Trieste Workshop

Fuel Safety Criteria

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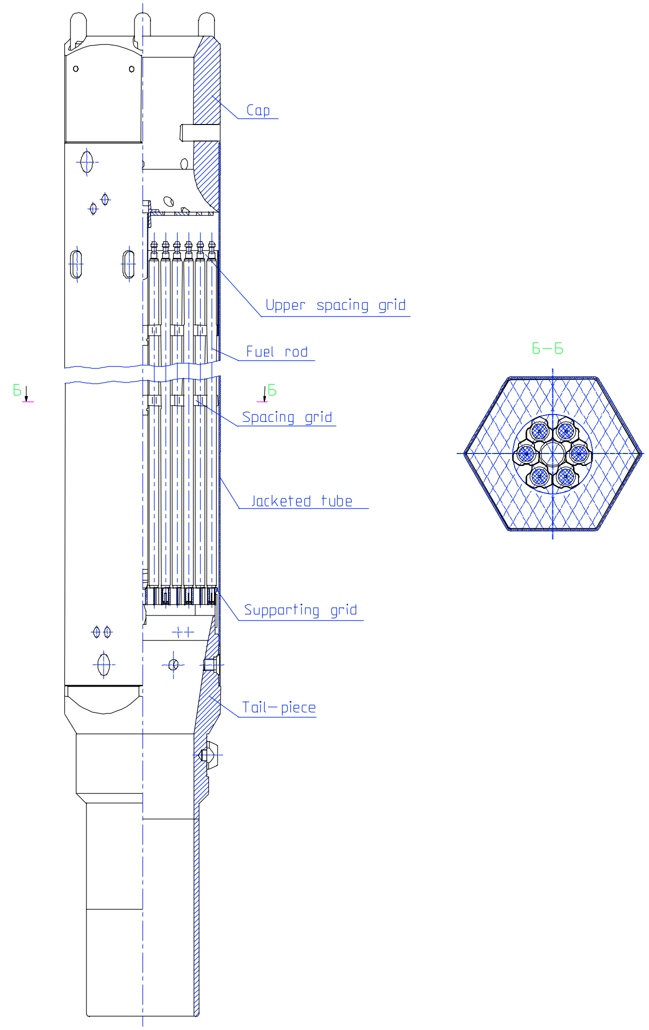
Safety Case overview

The design and operation of Nuclear Fuel is regulated by government authorities and formal procedures are in place to demonstrate that the fuel is designed, manufactured and operated in an acceptable way.

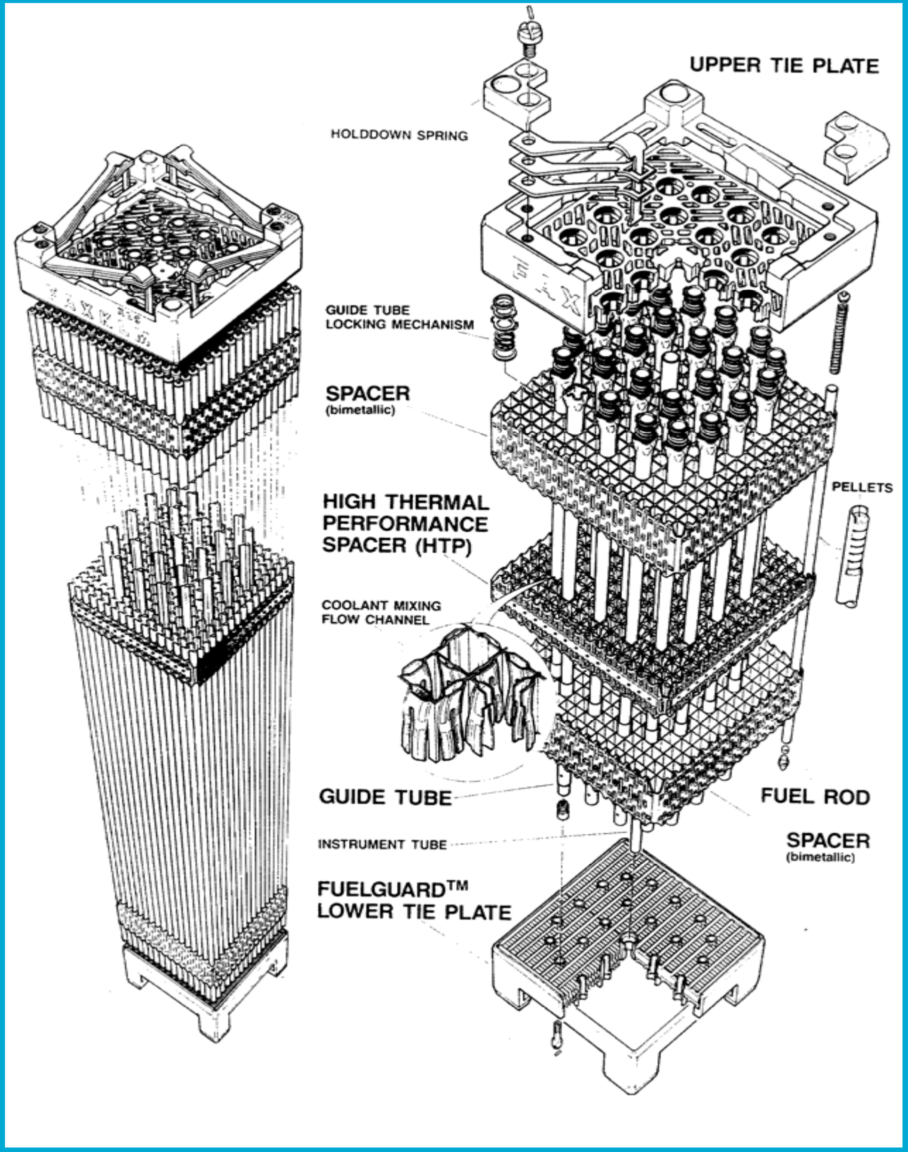
A safety case for operation will need to show that the fuel operates without failure for normal operation, which will include expected transients.

The fuel will also need to behave acceptably in the case of accident conditions.

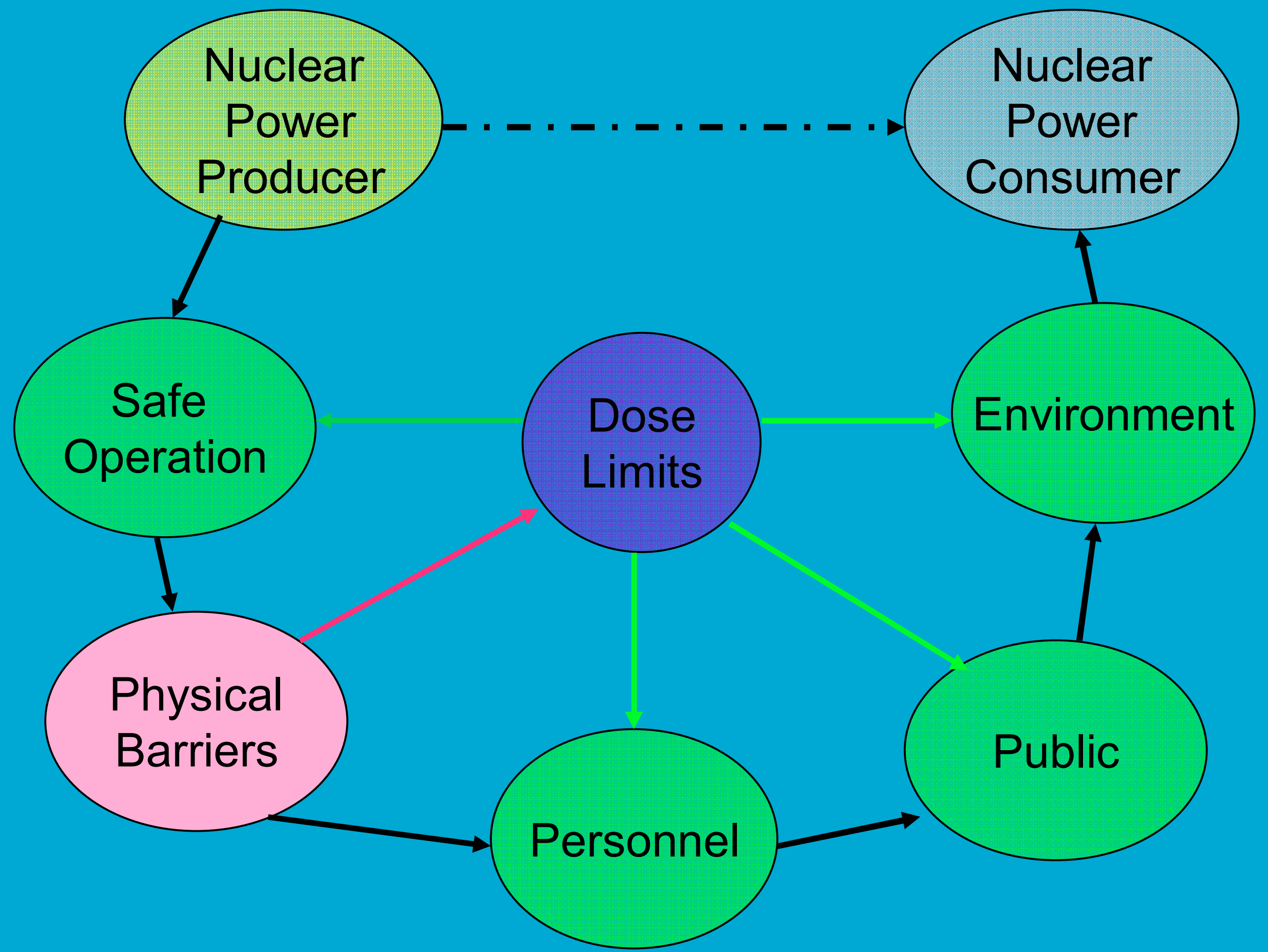
WWER Fuel Assembly



PWR Fuel Assembly



Safety Environment



Safety Case overview

A safety case is in place to demonstrate that the fuel can operate without significant risk to the public and environment.

