuel in Germany.

Appendix III

SUMMARY OF THE IAEA TECHNICAL MEETING ON HANDLING DAMAGED FUEL, DECEMBER 2005, VIENNA

R.E. Einziger

Chairperson

Nuclear Regulatory Commission

Washington, D.C., USA

III.1. INTRODUCTION

International experience with storage of SNF has resulted in an extensive technical basis and an appropriate understanding of operational practices. The majority of IAEA Member States have not yet decided upon the ultimate disposition of their SNF, so interim storage is the only current solution for these countries. Interim storage, especially dry storage, is becoming increasingly important as storage durations are extended longer than previously anticipated. In October 2004, it was recommended that the IAEA organize a technical meeting focused on handling of damaged spent fuel. The relevance of this topic was endorsed by the Technical Working Group for Nuclear Fuel Cycle Options and Spent Fuel Management. Accordingly, the IAEA convened a meeting to focus on the technical aspects of handling damaged spent fuel at its headquarters in Vienna on 6–9 December 2005. The meeting was attended by representatives from numerous countries (see Appendix I). Notably absent were representatives from Japan, the Russian Federation and Canada.

In his opening statement to the meeting participants, the chairman emphasized the need to limit the amount of fuel categorized as ‘damaged’ since this fuel usually requires extra handling that results in additional cost, time and dose to the worker. He emphasized that there were three fundamental questions that needed to be answered:

(1) What is damaged fuel?
(2) How do we detect damaged fuel?
(3) How is damaged fuel best handled?

III.2. PRESENTATIONS

As a background for discussion of these topics, each delegate to the meeting was allowed to make a presentation on the handling of SNF in his or her country or problems and restrictions handling damaged fuel. These papers are listed in Appendix II. Most of the papers gave a general overview of fuel storage in their country and some discussed causes of in-reactor damage. Some of the more informative papers are summarized below.

W. Goll’s paper gave a good review of the distribution of fuel failure types in Framatome fuel, and has excellent photos of defected fuel. Contrary to the US policy, damaged fuel in Germany cannot be placed in dry storage but must be canned and remain in wet storage. D. Hoffmann, also of Germany, gave a paper on handling fuel. In Germany, ‘intact’ means that the fuel assembly has no indication of operating leakage while in-reactor, and can be handled by normal means. This is more restrictive than in the USA, where double containment is required and the number of failed rods (1, 10 and 100%) as specified in the US NRC Standard Review Plan (SRP) is used in the safety analysis. Additional modifications to the German Atomic Energy Act are needed, and are expected (2007–2010) to put damaged fuel in dry storage.

V. Gryshchenko’s Ukrainian paper dealt with damaged Chernobyl fuel. Two independent barriers are required against radioactive material release but the cladding cannot be one of these safety barriers. On the other hand, they require that the cladding be protected against degradation by requiring an inert atmosphere and a 300°C temperature limit. V. Gryshchenko wanted better clarification on the meaning of pinholes and hairline cracks, and implied that it was the responsibility of the regulator to define these terms. He also felt that the fuel vendors should be responsible for qualification of the fuel for the back end of the fuel cycle.

S. Vedamoorthy of India was concerned about damaged CANDU fuel. India does not consider leakers as damaged. They are only concerned about fuel handling problems. Damaged fuel was pins that escaped a bundle during on-line handling and jammed the handling machine. This is a good example where function drove the definition of damaged fuel. P. Poskas of Lithuania described an interesting situation while handling RBMK fuel at Ignalina. A number of rods had no visible plastic deformation but had circular brittle cracks in the upper parts of the assemblies. These were placed in a pool where they are going to have long term monitoring for degradation.

R. Einziger of the USA proposed a new definition of damaged fuel based on the function assigned to the fuel. If the fuel could perform its intended function, then it should not be considered damaged. This allowed the definition to conform to the regulatory and operational limitations of each country. He also indicated that fuel that was considered damaged in one part of the fuel cycle, might not be considered damaged, under this definition, in another part of the fuel cycle.

It became quite clear that there was difficulty in terminology. What was ‘intact’ to one country was ‘damaged’ to another. Fuel could be referred to as breached, failed, leaky, fractured, broken, cracked, untight or split. All the terms meant that the cladding did not contain gas but no indication of the extent of the defect could be inferred from the terms. Some countries followed the US lead in terms of definitions while other countries slightly modified those terms. The biggest difference with the US view was that many countries did not consider rods with pinholes or tight hairline cracks as intact and many countries would not allow ‘damaged fuel’ in dry storage.

