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Failure Mode Effects and Criticality Analysis for Nuclear Fuel Reliability Improvement of a Commercial PWR

ISSNP-SS-03

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Part 1

Introduction &Background

STSS: International Symposium on Socially and Technically Symbiotic Systems

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Review of the fuel reliability

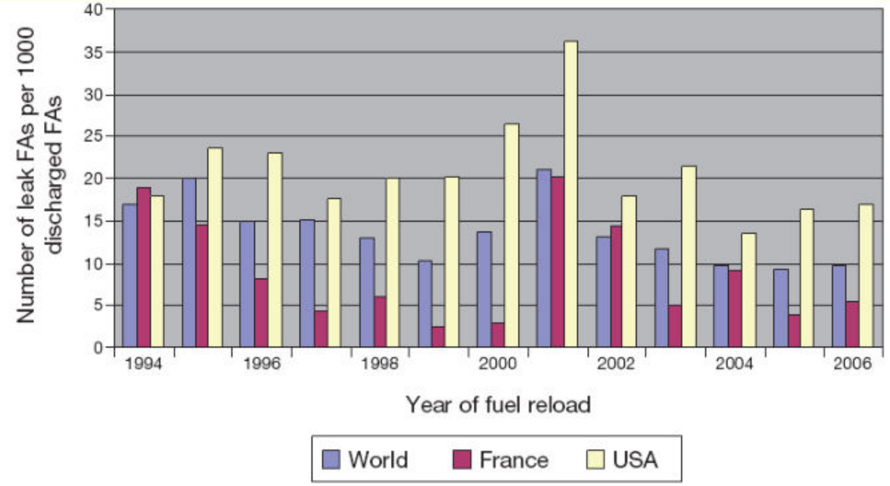

Fig.1 FA failures from 1994~2006

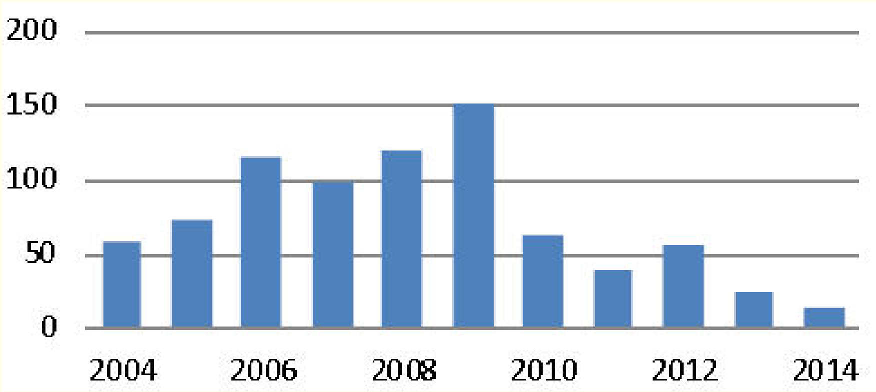

Fig.3 Failed rods of Westinghouse

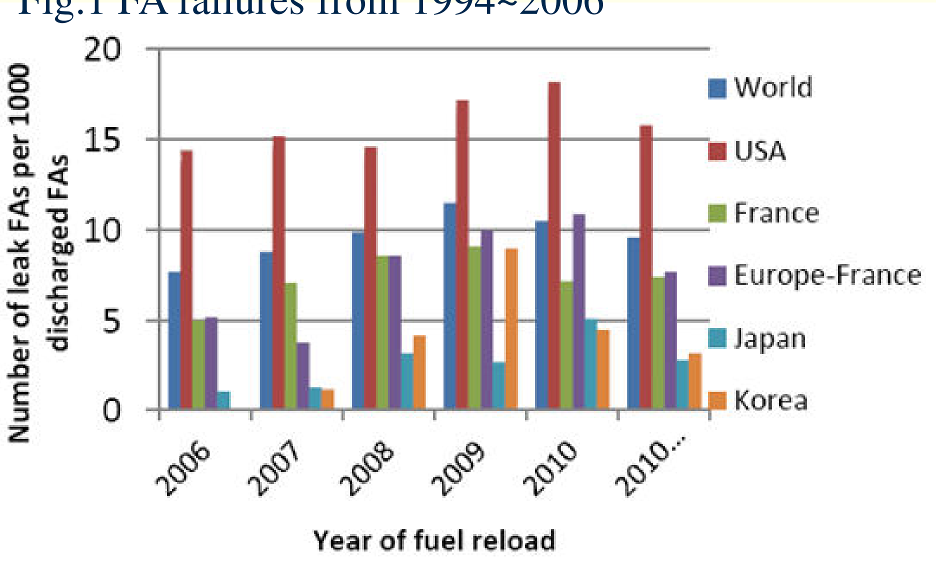

Fig.2 FA failures from 2006~2010

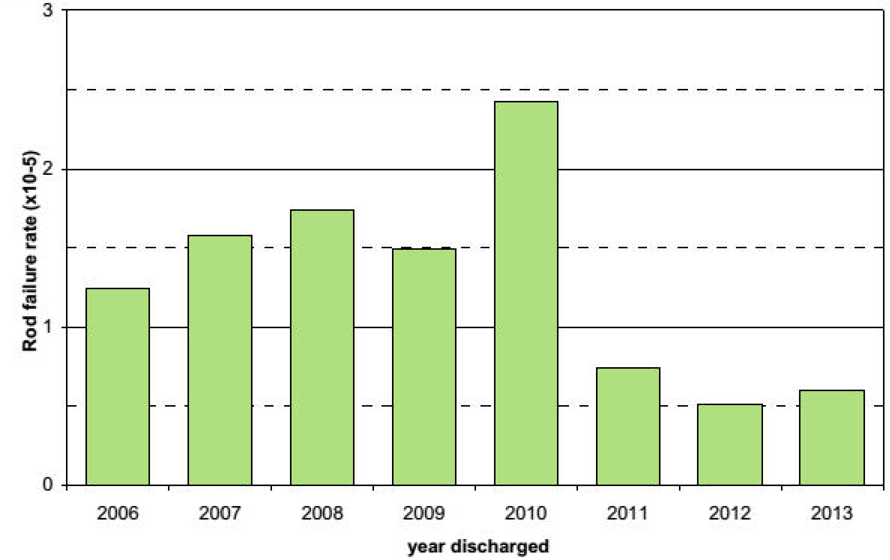

Fig.4 Fuel failure rate of Frametome

Review of the fuel reliability

- Fuel reliability is consistently improving by the new materials, advanced mechanical design;
- However, the fuel reliability is challenged by the pursuit of the high economic benefits which usually employs the challenging operation strategies such as longer refueling cycle and higher fuel burnup
- The fuel zero failure rate target was firstly proposed by the American Institute of the Nuclear Power Operations in 2006. This target is really challenging and need much more effort to achieve it.
- Lots of researches and engineering work focus on improvement of the fuel reliability such as the WANO fuel reliability indicator which publish the report every year, the fuel reliability improvement of Westinghouse, the fuel reliability program of INPO.
- As well as, the advance fuel design such as the accident tolerant fuel is promising to achieve the zero fuel failure rate.
- Fuel reliability is challenging and needs more effort.