This does not mean that fuel failure is not allowed, but that the extent of failure and the consequences to the public are contained. This implies that frequent events should not lead to large failures, but that large failures may be tolerable in the case of rare, severe accidents, where other mitigation can be claimed.

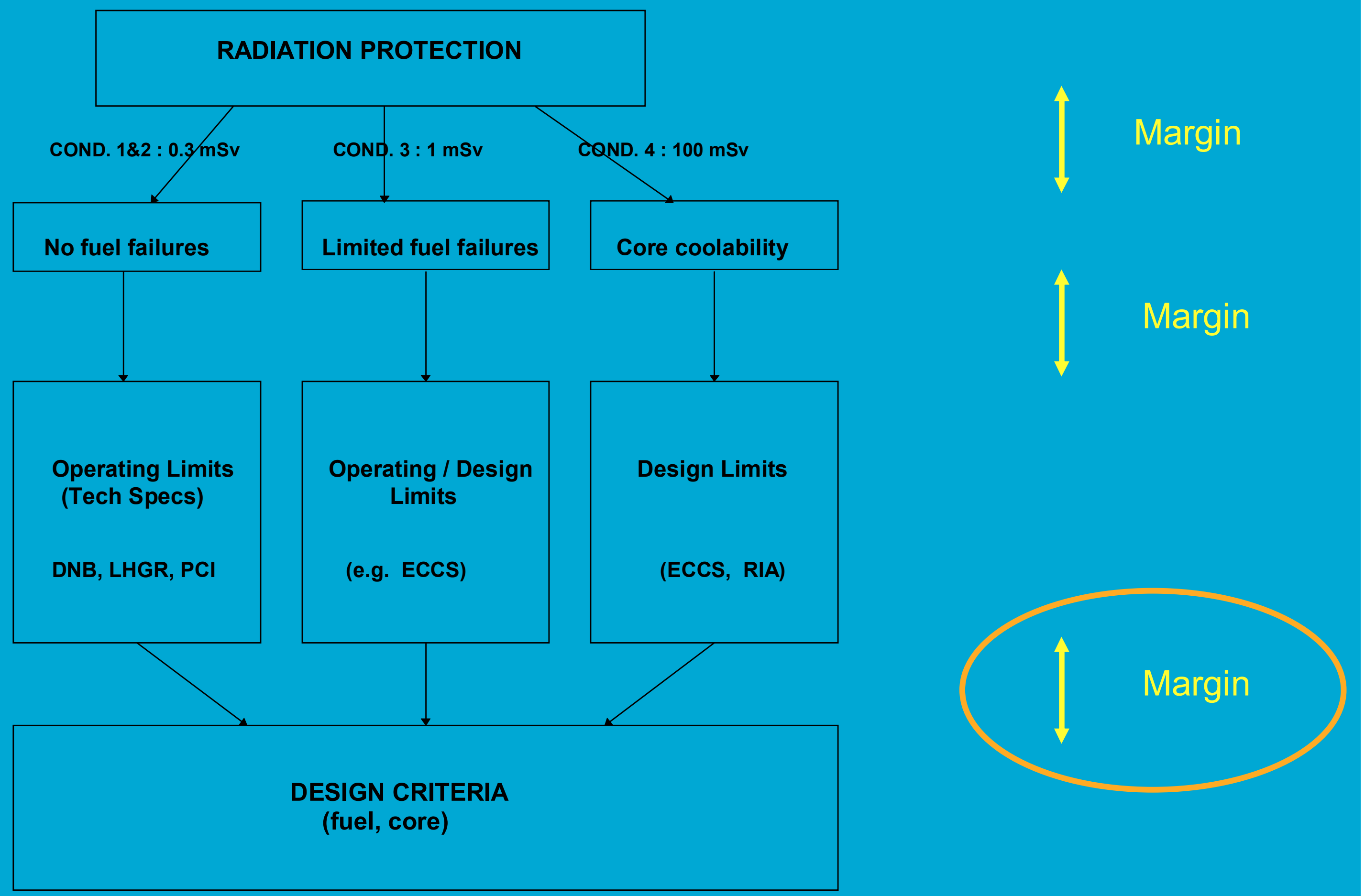
Safety Barriers

1st barrier Fuel matrix	Controlling the power	Controlling the power during NO, transients, accidents, shutdown conditions	Pellet stress pellet cracking FGR
2nd barrier Fuel cladding		Cooling the fuel during NO, transients, LOCA, cold shutdown, refueling	Cladding Strain stress, cracks, PCI
3rd barrier Primary circuit boundary	Cooling the fuel	Confinement leak-tightness during NO	Primary circuit Integrity
4th barrier Containment	Confining the radio-active materials	Confining the RAM during LOCA	Confinement integrity

Safety related criteria

Safety requirements

(Operating) limits



Safety Margin : Operating / Design Limits

⇩ Defined by making 'conservative' assumptions:

- ✦ Fuel and plant data: allowable (not nominal), bounding values
  (Example: EOL cladding oxidation, rod internal pressure, FGR, power history; scram setpoints, valve opening / closure times)
- ✦ Worst case scenarios
  (Example: shutdown reactivity with strongest control rod withdrawn, steamline break with SG tube failure)
- ✦ No credit for plant systems / functions that are not 'safety grade'
  (Example: recirculation runback, partial rod insertion; any operator action)
- ✦ Bounding models / model parameters
  (Example: heat transfer coeff., 10CFR50.46 App.K data for LOCA analysis)

Functional Requirements

Nuclear Fuel has to work:

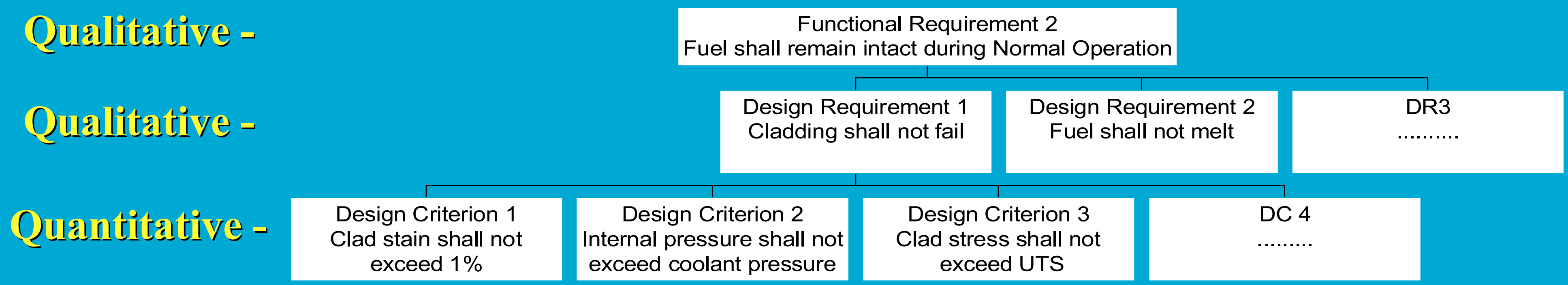
It must produce useable power, reliably and safely.

It is usual to have, as a first step in fuel design, a clear understanding of what you require the fuel to do!

Functional Requirements

Functional requirements provide a simple list of what the fuel must do. The wording may differ from country to country - there are differing Regulatory Requirements that must be met.

Hierarchy of Requirements and Criteria



A safety case may need to demonstrate that over one hundred Design Criteria have been met, some may be easy, others more difficult.

Functional Requirements

These requirements could include:

FR1: The fuel must be able to provide the required quantity of energy

FR2: The fuel must retain fission products during normal operation and expected transients

FR3: The fuel must remain capable of safe handling following a Design Basis Accident

FR4: ……..

Design Requirements

The Functional Requirements can be met through a choice of Design Requirements, that are still qualitative, but are sufficient to ensure that each Functional Requirement can be met.

