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Summary Report on Fuel Related Events

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INTRODUCTION

Fuel performance and reliability, especially fuel integrity, is one of the major aspects for the safe operation of nuclear power plants. Over the years, a very significant effort has been put into analysing and understanding the causes of the fuel failures, and important strategies in design, engineering, manufacture, inspection, operation and management have been developed to try to eradicate them. The results of this effort are reflected in improvements relating to the use of new materials, a more robust design, new fabrication methods, more efficient inspections of the newly built fuel assemblies, quality assurance and better operational strategies. The extension of fuel burnup, power increases and more aggressive operating conditions have also driven the search for better performing fuels, by designing better cladding, investigating pellet-cladding interaction and other fuel failure mechanisms and strategies.

However, despite these efforts and improvements, fuel failure events during operation, fuel handling, and fuel storage continue to occur. Based on the analysis of 169 fuel related events reported in nuclear power plants worldwide, this summary report brings together the main insights, recommendations and conclusions to contribute to reduce the number of fuel failure events.

MAIN INSIGHTS

In-core fuel failures.

The following in-core fuel failure mechanisms were identified:

- Debris fretting
- Grid to rod fretting
- Baffle jetting
- Pellet Cladding Interaction
- Hydriding
- Corrosion
- Manufacturing defects
- Insufficient cooling
- Dimensional changes during operation (rod growth caused by irradiation, fuel/fuel channel bow/twist, etc)
- Power oscillation/instabilities
- Calculation/simulation/calibration/instrument error.

The main causes of most in-core fuel failures are related to a deficient design of the fuel assemblies or its components, or to the deficient design of non-routine interventions such as fuel cleaning or reactor coolant system decontamination. Human performance (i.e. operation errors, water chemistry errors, or selection of erroneous models or parameters) is the predominant cause of power oscillations and calculation error events.

Short term remedial actions taken for in-core accidents are aimed at continuing operation until a more definitive solution is implemented, and usually consist in the recovery of the affected fuel assembly, its repair or substitution, the application of temporary measures (design patches, operational restrictions), and the increase in the surveillance of the fuel by radiological monitoring of the reactor coolant while in operation, or during outages.

Long term remedial actions are mainly concentrated on design modifications in fuel assemblies and other hardware, and improvements in operational practices.

Remedial actions taken have shown themselves to be effective in reducing the frequency of in-core fuel failure modes. Phenomena such as manufacturing defects, dimensional changes and baffle jetting have not been reported in the last 15 years, and only events caused by debris fretting, corrosion, insufficient cooling and calculation errors have been reported in the last 5 years. Thus, specific measures to cope with these failure modes still need to be further enhanced.

Fuel handling events

Refuelling of nuclear power plants is a well established and reliable routine operation which, depending on the reactor type, is done on power or during cold shutdown. On-power refuelling requires complex automatic fuelling machines, whereas off-power refuelling is a semi-automatic operation requiring more direct human intervention. The main causes of fuel failure events are human error and equipment failures. Human errors are the most frequent cause of fuel handling events in reactor types with refuelling during cold shutdown. Fuelling machine or tools failures are more frequent in reactor types with automatic on-power refuelling.

Human errors include errors in rigging and positioning the fuel assembly, operation of the refuelling tools, inadequate planning, inadequate control and monitoring, inadequate implementation of procedures, insufficient attention to or compliance with the administrative procedures to avoid core loading errors. Fuel machine or tools failures include the failure of components (hooks, grapples, motors, fuel structure), insufficient resistance and durability of some fuel handling equipment, deficient design (grid snagging, bulges), and insufficient monitoring and control systems (weight cells, lighting, TV cameras, interlocks).

Remedial actions consist in the recovery, repair or disposal of the affected fuel bundle, the repair or design modification of the refuelling machines (by implementing supplemental aids to the operators), additional training, improved procedures, better surveillance and more efficient organization.

Storage events.

Regardless of the final fuel management strategy selected, after the fuel is burned in the reactor core, it is taken to a wet storage facility (spent fuel pool) designed to comply with the spent fuel safety criteria. By comparison with the initial designs, spent fuel pools have had to adapt to the growing need for storage capacity of fuel with different characteristics from those originally planned.