Review of factors the fuel failure

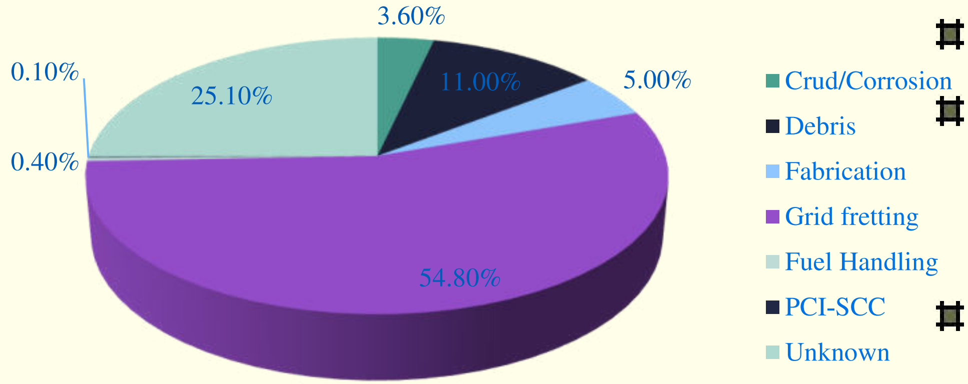

Fig. 5 PWR Fuel failure type from 1994 to 2006

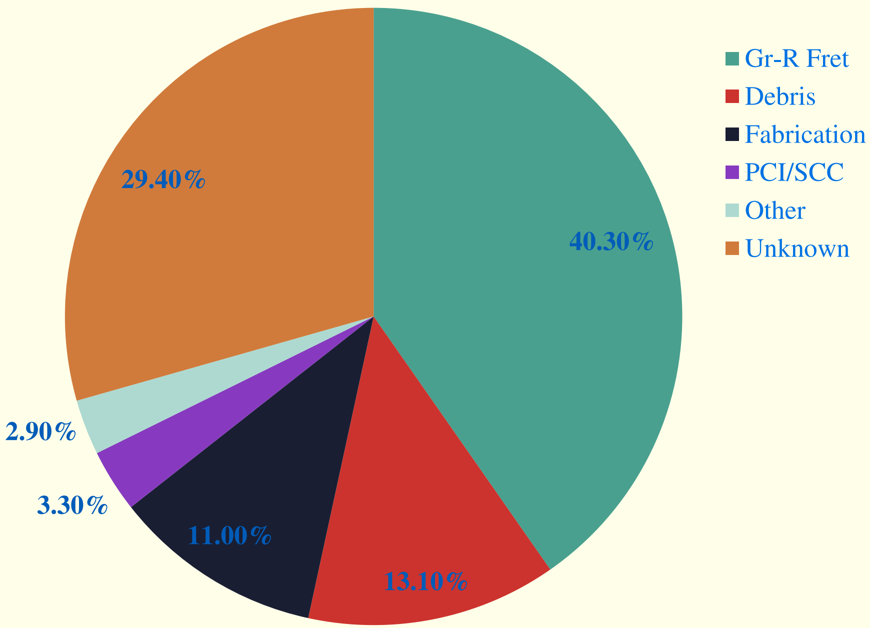

Fig.6 PWR Fuel failure type from 2006 to 2010

- Many factors can lead to fuel failure
- Nowadays, some fuel failures such as the Grid To Rod Fretting, are nearly avoided by improving the mechanical design.
- Therefore, each factor should be analyzed deeply in order to find the fundamental reasons which result in the fuel failure.
- The fuel failure related to different phases of the fuel life cycle such as fuel design, fuel fabrication, fuel transport, fuel handling, power operation, etc..
- The fuel design and fabrication quality fundamentally determine the performance of the fuel. Fuel reliability relates to the fuel design, fabrication and the procedure of the plant operation.