Design Requirements

For example, FR2 (The fuel must retain fission products during normal operation and expected transients) will be met if the following Design Requirements (among others) are met:

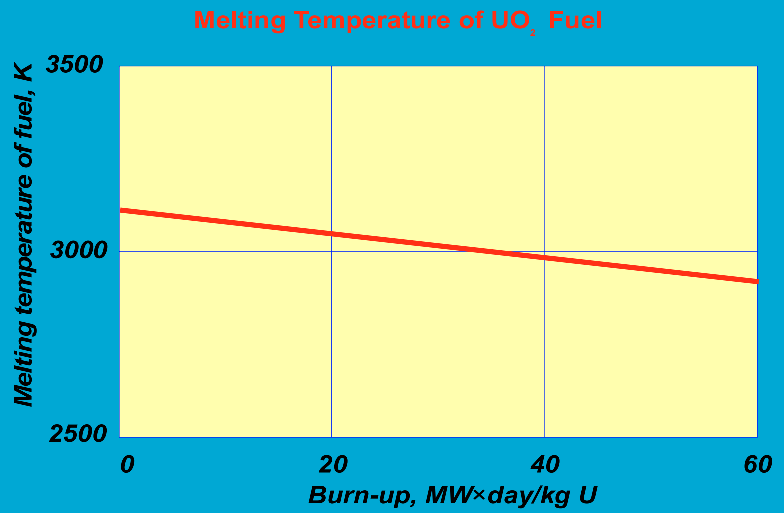
- DR1: The cladding shall remain intact during Normal Operation and Anticipated Transients,
- DR2: The fuel shall not melt
- DR3: ……

Design Criteria

Each Design Requirement can be shown to be met if a number of quantitative criteria are met.

For example, the DR that fuel shall not melt in normal operation can be met by ensuring that the fuel centre temperature does not exceed 2590°C and that the local rod power does not exceed a specified level (eg 65kW/m).

These Design Criteria are well defined numbers and allow for uncertainties in the data (for fuel melt temperature) and calculational uncertainties.



Design Criteria

The DR for no fuel melt would also include a further DC, that the clad does not lift off the fuel, degrading heat transfer.

This criterion could in turn be met by another Design Criterion, which requires a calculation showing, for example, that the rod internal pressure does not exceed coolant pressure. Alternative approaches are possible (eg limited overpressure may be allowable) and it is clear that there is not a single, unique set of DCs suitable for use worldwide.

Design Criteria

Design Criteria are compromises. Clearly fuel will not melt if it is not in a reactor, equally a criterion that allows a fuel centre temperature maximum of – say – 300^{o}C will severely constrain operation of the fuel, whilst certainly preventing melting.

This need to choose a Design Criterion that permits operation whilst protecting the public through a safety case demonstration means that there is always pressure to reduce margins and increase the accuracy of calculations and to better understand if the Criterion is actually required or needs amendment.

Operational Conditions

Nuclear fuel must be shown to be safe for use under various conditions.

The first of these is during Shipping and Handling, and a single Design Requirement would be that the fuel shall not experience loads in excess of design loads. The fuel rods shall not move axially and the fuel pellet stack shall not move axially.

Associated Design Criteria would specify the loads and stresses needed to meet the Design Requirement.

Operational Conditions

Nuclear fuel is then required to withstand Normal Operation and also Frequent Faults, often known as Class 1 Transients. These are conditions that the fuel can reasonably expect to see in use.

Frequent faults are defined as a transient condition that can be expected to occur with a return frequency of around 10^{-2} per year (some countries use a return frequency of 10^{-3}). Events such as a turbine trip or loss of grid connection are examples, such events will cause power transients that could affect the integrity of the fuel.

Operational Conditions

Finally, the fuel needs to be designed to survive Infrequent Faults (Class 2 transients). These events, such as Loss of Cooling Accident (LOCA) can be severe and the fuel is not necessarily expected to survive such faults without cladding failure.

It would be expected that such fuel would be sufficiently damaged that continued operation would not be possible. However the design must be such that coolability is not impaired so that any fault will terminate safely, and subsequent handling of the fuel should be possible.

Operational Conditions

"Beyond Design Basis Accidents".

Under these scenarios, the fuel is assumed to fail and the requirement for fuel is that it retains coolability. The safety case for radiological protection is made on the basis of frequency of occurrence and mitigation by engineering features of the Nuclear Power Plant.

Design Criteria that are safety case related

Many Design Criteria are “generic” in nature, they reflect the use of mechanical design codes (eg ASME) for welds or joints. These are necessary for safety, but comparatively routine, and are met during manufacture and the associated QA and QC programmes.

However, many Design Criteria are more directly related to safety and are the subject of widespread attention throughout the world. These criteria can be affected by core design and operational needs.

Design Criteria that are safety case related

A Design Criterion may apply to one or more of the four operational conditions, if it is only intended for use in Infrequent Fault conditions it would not be appropriate to consider it for less onerous operation, where the normal operation DC might be more limiting.

Two types of safety related criteria

An alternative view:

- Safety related criteria:
  - Requirements: qualitative
    Example: avoid mechanical fracture during a transient due to PCMI
  - Limits: quantitative
    Example: peak fuel cladding temperature < 1200 deg. C

Design Criteria that are safety case related: The OECD/CSNI list

Safety related criteria	Category	New elements affecting criteria	List of New design elements:
CPR/DNBR	A, B, C	1, 2, 5, 6, 7, 9	**1** New fuel designs **2** New core designs **3** New clad materials **4** New manufacturing processes **5** Long cycles **6** Power uprates **7** High Burn-up **8** MOX **9** Mixed core **10** Water chemistry **11** Operating practices
Reactivity Coefficient	B, C	2, 5, 6, 7, 8, 9	
Shutdown margin	A, B, C	1, 2, 5, 6, 7, 8, 11	
Enrichment	A, B, C	1, 2, 5	
Crud deposition	A	1, 2, 3, 4, 5, 7, 10	
Strain Level	A, B	1, 3, 4, 7, 8	
Oxidation	A, B, C	3, 4, 7, 8, 10	
Hydride concentration	A, B, C	3, 4, 7, 8, 10	
Internal gas pressure	A, B, C	1, 5, 6, 7, 8	
Therm-Mech loads	A, B	1, 3, 4, 7	
PCI	A, B, C	1, 2, 3, 4, 6, 7, 8, 11	
Fuel fragmentation (RIA)	C	7, 8	
Fuel failure (RIA)	C	1, 3, 4, 7, 8	
Cladding embrittlement/PCT (non-LOCA run away oxidation)	C	3, 4, 7, 8	***Categories:*** A – Normal operation B- Frequent faults (anticipated transients) C – Infrequent faults (postulated accidents)
Cladding embrittlement / oxidation	C	3, 4, 7, 8	
Blowdown/ seismic loads	C	3, 7	
Assembly holddown force	A, B, C	1, 11	
Coolant activity	A, B, C	5, 6, 7, 8	
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Design Criteria that are safety case related

Critical Power Ratio for BWRs and Departure from Nucleate Boiling Ratio for PWRs – CPR and DNBR

These criteria are related to the critical heat flux (CHF), and are in place to ensure that appropriate cooling of the fuel rods is maintained.

Various statistical limits are in place, eg no more than 0.1% of rods shall fail due to DNB in a frequent fault. Generally analysis is statistical in nature and appropriate statistical account is taken for the many uncertainties in the analysis.

Design Criteria that are safety case related

CPR and DNBR (cont.)

The heat transfer properties of a fuel assembly are dependent on fuel assembly design and the manufacturers have heat transfer correlations that are used in analysis. Analysis is also carried out on specific core designs and be be complicated by mixed core issues. Analysis is carried out at many points during a cycle and is carried out using Monte-Carlo techniques.

WWER manufacturers also use CHF correlations

Design Criteria that are safety case related

CPR and DNBR (cont.)

Important issues can arise from manufacturers proprietary information. For example, each manufacturer will have his own DNB correlation, which is commercially confidential, and only applicable to their fuel design.

If a utility changes its fuel vendor, the new vendor will not have access to the old correlation and the mixed core will be designed with conservative assumptions.

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Design Criteria that are safety case related

Reactivity of the fuel

Enrichment: There is a limit of 5% ^{235}U due to practical handling difficulties and limits on criticality experiments above 3.5% ^{235}U.

Design Criteria that are safety case related

Reactivity of the fuel

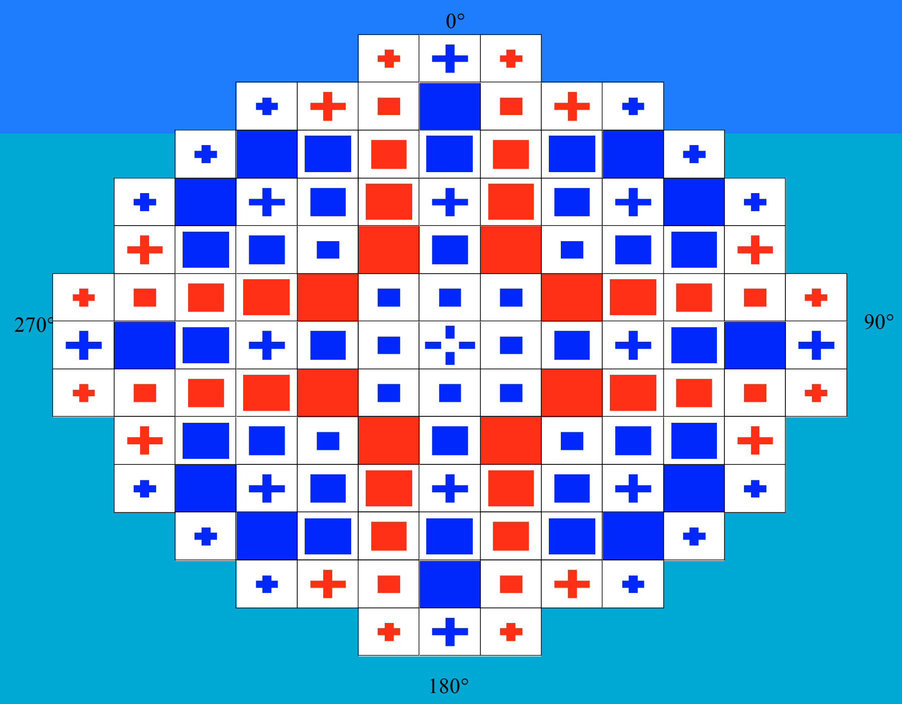
Reactivity coefficients limit core design. A core must have a negative reactivity coefficient to prevent accidents such as Chernobyl. Several items contribute: void coefficients, temperature and Doppler coefficients, for PWR the sum of these must be negative – for WWER all coefficients must be negative at all times!