The following categories of events during storage have been identified:

- Events in which the margin to criticality had been reduced.
- Events with loss of cooling
- Events with actual or potential fuel integrity concerns
- Events with radiological impacts.

The main causes of these events are human error and, to a lesser extent, design deficiencies. Some of these deficiencies originated in the initial design of the spent fuel pool, but sometimes the design deficiencies result from a change in the characteristics of the fuel to be stored (i.e. higher enrichment and burnup fuel, reracking for a more compact storage configuration, higher thermal power).

Events with a reduction in the margin to criticality and events with fuel integrity concerns are scarce, and they are specifically caused by an incorrect concentration of boron, incidents with neutron absorbers in structures, errors in the calculation of the shutdown margin, or failure in the control and monitoring of the spent fuel pool water chemistry. Restoring the boron concentration, repairing the neutron absorber in the structures, and correcting the calculations is sufficient to recover the criticality margin.

Events with loss of cooling (including falls in the level of the spent fuel pool water) are more frequent, and are caused by the characteristics of the spent fuel pool cooling system (interconnections and manual operation), by leakages in the liner, and the lack of monitoring systems, possibly leading to delay in detecting the problem. However, these events are slow, and there is usually enough time to regularize the cooling function.

Events with radiological impact are frequent, due to the numerous activities and circumstances that could lead to radiological exposure of the workers. The main cause of these events is the lack of careful planning of activities in the spent fuel pool building and lack of analysis to identify all possible sources of radiological exposure.

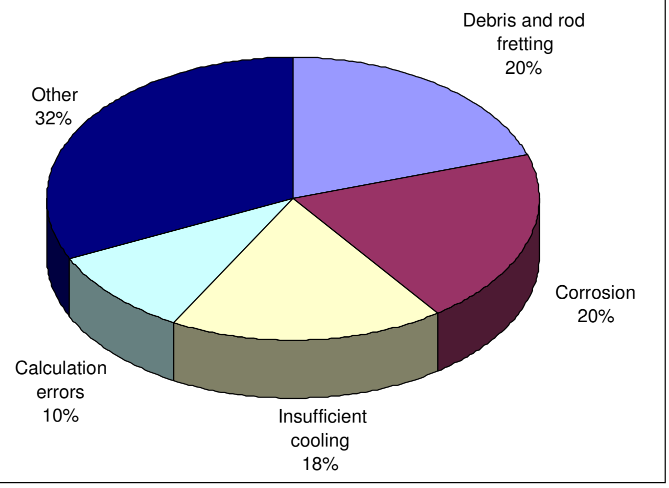
MAIN FINDINGS

Operating experience in the use of fuel over the years indicates that there is not one particular fuel design which stands out in relation to the others. Despite the great efforts put into improving the design and manufacture of the fuel assemblies, which has allowed a better performance and higher operational margins, more demanding operating conditions for the fuel have raised concerns about fuel performance. Examples of such conditions are:

- higher enrichment
- higher burnup
- operation of a mixed core with assemblies of different designs,
- lead fuel assemblies testing.
- core power management strategies
- fuel unloading strategies to achieve shorter outages.
- singular practices: system decontamination and fuel cleaning.

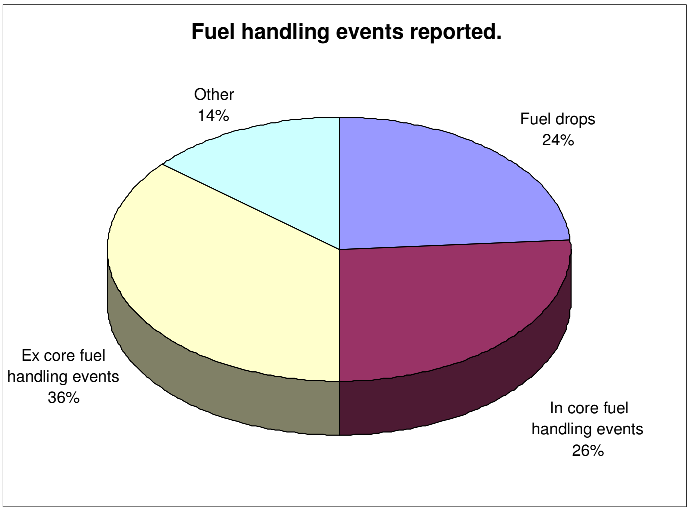
The result of these counteracting trends is that in-core fuel performance has improved significantly, but there are still some fuel failure causes which need to be addressed, such as debris and grid to rod fretting (20 % of in-core events reported in the last 15 years), insufficient cooling (18 %), corrosion (20 %), and calculation errors (10 %).