Part 2

Research framework

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Research framework

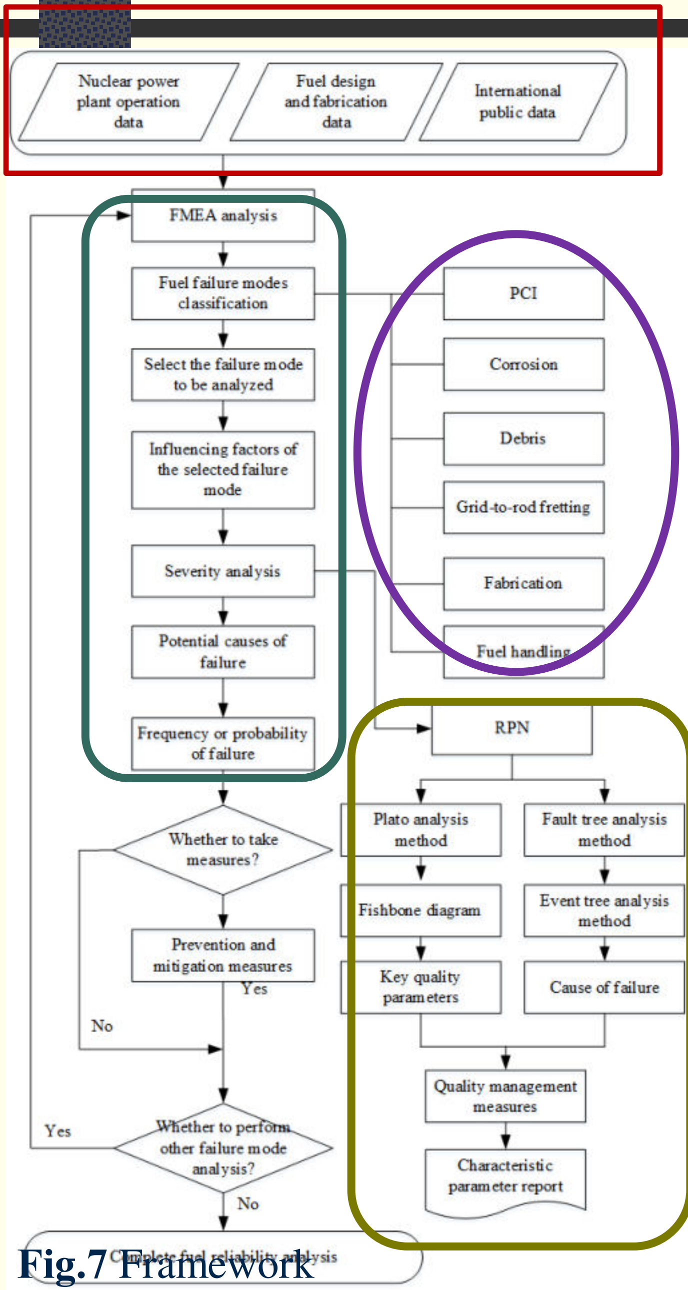


Fig.7 Framework

- Data collection
- Fuel failure mode analysis (PCI and corrosion)

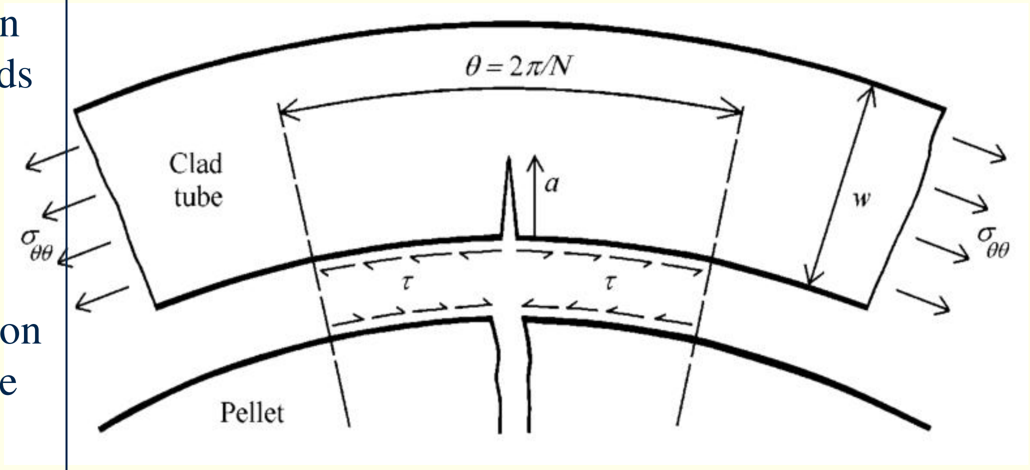
  Although PCI and corrosion are not the most frequent contribution to the fuel failure of the known reasons but PCI and corrosion caused fuel failures are heavily determined by the fuel design, process of fuel fabrication and the reactor operation and they may be fundamentally prevented by improving the fuel design, fuel fabrication and reactor operation.
- Fuel performance analysis

  Fuel performance calculation for different characteristic parameters.
- FMECA analysis

  Based on the performance calculation results, build the FMECA table and give the qualitative and quantitative advices.