Design Criteria that are safety case related

Reactivity of the fuel

The shutdown margin is to ensure that there is enough worth in the control system that the reactor can be shut down (and held at shutdown) even if the most important control rods are stuck out of the core.

Example of a multiple region PWR core design



U-FA, 4.55 w/o U235 | **MOX-FA, 5.84 w/o Pu-fiss**

1st Irrad. Period

2nd Irrad. Period

3rd Irrad. Period

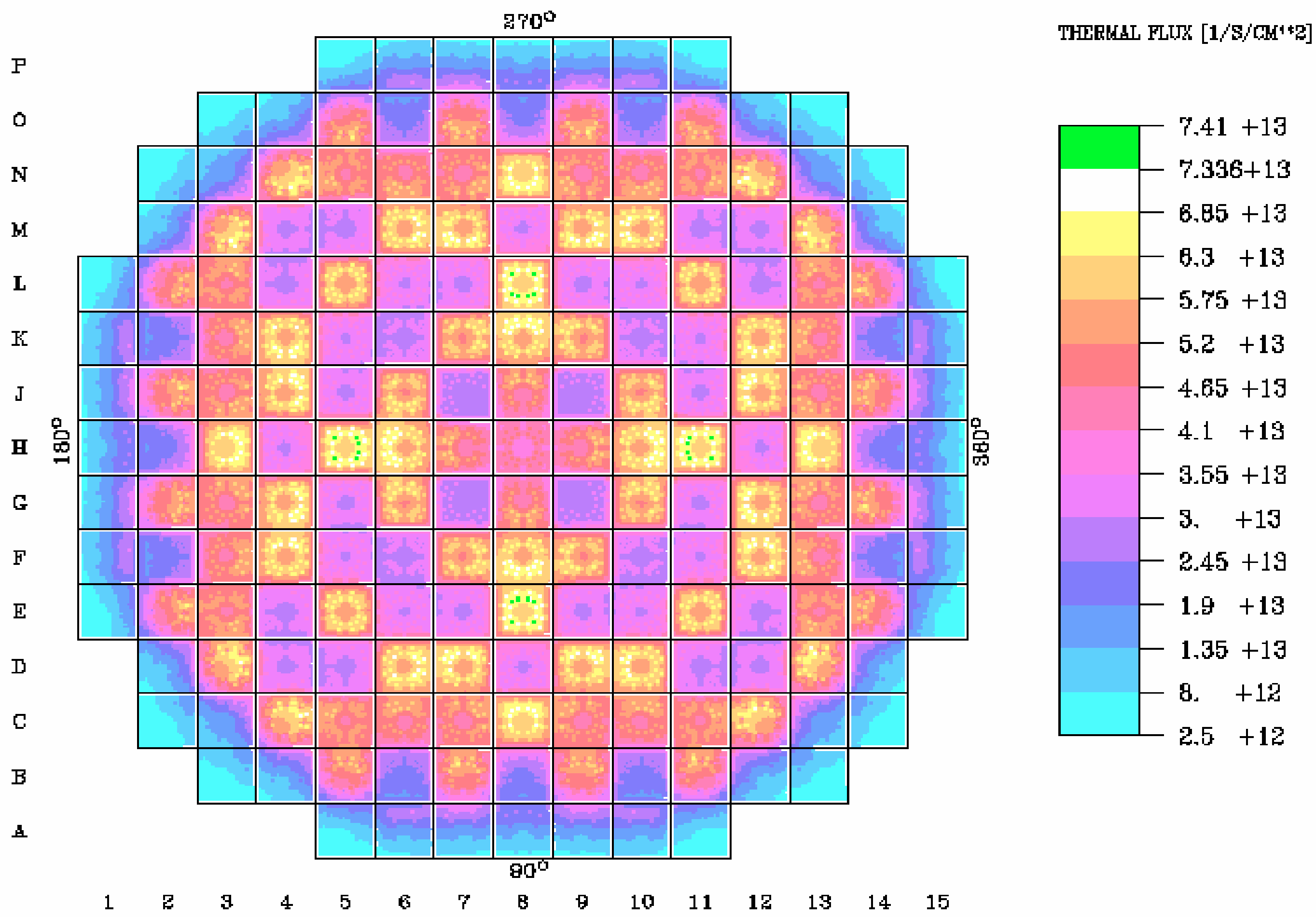
4th Irrad. Period

5th Irrad. Period

6th Irrad. Period

1 U-FA, 7th Irrad. Period

PWR, low leakage core loading (example)



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Design Criteria that are safety case related

Crud

Crud deposition is a phenomenon that has caused significant problems, in PWRs the crud on the fuel can lead to power redistribution in the core due to boron concentrating in the crud. Occasionally enhanced corrosion and subsequent rod failure has occurred due to inadequate heat transfer through the crud.

Design Criteria that are safety case related

PWRs

- Assumed amount of crud taken into account for fuel/core design
- Influences corrosion performance, H-uptake
- Causes axial offset problems
- Dependent on water chemistry conditions

WWERs: no criterion

- different water chemistry --> almost no crud deposit on fuel
- large amounts of crud in primary circuit --> high dose rates & low-level waste

Crud problems PWRs

- **(1)** Axial Offset Anomaly (AOA):
  - Crud buildup in upper part of PWR core, particularly high power assemblies
  - $LiBO_2$ absorbed in crud layer --> power distribution shifts to the bottom: AOA
  - Reduction in SDM, increase in local peaking
  - Burnup effect (long term) --> power shifts to top
    - Observed in high energy PWR cores
    - Analysis: amount of subcooled boiling is most significant --> evaluate and limit nucleate boiling in top of core --> fewer AOA problems
    - Limits affected: SDM, thermal-mechanical (power peaking)

Crud problems PWRs

- (2) CILC (crud induced localized corrosion, 1970’s): Cu, nodular corrosion ----> smaller size SPP, not critical PWR

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Design Criteria that are safety case related

Stress and strain limits are generally conservative, eg 1% yield stress or 1% elastic and plastic circumferential strain.

Stress and strain analysis are carried out by code calculations, but it is much easier to validate a code against strain, which is experimentally measureable, rather than stress.

Such limits are part of an overall "Thermo-mechanical limit"

Design Criteria that are safety case related

- Prevent cladding damage due to large static and cyclic loads
- PWRs:
  - max. allowed stress (load), usually function of yield and tensile strength
  - max. strain (deformation, creep)
  - limit cumulative effect of cyclic loads
  - analytical verification, fuel/core design
- WWERs:
  - cladding stress < yield strength
  - no strain limit
  - fatigue limit, including creep
- WWER stress criterion more conservative
  Therefore almost no plastic strain --> no limit needed
  Creep included in WWER fatigue limit

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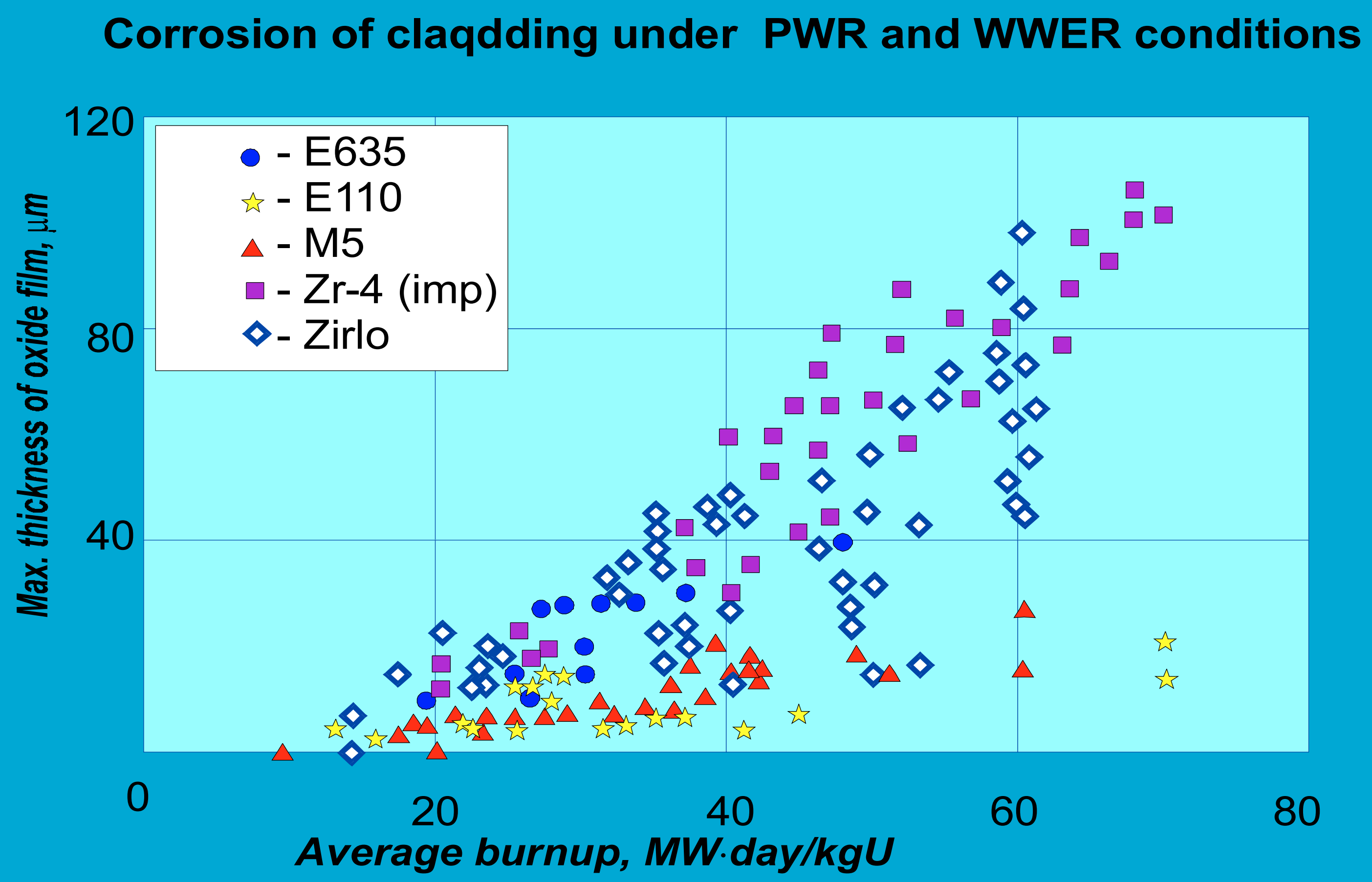
Oxidation, hydriding