Most significant in core fuel failure causes reported in the last 15 years

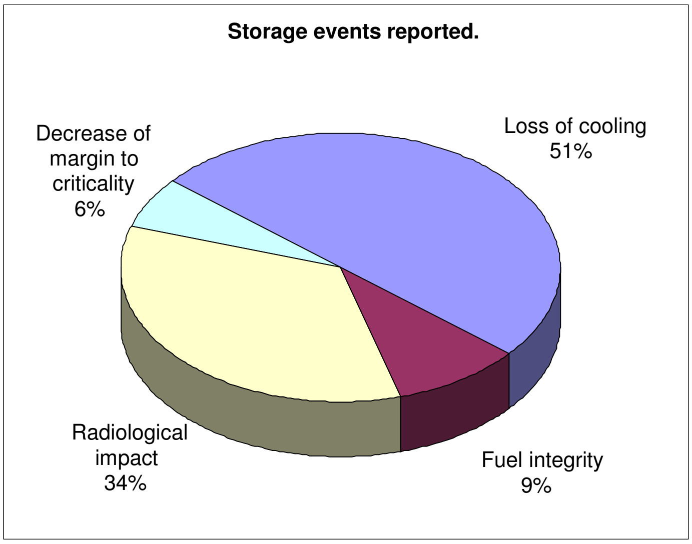


Non-routine practices, such as systems decontamination or fuel assembly cleaning, have also highlighted the need for a thorough assessment in order to take account of unforeseen consequences, in particular fuel cooling and the behaviour of the fuel materials with regard to corrosion and crud buildup after using decontamination and cleaning chemicals.

Fuel handling events involve a very specific kind of fuel failure. A large number of rapid uncomplicated operations have to be carried out repetitively. Depending on the plant design, the operations are mainly automatic (such as the automatic refuelling of on-power refuelling systems), or semi-automatic, where an operator closely monitors and handles the refuelling tools himself. Due to the nature of the operations, automatic systems are more prone to non human errors, whereas manual or semi-automatic systems are more prone to human errors. Nevertheless, due to the particularities of the automatic systems, human intervention is usually also very intense, including the programming of the machine. As a result events caused by human errors are also significant, and add to the design, documentary and operational potential deficiencies of the automatic systems. Overall, 24 % of the events analysed involved fuel drops, 26 % involved fuel handling problems in core (misposition, incorrect insertion), and 36 % involved handling problems ex-core (mainly refuelling machine malfunctions).



Storage events can be caused by a reduction of the shutdown margin, the loss of the fuel bundle integrity, and the loss of the spent fuel pool cooling. Another group of events with radiological impact is also included in this analysis, even though most of the events actually have nothing to do with fuel. Operator errors while operating the spent fuel pool systems or other personnel errors while conducting interventions in the spent fuel pool systems are among the main causes of the selected events. Design and operation are also significant causes, particularly since the conditions and characteristics of the spent fuel currently being discharged from the reactor core are more demanding (residual heat, full core offload practices) than the conditions of the fuel for which the spent fuel pool and its auxiliary systems were designed. Spent fuel storage system Probabilistic Safety Assessments (PSA) are used to find the weaknesses of the system and to help the operator to decide how to monitor them. Half of the events analysed consisted in loss of cooling, and 34.4 % were events with radiological impact.



MAIN RECOMMENDATIONS

FUEL DESIGNERS.

Fuel designers should continue developing fuel designs with improved materials to accommodate the current fuel operation conditions pertaining to higher burnup, higher power density, power management, etc. so that phenomena like Pellet Cladding Interaction, corrosion and hydriding are no longer a concern. For example, Niobium alloys for the cladding or stainless steel for the fastening components reduce the risk of corrosion and hydriding. Different characteristics of the fuel pellet (shape, composition or manufacturing method) reduce the effect of Pellet Cladding Interaction.