PCI caused fuel failure mechanism

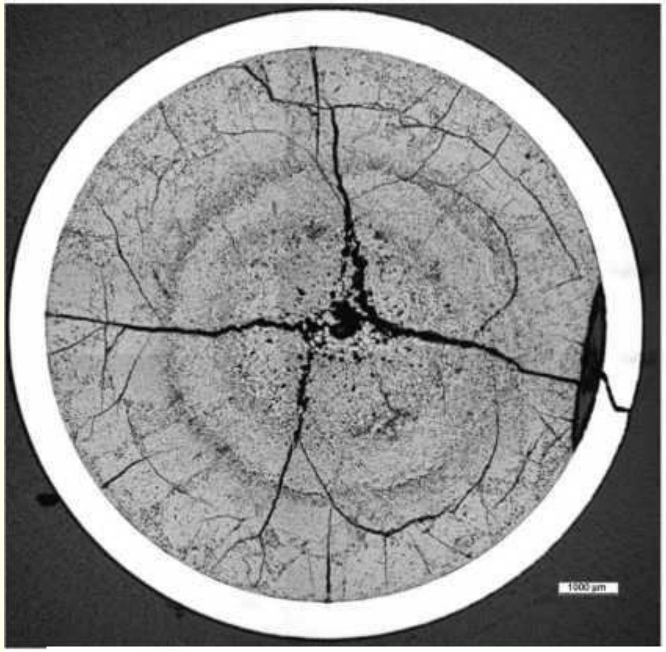
- The fuel failure mechanism caused by PCI can be described as: a rapid increase in power leads to a rapid increase in the temperature of the pellets, and rapid expansion of the pellets. At this time, the thermal expansion and outward creep of the cladding are too late to offset the thermal expansion of the pellets, so the force on the cladding increase, and it can cause damage to the cladding severely.
- Therefore, PCI is a coupled thermal, chemical and mechanical process that can lead to cladding cracking and subsequent radioactive fission products release into the primary reactor coolant loop.
- PCI failure usually occurs when a local power raise during a short period of time in irradiated fuel.
- PCI/SCC (Stress Corrosion Cracking) failure is generally caused by the localized strains around the cladding crack and the presence of the aggressive chemical fission products such as iodine, which induce the stress corrosion cracking.



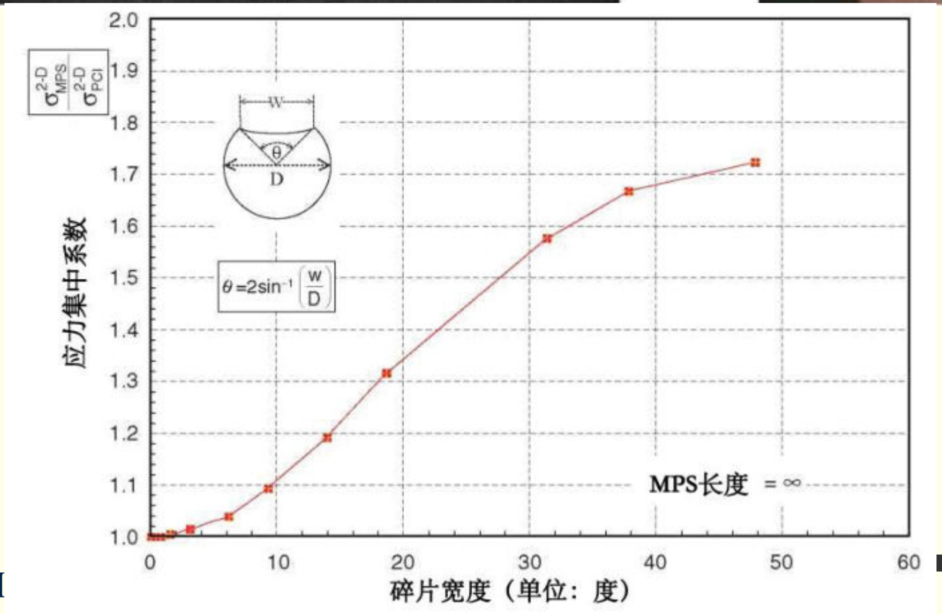
- The classical PCI failure mechanism can generally summarized as the large temperature gradients and the swelling of the pellets reduce and close the gap between the pellet and cladding and produce a high contact force between pellet and cladding. Then the further rapid thermal pellet swelling make the cladding crack.