- **PWRs:**
  - Only design limits defined (e.g. 100 µm, 500-600 ppm)
  - Corrosion / hydriding of cladding foremost limiting parameter for fuel lifetime (high burnup!)
  - Not directly responsible for cladding rupture/fracture, however influence stress/strain performance
  - Fracture toughness possible criterion ??
- WWERs:
  - Design limits defined (different values, different fuel designs)
  - Corrosion very low for ZrNb materials + different water chemistry

- No limits on internal oxidation, which becomes more important at high burnup

Design Criteria that are safety case related



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Cladding embrittlement/PCT (non-LOCA run away oxidation)	C	3, 4, 7, 8
Cladding embrittlement / oxidation	C	3, 4, 7, 8
Blowdown/ seismic loads	C	3, 7
Assembly holddown force	A, B, C	1, 11
Coolant activity	A, B, C	5, 6, 7, 8
Gap activity	C	5, 6, 7, 8
Source term	C	5, 6, 7, 8

List of New design elements:

1 New fuel designs
2 New core designs
3 New clad materials
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5 Long cycles
6 Power uprates
7 High Burn-up
8 MOX
9 Mixed core
10 Water chemistry
11 Operating practices

Categories:

A – Normal operation

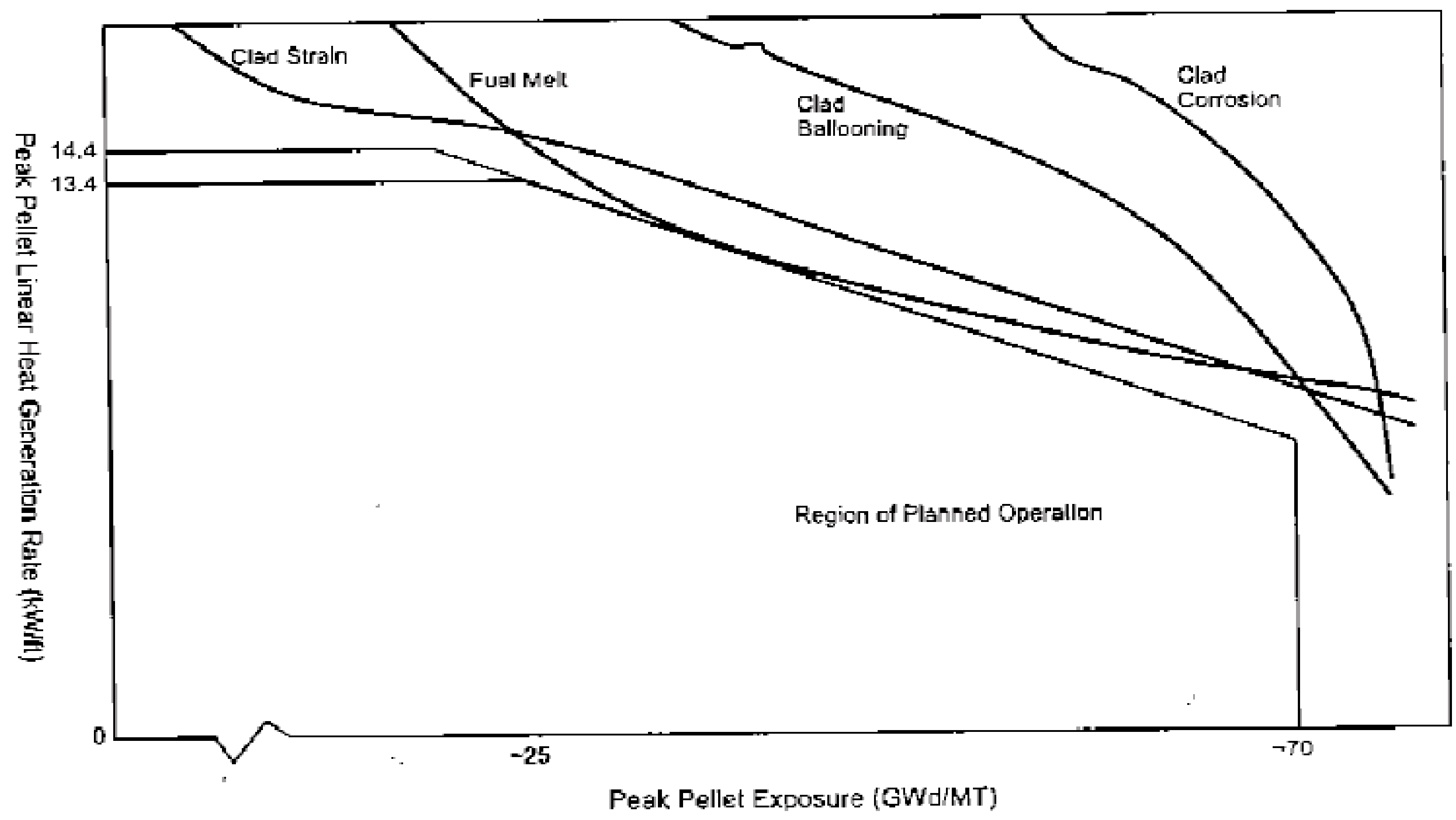
B- Frequent faults (anticipated transients)

C – Infrequent faults (postulated accidents)

Rod internal gas pressure

- PWRs: two criteria
  - rod internal pressure < RCS pressure (prevent outward creep)
  - limit rod pressure such that instant. cladding creepout rate due to rod pressure>RCS pressure does not exceed instant. fuel swelling rate (fuel-to-clad gap does not open: "lift-off")
- Some WWER countries: one criterion
  - rod internal pressure < 90% of RCS pressure
  - more restrictive / conservative approach