Mechanical design should preclude debris and grid to rod fretting, by providing filtering mechanisms to trap debris (debris catchers) before it enters the core, and by reducing the cladding wear by improving grid-to-rod contact, using wear resistant cladding, and avoiding fuel bundle vibration caused by the coolant flow by adequate hydraulic design and stiffening of the fuel structure by inserting additional spacer grids and thickening guide tubes..

Fuel handling should be facilitated by carefully designing the fuel bundle, in particular the bottom and top heads, grids and bulges to reduce the risk of snagging, incorrect insertion of fuel bundles and fuel drop.

Fuel manufacturers should continue improving their inspection and quality assurance practices so as to avoid issuing any fuel bundles with flaws.

OPERATORS

Operators should select an updated fuel design. Up-to-date fuel designs cope with many of the fuel failure mechanisms such fretting, Pellet Cladding Interaction, and corrosion induced failures.

Operators should pay special attention to improving operation and maintenance practices, in particular:

- Adopting foreign material exclusion practices in all aspects of the nuclear power plant operation (maintenance, etc), especially preventive measures to avoid dropping foreign materials in the primary coolant system, to reduce the impact of debris fretting related events.

- Analysis of consequences of singular interventions. Singular interventions, such as primary circuit decontamination and fuel cleaning, present the risk of fuel failure if the evaluation of the potential consequences is insufficient or incomplete. Careful evaluation of the design and the analysis of potential consequences is needed. In particular, to avoid accelerated corrosion and/or crud deposition (and thus a risk of clogging the cooling channels and insufficient cooling events) in the fuel bundle after primary circuit decontamination, the operator must ensure that all the remainder (residues) of the chemical species used are flushed out of the primary circuit., because they could cause. Alternative remedial actions, such as passivation of the inner system surfaces and reactor coolant chemical monitoring and control, can reduce the corrosion and crud buildup. In the case of fuel cleaning, the device must be adequately designed (to consider all foreseeable operating conditions) and monitored (to quickly identify any abnormal occurrence) in order to avoid the insufficient cooling and melting of the fuel.

- Water chemistry control and monitoring aims to reduce the impact of the different corrosion phenomena. However, water chemistry strategies involve adding different elements which have competing effects. Succeeding in balancing the water chemistry with the correct amount and type of additives is a slow process. Operators should plan a step-by-step approach with sufficient time, so that the effect of each change in water chemistry can be adequately assessed and tested.

Special attention should be given to human and organisational factors, especially during routine or repetitive operations (i.e. refuelling), to avoid human performance presenting a significant risk. Careful drafting of procedures and other guidance, training, coordination, supervision, revision, adequate staffing, motivation, etc. are all activities that improve human performance.

In particular, fuel handling aids are beneficial in reducing the risk of fuel handling events. Fuel handling aids include instrumentation, surveillance equipment, interlocks, and design modifications to eliminate refuelling machine failures as far as possible. In combination with sound procedures and operational documentation, as well as training and rehearsal (in the case of unusual operations), fuel handling aids reduce the risk of fuel handling events.

Fuel characterisation should be a requirement when spent fuel is to be transferred from the spent fuel pool to a dry storage system. The history of each fuel assembly, with special reference to its integrity, could shape the spent fuel management strategy. Failed fuel stored in the spent fuel pool for many years needs to be characterised and even repaired before it is placed in a dry spent fuel storage facility. Fuel integrity needs to be assessed in order to evaluate whether the affected fuel assembly can even be handled with the normal fuel handling tools. Attention should be also paid to long-term degrading phenomena, such as delayed hydrogen-assisted fuel cladding failure. This phenomenon can pose a risk of fuel cladding failure during spent fuel management, especially if a dry storage system is to be used.

Activities in the spent fuel pool should be carefully planned and analysed, to identify all the possible sources of radiation exposure, either inadvertent, or caused by human intervention. If necessary, training and rehearsal of the activity should be planned and executed.

REGULATORY AUTHORITIES

Regulatory authorities should enhance the sharing of operating experience relating to fuel failure events. Being aware of operating experience will make it possible to identify whether any of the phenomena described in this report becomes more frequent, or ceases to be a concern. Continuous surveillance of the fuel performance could eventually identify new fuel failure phenomena caused by the current operating conditions of the new fuel designs. Regulatory authorities should enhance the operators to carry out systematic periodic fuel inspections of failed and intact fuel assemblies in nuclear power plants, which is considered a valuable tool to achieve this objective.