PCI caused fuel failure mechanism

- The non-classical PCI failure correlates with the missing pellet surface (MPS) defect.
- The presence of MPS results in local hot spot in the fuel and cold spot in the cladding, which lead to the formation of local interaction force



✓ However the mechanism is clear, we want to study the impact of each parameter.



Corrosion caused fuel failure mechanism

- As the fuel rods are immersed in the high temperature and pressure primary water, the corrosion caused fuel failure is mainly due to the reaction of water and zirconium alloy metal, the crud induced localized corrosion and the fission deposition induced corrosion.
- The water and zirconium metal reaction form an oxide layer and generate hydrogen. The hydrogen is partly absorbed by the cladding which causes the hydriding of zirconium. The difference in density and thermal expansion of materials between the oxide layer and metal causes the tension, internal stresses and strains in cladding.
- Furthermore, the thermal conductivity of the oxide layer is much smaller that that of zirconium metal, which causes the decrease of the heat transfer from the pellet over the cladding to the coolant.
- Consequently, the maximal temperature of the fuel pellet increases which will furtherly favor the increase of the oxide layer. When the oxide layer exceeds certain limits, it might crack and then washed away by the coolant which can lead to cold spots, further oxidation, further hydrogenation and later cladding breach.
- Similarly with the cracked oxide layer, the crud and fission deposition can also result in localized oxidation, hydrogenation and cladding breach.

✓ However the mechanism is clear, we want to study the impact of each parameter.

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Part 3

Results

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Characteristic parameters for PCI and corrosion

- The fuel design parameters consist of the pellet designed density, the designed pellet diameter, the designed pellet height, the designed cladding inner and outer diameters.
- The fuel fabrication parameters include the pellet product density, the product pellet diameter, the product pellet height, the product cladding inner and outer diameters.
- The parameters related to the reactor operation are reactor power, fuel burnup, transient peak power, long-term low power running period.

- Cladding material which determines the mechanical property of the fuel rods;
- Fuel enrichment and O/U ratio which have an effect on the fission gas release and thus impact the pressure of the fuel rods;
- The dimensions of the pallet and the cladding which fundamentally determine the stress and the heat conduct of the cladding;
- The plenum length and pressure of He which directly have effect on the inner pressure and the heat conduct.

Results for PCI analysis

- a typical CPR1000 unit
- the strain energy density and the margin are calculated to represent fuel performance
- And the calculated strain energy density and margin under different parameters is compared with the nominal conditions

Key parameters	Value	Strain energy density (MPa)	Margin (MPa)	Margin ratio	Phase of fuel
Nominal condition	-	0.6187	2.2513	1.0000	-
Cladding material	Low tin Zr-4	0.7418	2.1282	0.9453	Fuel Design and Fabrication
	Standard Zr-4	0.7443	2.1257	0.9442	Fuel Design and Fabrication

- Through the performance analysis of the characteristic parameters, it is found that the cladding material, the pallet density, the Transient peak power and the Long-term low power operation have more impact on the fuel performance.