Example of thermal-mechanical limit



Design Criteria that are safety case related: The OECD/CSNI list

Safety related criteria	Category	New elements affecting criteria
CPR/DNBR	A, B, C	1, 2, 5, 6, 7, 9
Reactivity Coefficient	B, C	2, 5, 6, 7, 8, 9
Shutdown margin	A, B, C	1, 2, 5, 6, 7, 8, 11
Enrichment	A, B, C	1, 2, 5
Crud deposition	A	1, 2, 3, 4, 5, 7, 10
Strain Level	A, B	1, 3, 4, 7, 8
Oxidation	A, B, C	3, 4, 7, 8, 10
Hydride concentration	A, B, C	3, 4, 7, 8, 10
Internal gas pressure	A, B, C	1, 5, 6, 7, 8
Therm-Mech loads	A, B	1, 3, 4, 7
PCI	A, B, C	1, 2, 3, 4, 6, 7, 8, 11
Fuel fragmentation (RIA)	C	7, 8
Fuel failure (RIA)	C	1, 3, 4, 7, 8
Cladding embrittlement/PCT (non-LOCA run away oxidation)	C	3, 4, 7, 8
Cladding embrittlement / oxidation	C	3, 4, 7, 8
Blowdown/ seismic loads	C	3, 7
Assembly holddown force	A, B, C	1, 11
Coolant activity	A, B, C	5, 6, 7, 8
Gap activity	C	5, 6, 7, 8
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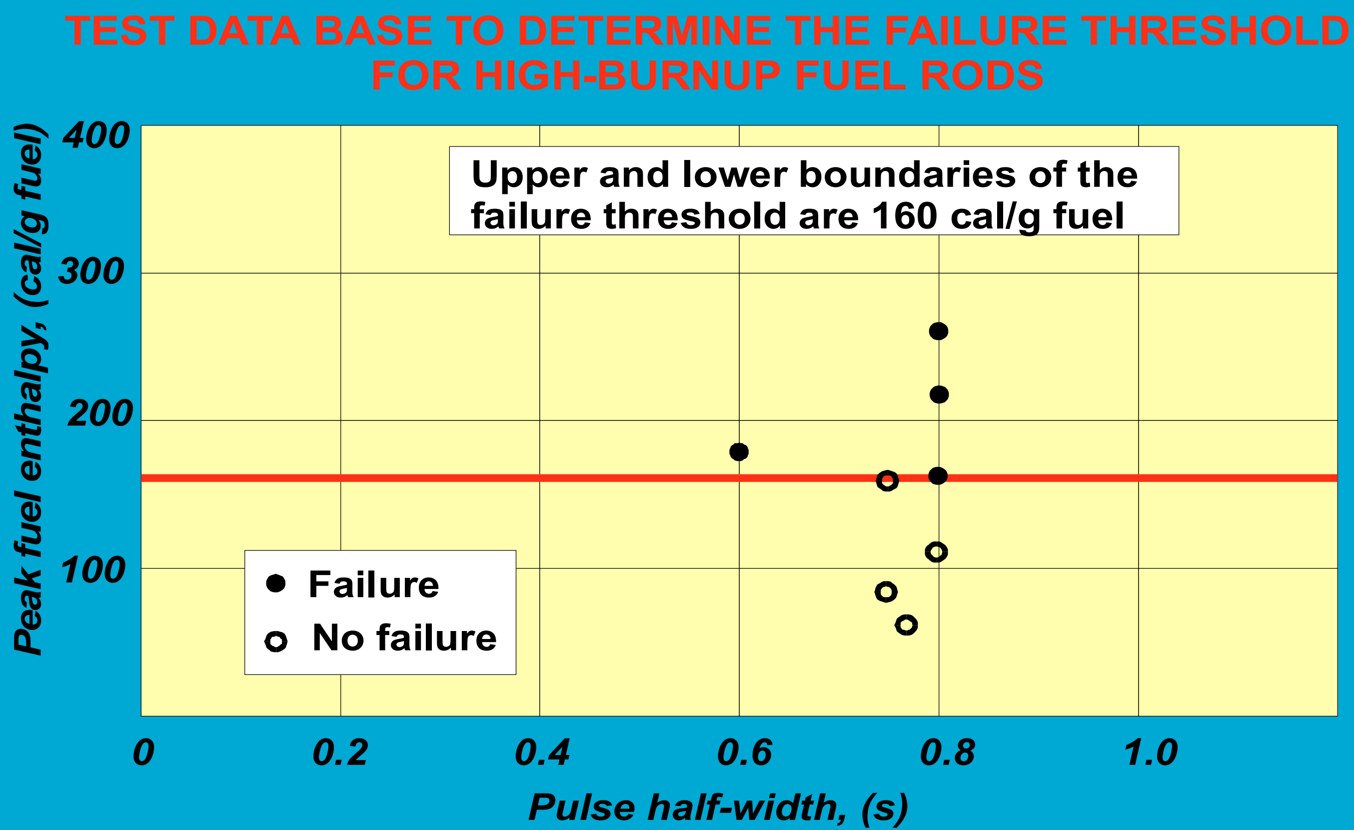
Design Criteria that are safety case related



PCI

- Pellet-Clad-Interaction: stress corrosion cracking
- Stress and corrosion of cladding necessary

- Widely investigated in the 1970's
- Control: PCIOMRs (operating rules)
  - limit power ramps
  - condition fuel to power ramps
- Fuel type / vendor dependent limits
- Remedy: PCI resistant fuel
  - liner/barrier: Zirconium coating inside clad
  - additives: Sn, Fe

Design Criteria that are safety case related: The OECD/CSNI list

Safety related criteria	Category	New elements affecting criteria
CPR/DNBR	A, B, C	1, 2, 5, 6, 7, 9
Reactivity Coefficient	B, C	2, 5, 6, 7, 8, 9
Shutdown margin	A, B, C	1, 2, 5, 6, 7, 8, 11
Enrichment	A, B, C	1, 2, 5
Crud deposition	A	1, 2, 3, 4, 5, 7, 10
Strain Level	A, B	1, 3, 4, 7, 8
Oxidation	A, B, C	3, 4, 7, 8, 10
Hydride concentration	A, B, C	3, 4, 7, 8, 10
Internal gas pressure	A, B, C	1, 5, 6, 7, 8
Therm-Mech loads	A, B	1, 3, 4, 7
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Blowdown/ seismic loads	C	3, 7
Assembly holddown force	A, B, C	1, 11
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Categories:

A – Normal operation

B- Frequent faults (anticipated transients)

C – Infrequent faults (postulated accidents)

Design Criteria that are safety case related: Fuel rod integrity criteria

These criterion were originally derived on the basis of experiments with unirradiated fuel. There is considerable discussion and work being carried out to ensure that they are suitable for use with high burnup fuel arising from new burnup limits.

Experimentation on high burnup fuel is very expensive and difficult.

They are related to accident conditions only.

Design Criteria that are safety case related: Fuel rod integrity criteria

Typical numerical values

Fault type	Oxidation and Hydriding	Cladding Temperature	Energy Deposition
LOCA	Maximum local oxidation <17%	Peak Clad Temperature <1204°C	-
PCM and ATWT	Time at Temperature Curve [1]	-	-
RIA	-	Peak Clad Temperature <1482°C	752 kJ/kg [2]

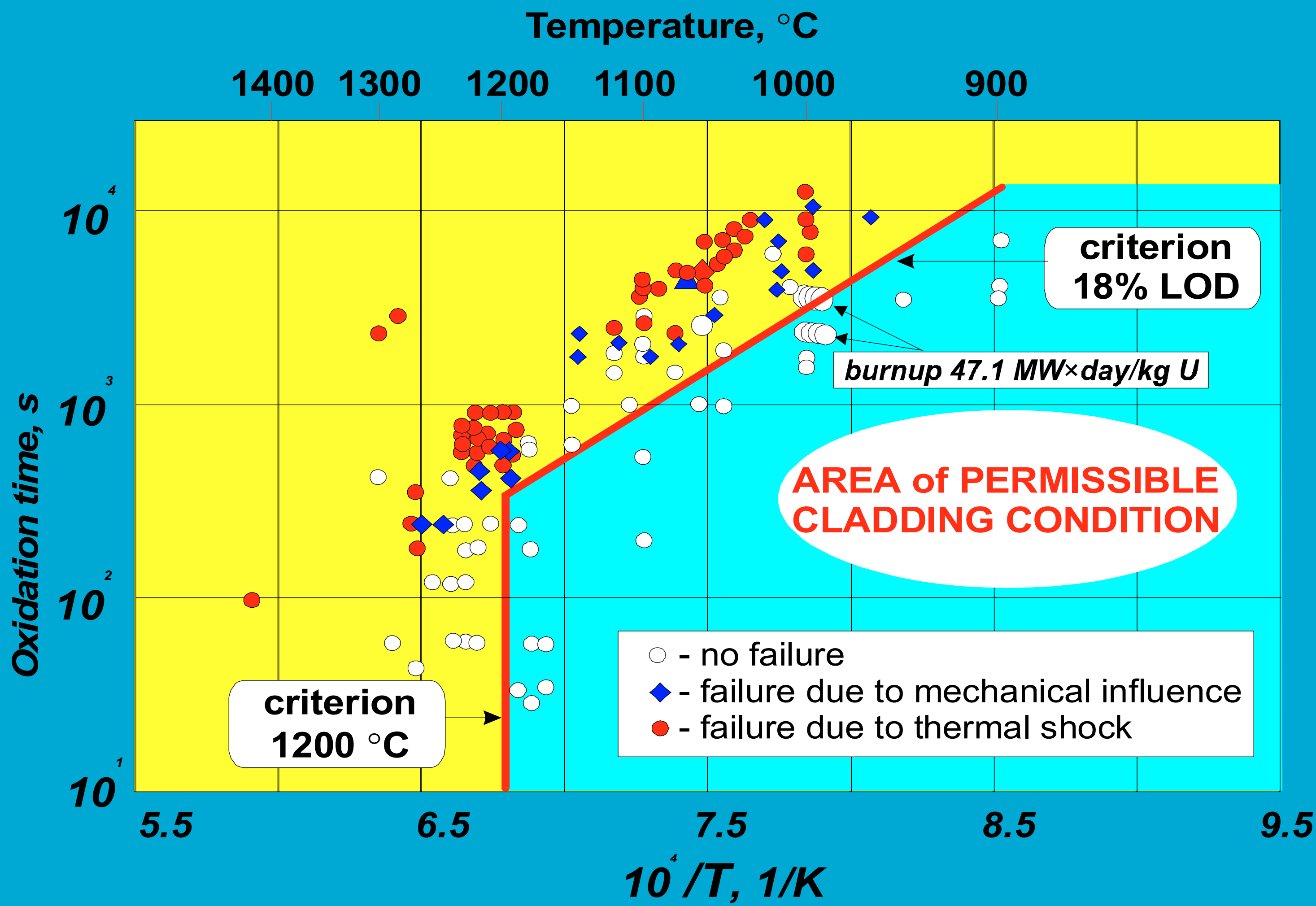
Notes:

1 See Figure 10 of IR4.3(1) Handling Criterion

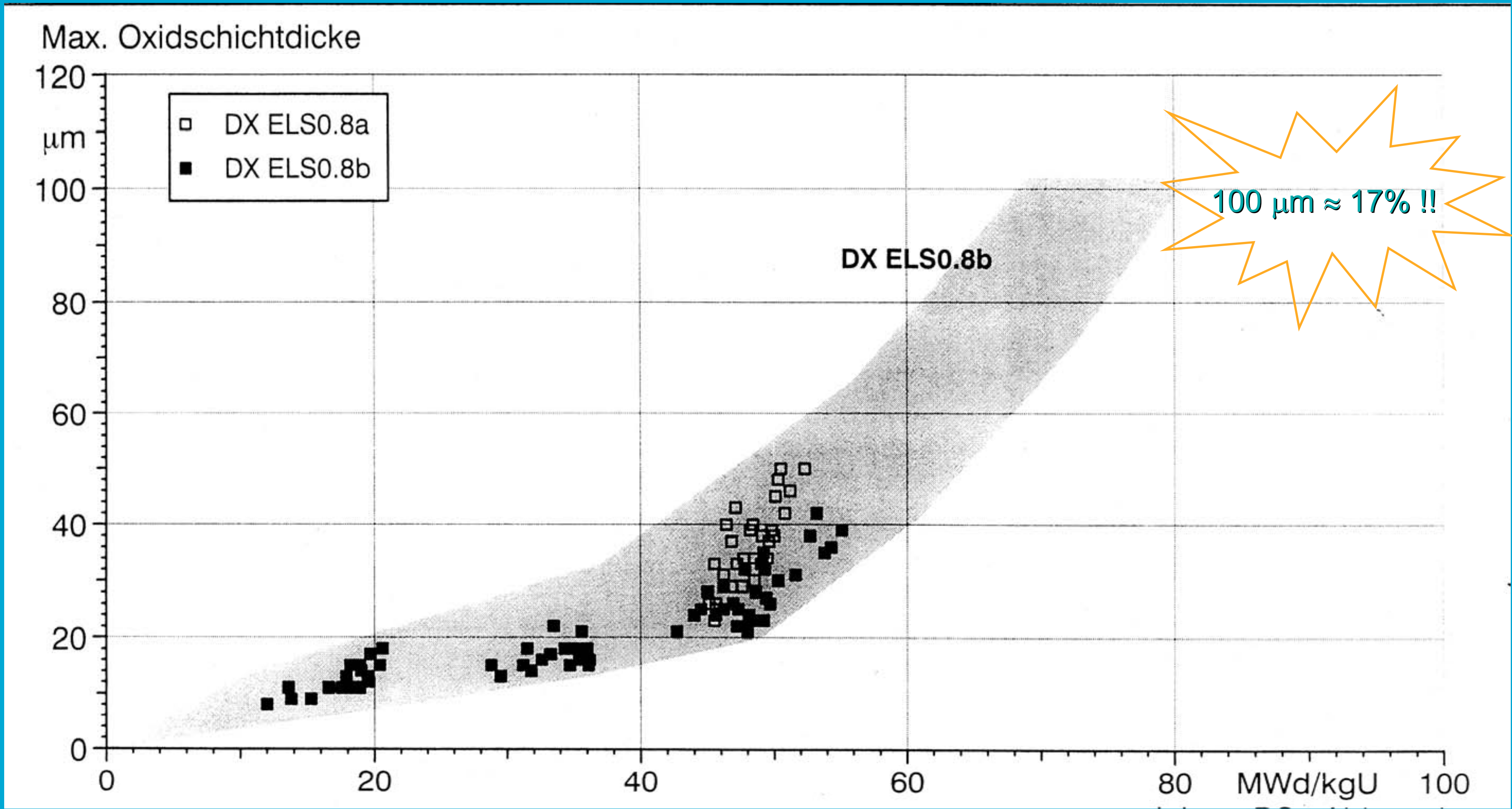
2 This limit is reduced to 251kJ/kg for pre-failed fuel, which has become waterlogged. However, the number of these rods is so small that their effect on core degradation can be neglected.

Design Criteria that are safety case related

Diagram of E-110 cladding failure



Cladding oxidation PWR (sample)



RIA - test results and (possible) limits

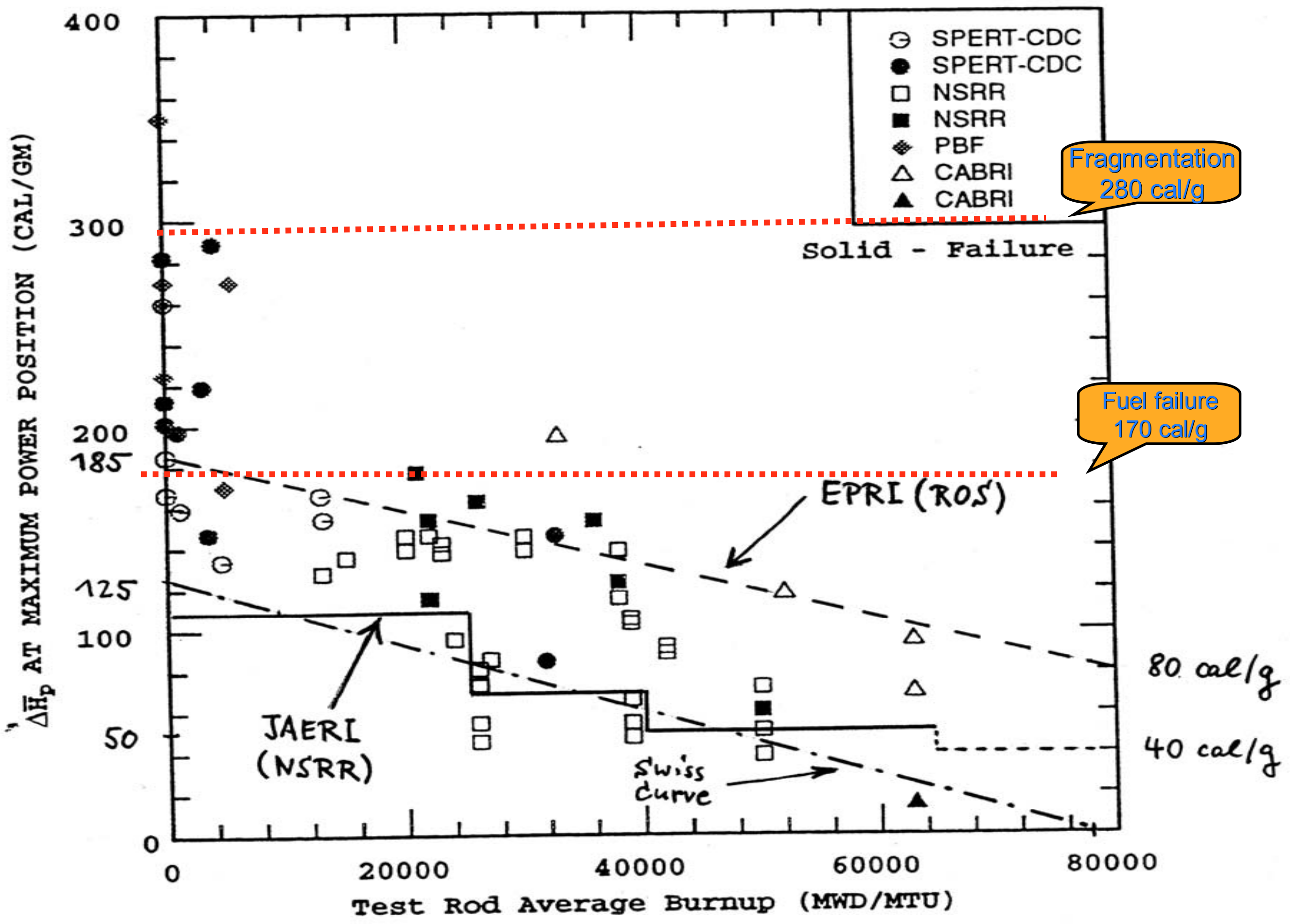


Figure S-1
Database of RIA-Simulation Tests Performed on LWR-Type Test Rods

Design Criteria that are safety case related: The OECD/CSNI list

Safety related criteria	Category	New elements affecting criteria	List of New design elements:
CPR/DNBR	A, B, C	1, 2, 5, 6, 7, 9	**1** New fuel designs
Reactivity Coefficient	B, C	2, 5, 6, 7, 8, 9	**2** New core designs
Shutdown margin	A, B, C	1, 2, 5, 6, 7, 8, 11	**3** New clad materials
Enrichment	A, B, C	1, 2, 5	**4** New manufacturing processes
Crud deposition	A	1, 2, 3, 4, 5, 7, 10	**5** Long cycles
Strain Level	A, B	1, 3, 4, 7, 8	**6** Power uprates
Oxidation	A, B, C	3, 4, 7, 8, 10	**7** High Burn-up
Hydride concentration	A, B, C	3, 4, 7, 8, 10	**8** MOX
Internal gas pressure	A, B, C	1, 5, 6, 7, 8	**9** Mixed core
Therm-Mech loads	A, B	1, 3, 4, 7	**10** Water chemistry
PCI	A, B, C	1, 2, 3, 4, 6, 7, 8, 11	**11** Operating practices
Fuel fragmentation (RIA)	C	7, 8	
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Cladding embrittlement/PCT (non-LOCA run away oxidation)	C	3, 4, 7, 8	***Categories:***
Cladding embrittlement / oxidation	C	3, 4, 7, 8	A – Normal operation
Blowdown/ seismic loads	C	3, 7	
Assembly holddown force	A, B, C	1, 11	B- Frequent faults (anticipated transients)
Coolant activity	A, B, C	5, 6, 7, 8	
Gap activity	C	5, 6, 7, 8	
Source term	C	5, 6, 7, 8	C – Infrequent faults (postulated accidents)

Design Criteria that are safety case related

These criteria will often be specific to the plant location and to the maximum expected earthquake. Japan and the UK have different earthquake experience and therefore probabilities!