Special attention should be paid to one-off operations or tasks that might have consequences for fuel in the following cycles. Means should be used to detect whether all the possible consequences of such one-off operations have been correctly evaluated, so as to identify all foreseeable conditions that could affect fuel behaviour.

Easy, routine repetitive operations can lead to careless performance. Mechanisms to ensure adequate and sufficient supervision and checking should be implemented by the operator and enhanced by the regulator.

GOOD PRACTICES

As a complement to the recommendations above, a list of current practices broadly applied in nuclear power plants are presented below. These good practices can be considered to be an important result of operational experience feedback practices because they originated in corrective actions or lessons learned of actual events

Adequate and accurate monitoring are established and maintained to detect and locate a possible fuel failure, or potential conditions for fuel failure. The surveillance is useful in deciding whether to continue operation or to shut down. The method generally used is radiation monitoring of the fuel coolant, with alarm levels adjusted below the technical specification limits to account for fuel failure detection. Prompt detection and location of a failed rod could allow operational actions to be taken (i.e. power reduction) to limit the consequences of the fuel failure. Other examples include the installation of spent fuel pool level instrumentation.

When switching to a new fuel assembly design and operating mixed cores, the operating conditions of the core are analysed very carefully. The possible negative impacts of operating a mixed core are flow inhomogeneities (potential for flow induced vibration or insufficient cooling), and mechanical incompatibility (grid snagging). Hydraulic testing of new fuel designs is usually a necessary precondition, although in some particular cases mixed cores have led to higher rates of fuel failure.

Similarly, when switching to longer cycles, careful assessment is done in order to identify all possible effects of the operational strategies of longer cycles, with respect to core power profiles, reactivity, “spectral shift”, radiation growth, etc.

When changes take place in core operation strategies (higher burnups, longer cycles, more aggressive operational strategies), the following operations, among others are performed very thoroughly: revaluation of actions currently carried out (i.e. fuel assemblies loaded in intermediate positions for fuel shuffling, full core off-loading in refuelling outages, higher residual heat load to the spent fuel pool cooling system, etc.).

Regarding strategies in BWR operation, instability is assessed when defining the core power - core flow map, as well as careful design and verification of the control rod patterns. Power profiles in all likely conditions are carefully taken into account to ensure that peak values are covered under the core licence analysis. Protective actions, i.e. not only manual or procedural, but also automatic actions, have been implemented.

When performing calculations to define fuel limits, or when using models and computers for safety calculations, special attention is paid to the correctness of the model, its implementation, the calculation, and its verification. This is done with regard to the model itself and its coding, but also with regard to the conditions in which the model is applied. These conditions are taken into account in the model, and the model is verified to check that the assumptions, simplifications, parameter values, etc are valid under such conditions.

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Abstract
Fuel performance and reliability, especially fuel integrity, is one of the important aspects of the safe operation of nuclear power plants. The fuel rod cladding surrounding the fuel pellets represents the first barrier to the release of radioactive fission products. Fuel integrity must be maintained during normal operation and expected transients, and fuel damage must be limited during postulated accidents.

Over the years, a very significant effort has been put into analysing and understanding the causes of fuel failures, and important strategies in design, engineering, manufacture, inspection, operation and management have been developed to try to avoid them. The results of this effort are reflected in improvements regarding the use of new materials, a more robust design, new fabrication methods, more efficient inspections of newly built fuel assemblies, quality assurance and better operational strategies. More demanding operational conditions for the fuel, or singular interventions like system decontamination or fuel cleaning, have raised concerns about fuel performance. The result of these counteracting trends is that fuel performance has improved significantly over the years, but there are still some issues which need to be addressed, such as fretting, corrosion, fuel handling, and in storage events.

Based on 169 fuel related events reported in nuclear power plants worldwide, and on the work performed under the EU Clearinghouse on Nuclear Power Plant Operational Experience Feedback, this summary report lists the main causes of actual and potential nuclear fuel failures in three situations: in-core, during handling, and during storage. The report also includes the main recommendations to fuel designers and manufacturers, nuclear power plant operators and regulatory authorities to reduce the incidence of fuel related events, and a list of actions now widely and systematically applied in nuclear power plants that were originated by operational experience exchanges and now constitute a set of good actions that help reduce the number of reported fuel related events.

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