III.3. WORKING GROUPS

At the conclusion of the talks, the meeting broke into three working groups and addressed the three purposes of the meeting introduced by the chair in the opening session.

Group I concentrated on the question “What is damaged fuel?” It considered the following issues:

(1) What is ‘damaged fuel’?
(2) What are the safety functions of a fuel assembly during storage, transport and disposal?
(3) What are the integrity criteria for long term storage?
(4) Is there a better, possibly more publicly acceptable term, than ‘damaged fuel’?

The conclusion of this group was:

> “Rather than attempting to classify SNF as either damaged or not, it is recommended that they be categorized based upon their ability to perform their designated functions without requiring the fuel to be handled in a unique (or non-standard) manner. The chief functions performed by an SNF are related to its ability to maintain radiological confinement and to maintain their structural integrity. The criteria for satisfactory performance of these functions may vary as the fuels progress through their life cycle and also by the characteristics and capabilities specific to the facilities where they reside.”

The group presented an example of the methodology to classify fuel. The full group report is given in the text of this report.

Group II proposed a scheme for detecting ‘damaged fuel’:

(1) Detect presence of failed fuel by the reactor off-gas system;
(2) Determine whether the fuel can be dismantled;
(3) Use chart of techniques to decide on technique to use.

The chart has a list of techniques for determining rod and assembly defects, where they are applicable, sensitivity and pros and cons. The group would like to establish a database system on individual fuel assemblies from receipt of fuel at the utility up to storage. Data for such a system is probably already available at the individual reactors. Techniques for identifying individual damaged rods in assemblies that cannot be dismantled need more development with emphasis on data interpretation. The group indicated that there are a lot of techniques available but it is difficult to assess the data. Currently, there are no criteria set for determining when a rod or assembly is damaged and it may be very difficult to set defensible criteria.

Group III considered both cladding damage and structural damage during wet interim storage, dry interim storage and transport. The group listed a number of phenomena that needed to be dealt with during each of the above stages but never really arrived at a methodology that could be applied to any country's particular situation. The group provided analyses of how to develop a path forward for handling damaged spent fuel in one particular situation.

A glossary of terms and a summary of handling practices in the participating countries will eventually be developed. It is the chairman's position that considerable work needs to be done to develop a practical guide for directing the handling of spent fuel. This guide should include the following steps:

- The steps that need to be taken to get from where the fuel is to where it needs to be;
- Why there is an issue requiring that the step be taken;
- The characterization and operational concerns in accomplishing that step;
- The downside if the issue is not addressed;
- The upside if it is addressed;
- Alternatives.

This guide will eventually provide a basis for countries in the position to consider storage or transport to see what other countries are doing with damaged fuel, and will have advice on adapting those practices to their own situation and regulations.

III.4. STATUS AND FOLLOW-UP WORK

Other than possible re-wording for clarity and further expounding on some points, the task of Workgroup 1 to define damaged fuel or conversely 'intact' is essentially complete. The work of Group II is not yet finished but extensive progress has been made in making it a useful guide. The main work remaining is additional input and analysis for the chart of the techniques. This may require a meeting of those personnel from vendors and utilities that are versed in the use of the techniques. With better understanding of the limitations and accuracy of the available methods, a reasonable attempt at answering the other question posed by this group, i.e. 'the criteria' can possibly be made.

Now that Group I has provided an acceptable definition of damaged or intact fuel, and Group II has provided direction on how to locate and segregate this fuel, the topic of alternative paths to handling this fuel, originally assigned to Group III, can be approached more systematically. Group III has provided a pointer, in the form of a specific example, for the methodology that needs to be developed to identify the possible ways of handling damaged fuel under a particular country's regulations. This must now be generalized. This will probably require an additional meeting of cognizant people to draft the general method.

III.5. CONCLUSION

The workshop provided a forum for most of the countries with operating reactors to inform the group of their issues, regulations and methodologies for handling SNF. Based on this input, the workshop arrived at a flexible definition of damaged fuel that was based on the function that the fuel was to play in the safety of the storage system. The workshop also made progress in developing a tool for identifying the best methodology for identifying the damaged fuel. Considerable work still needs to be done to identify a methodology for choosing the best method of handling the damaged SNF

At the conclusion of the meeting, H. Forsstroem (IAEA) indicated that the methodology for defining 'damaged fuel' in terms of function was so simple and so obvious, he wondered why it had not been implemented sooner.