Mixed core issues can be important and there may be variation in the assembly response to Seismic/LOCA events with high burnup.

Design Criteria that are safety case related

Assembly holddown force is a requirement to ensure core stability. For PWRs the requirement is usually that vertical lift-off forces must not unseat assembly from fuel support structure for condition I and II events.

– but safety analysis has been used to justify the use of assemblies where the holddown springs may have failed through PWSCC of the holddown spring bolts!

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Design Criteria that are safety case related

Coolant activity limits are in place to ensure that the amount of activity available for release in an accident is limited. There are also operator dose considerations. This is generally monitored by the Plant, and the activity will arise from fuel failure in core.

Gap activity and source term limits are in place for more severe accidents where fuel rod failure can occur and fast release of the gap inventory can occur. There is usually a conservative safety case limit, and analysis to demonstrate compliance.

Results from comparison PWR-WWER

	Criterion	Summary of comparison
1	**DNB safety limit**	Difference only in CHF-correlations used
2	**Reactivity coefficients**	In some WWER operating countries, each reactivity coefficient must be negative
3	**Shutdown margin**	Additional requirement in Russia for new generation NPPs: no recriticality down to 100 deg C coolant temp.
4	**Enrichment**	No difference
5	**Internal gas pressure**	In some WWER operating countries, the more restrictive of the PWR criteria is used
6	**PCMI**	Same approach, however different basis for defining criteria
7	**RIA fragmentation**	Different limit values, approach identical
8	**Non-LOCA runaway oxidation**	Criterion A-9 applies to all DBA; different value for some PWRs, safety approach identical
9	**LOCA-PCT**	Same limit value, but different basis
10	**LOCA-Oxidation**	Almost same limit value, but different basis
11	**LOCA-H release**	No difference
12	**LOCA-long term cooling**	No difference in approach
13	**Seismic loads**	No difference in approach
14	**Holddown force**	No difference
15	**Criticality**	No difference

Results from comparison PWR-WWER

	Criterion	Summary of comparison
1	**DNB operating limit**	Same basic requirement, but different licensing approach (see Item C-9)
2	**LHGR limit**	Same approach
3	**PCI**	No difference in approach, rules/values are design dependent
4	**Coolant activity**	Same approach, WWERs have extra (lower) limit for decision on further operation
5	**Gap activity**	For WWERs, no separate criterion - covered by B-6
6	**Source term**	Different approaches, country dependent
7	**Control rod drop time**	No difference
8	**RIA fuel failure limit**	In some WWER operating countries, the number of failures not calculated. There is however a fuel vendor recommende failure limit (see text)

Results from comparison PWR-WWER

	Criterion	Summary of comparison
1	**Crud deposition**	For WWERs, no limit due to different water chemistry (see text)
2	**Stress / strain / fatigue**	Differences due to more restrictive stress criterion for WWERs, overal approach identical
3	**Oxidation**	Same approach, differences are due to different fuel designs
4	**Hydride concentration**	See C-3
5	**Transport loads**	Same approach
6	**Fretting wear**	Same approach, two additional design criteria for WWERs due to different spacer design
7	**Clad diameter increase**	Additional strain criterion for WWERs
8	**Cladding elongation**	Same criterion, applies to conditions I and II for PWRs and to conditions I to IV for WWERs
9	**Radial peaking factor**	Same criterion, different licensing approach
10	**3D peaking factor**	Same criterion, different licensing approach
11	**Cladding stability**	Same approach, additional design criterion for WWERs

Review of WWER and LWR Safety Criteria

- Fuel safety related criteria very similar (if not identical)
- Differences due to different fuel and/or different reactor type
- In some cases, WWER criteria more conservative (partly due to the Chernobyl accident)

Exposure limits (sample)

Country	Fuel type	Limit (MWd/kg)	Basis
Canada	CANDU	20	assembly average
Netherlands	various PWR	various spec. up to 60	rod/assembly average
France	various PWR	52 (UO_2), 42 (MOX)	assembly average
Germany	various PWR/BWR	52 - 57	assembly average
Hungary	various	60 (BNFL), 55 (Russian)	rod average
Japan	various BWR PWR	55 (UO_2), 40 (MOX) 48 (UO_2), 45 (MOX)	assembly average
Korea	various	60 (W), 58 (CE)	rod average
Spain	various PWR/BWR	various spec.	
Sweden	various PWR/BWR	various spec.	
Switzerland	various PWR/BWR	various spec. up to 60 (PWR) and 50 (BWR)	rod/assembly average
USA	various PWR/BWR	various spec. up to 62	rod average

Are fuel safety criteria still adequate?

- Industry trend: (further) reduce fuel cycle cost → optimize fuel/core operation
- Higher discharge burnup (industry programs aiming as high as 100’000 MWd/t)
- Advanced fuel / core designs and methods required to support these high burnups

Important 'new' design elements

- Advanced / optimized fuel & core designs:
  - smaller rods: PWR: 14x14 → 18x18
  - part length rods
  - burnable poison, axially varying U and Gd enrichment
  - MOX, RepU
  - low leakage core
  - mixed core
  - longer than annual cycles
- High burnup
- New cladding materials (Zirlo, M5)
- New manufacturing procedures (e.g. corrosion resistance)
- Power Uprates

Effect from “new” design elements (1)

- Oxidation, hydriding
  - Corrosion / hydriding of cladding foremost limiting parameter for fuel lifetime (high burnup!)
  - Concerns: effects from oxide spalling, high H concentrations transient/accident performance
  - Not directly responsible for cladding rupture/fracture, however influence stress/strain performance
  - Fracture toughness ??!!

- Rod internal gas pressure
  - Transients/accidents: excessive clad ballooning and bursting → core coolability (especially lift-off)
  - Rapid FGR increase at high burnup (RIM influence!) Especially important for transients/accidents
  - MOX fuel: higher FGR

Effect from “new” design elements (2)

- PCMI
  - High burnup concerns:
    - larger FGR (FG expansion contributes to strain)
    - clad ductility reduced (radiation embrittlement)
    - pellet-clad gap closed (limited free expansion of pellet)
  - Criteria should not change, but analysis and methods to be reviewed

Effect from “new” design elements (3)

- RIA - fragmentation, fuel failure
  - Tests CABRI, NSRR : signs of fuel particle dispersal at high exposure, enthalpies well below limit
  - High burnup issue:
    - Mechanism for particle dispersal (other than fuel melting)?
    - FG on grain boundaries, rapid gas expansion
    - RIM zone
  - Need for understanding of fragmentation process + effects of high burnup thereon, and for improved modeling ($\rightarrow$ tests !)
  - Criteria may be OK, however limit ?

Effect from "new" design elements (4)

- LOCA
  - ➢ Interpretation of 17% oxidation limit ? (different oxidation mechanisms)
  - ➢ Appropriateness of limits, especially at high burnup ?
    - ➢ Clad behavior during quenching / long term cooling
    - ➢ Fine fragmentation of fuel
    - ➢ Fuel relocation in ballooned region
    - ➢ Potential subchannel blockage
    - ➢ etc.
  - ➢ US review of 10CFR50.46 App. K ?
  - ➢ Basic safety requirements may still be adequate, however tests (especially at high burnup) needed to resolve open issues & for method validation
  - ➢ Test programs ongoing!

Effect from “new” design elements (5)

- Source term, gap activity
  - high burnup: FP release to gap increases (same for MOX fuel)
    --> assumptions may need to be revised
  - analyses performed regularly: fuel / core design dependent
    --> ‘new design elements’ accounted for
  - source terms: no large effect from e.g. high burnup, MOX
  - but: analysis methods must be adequate
  - also: large variation of assumptions between countries
  - Revised Source Term Implementation activities US ?

Effect from “new” design elements (6)

- Analysis methods
  - need for further improvements in methods, as performance can be affected by ‘new design elements’
  - understand and predict fuel performance
  - verification/validation important ---> research important!
  - trend towards best-estimate methods; here uncertainty analysis needed!

Power peaking problems PWR

- Highly optimized fuel & core designs ----> power mismatch ----> excessive power peaking
- Control rods with “large” quantum step

- Criteria affected: LHGR, PCMI (overpower), PCI

- Limit by design of fuel / core
- Improve materials

References

Fuel Safety Criteria Technical Review
NEA of the OECD CSNI/R(99)25,OECD, Paris (2001)

Analysis of Differences in Fuel Safety Criteria for WWER and Western PWR Nuclear Power Plants
IAEA publication: IAEA-TECDOC-1381 (November 2003)

Any Queries?