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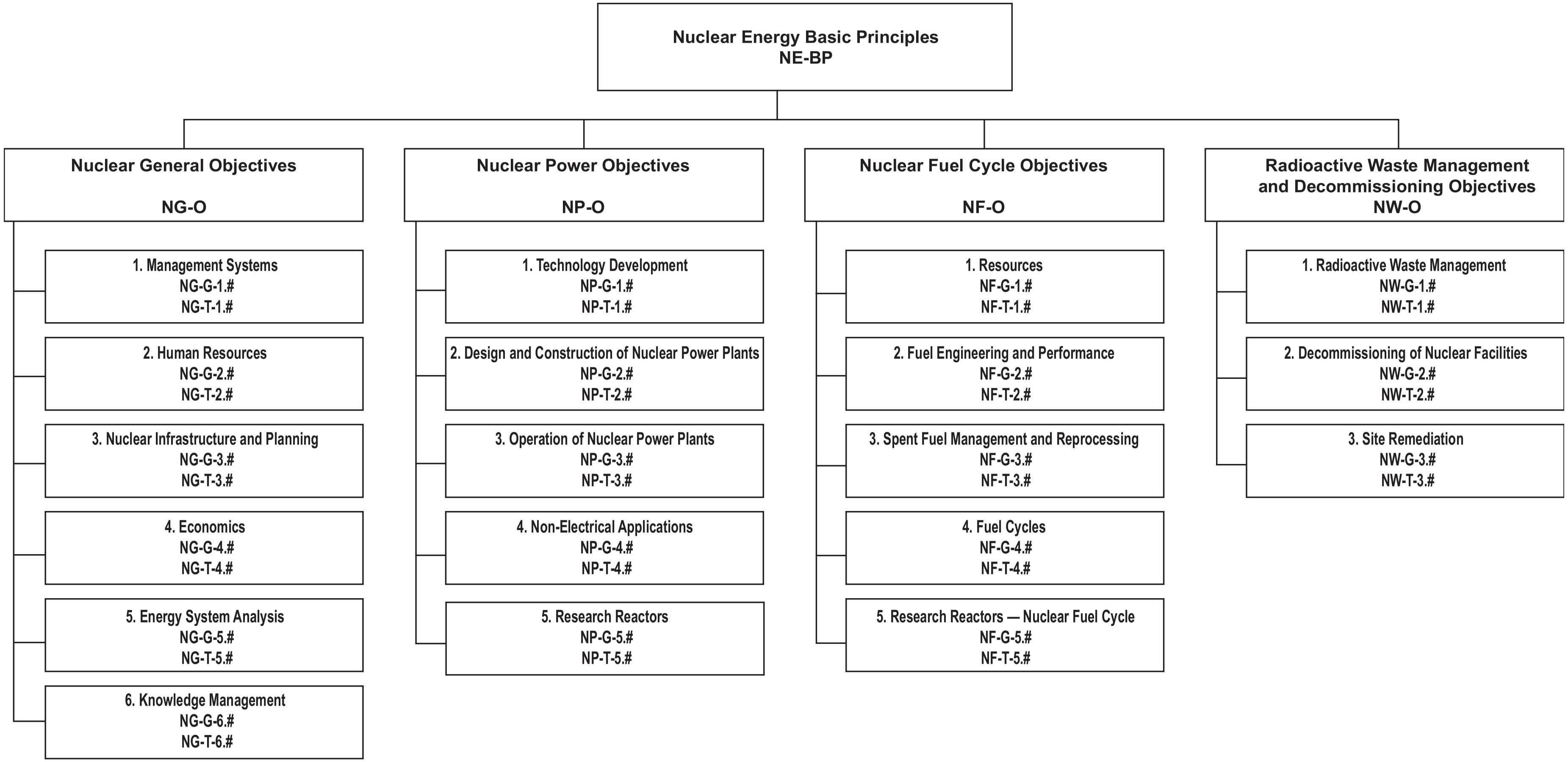
Structure of the IAEA Nuclear Energy Series



Key
BP: Basic Principles
O: Objectives
G: Guides
T: Technical Reports
Nos. 1-6: Topic designations
#: Guide or Report number (1, 2, 3, 4, etc.)

Examples
NG-G-3.1: Nuclear General (**NG**), **G**uide, Nuclear Infrastructure and Planning (topic **3**), **#1**
NP-T-5.4: Nuclear Power (**NP**), Report (**T**), Research Reactors (topic **5**), **#4**
NF-T-3.6: Nuclear Fuel (**NF**), Report (**T**), Spent Fuel Management and Reprocessing, **#6**
NW-G-1.1: Radioactive Waste Management and Decommissioning (**NW**), **G**uide, Radioactive Waste (topic **1**), **#1**

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 978–92–0–103809–8
ISSN 1995–7807