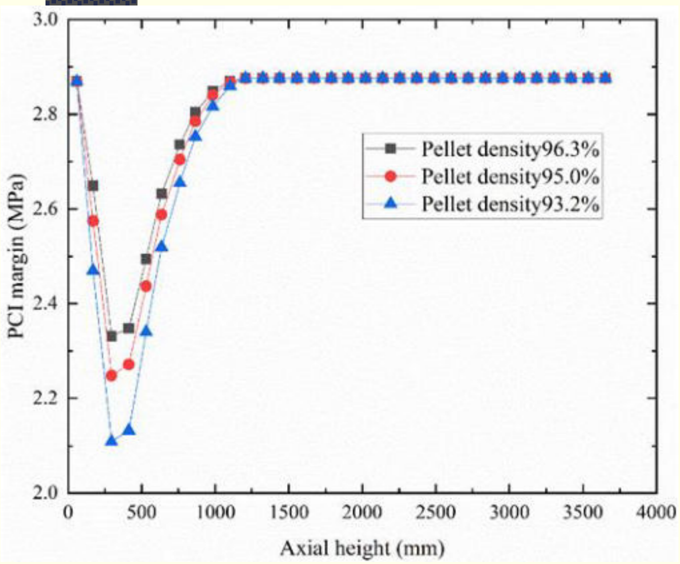
Results for PCI analysis

Key parameters	Value	Strain energy density (MPa)	Margin (MPa)	Margin ratio	Phase of fuel
Pellet density	Minimum	0.7354	2.1346	0.9482	Fuel Design
	Max	0.5545	2.3155	1.0285	
Cladding outer diameter	Minimum	0.6202	2.2498	0.9993	Fuel Design
	Max	0.6179	2.2521	1.0004	
Cladding inner diameter	Minimum	0.6644	2.2056	0.9797	Fuel Design
	Max	0.5801	2.2899	1.0171	
Pellet diameter	Minimum	0.6096	2.2604	1.0040	Fuel Design
	Max	0.6349	2.2351	0.9928	
Pellet height	Minimum	0.6192	2.2508	0.9998	Fuel Design
	Max	0.6183	2.2517	1.0002	
Fuel enrichment	Minimum	0.6172	2.2528	1.0007	Fuel Design
	Max	0.6201	2.2499	0.9994	
O/U ratio	Minimum	0.6200	2.2500	0.9994	Fuel Design
	Max	0.6197	2.2503	0.9996	
Pressure of He	Minimum	0.6167	2.2533	1.0009	Fuel Design
	Max	0.6209	2.2491	0.9990	
Plenum length of the fuel rod	Minimum	0.6200	2.2500	0.9994	Fuel Design
	Max	0.6174	2.2526	1.0006	

Results for PCI analysis

Key parameters	Value	Strain energy density (MPa)	Margin (MPa)	Margin ratio	Phase of fuel
Pellet density	Minimum	0.6485	2.2215	0.9868	Fuel Fabrication
	Max	0.5804	2.2896	1.0170	
Cladding outer diameter	Minimum	0.6204	2.2496	0.9992	Fuel Fabrication
	Max	0.6179	2.2521	1.0004	
Cladding inner diameter	Minimum	0.7705	2.0995	0.9326	Fuel Fabrication
	Max	0.5801	2.2899	1.0171	
Pellet diameter	Minimum	0.6177	2.2523	1.0004	Fuel Fabrication
	Max	0.6219	2.2481	0.9986	
Pellet height	Minimum	0.6189	2.2511	0.9999	Fuel Fabrication
	Max	0.6187	2.2513	1.0000	
Reactor power (W/cm)	186	0.6187	2.2513	1.0000	Reactor Operation
	204.6	0.4516	2.4184	1.0742	
	167.4	0.8066	2.0634	0.9165	
Fuel burnup (MWd/tU)	24707	0.6187	2.2513	1.0000	Reactor Operation
	188	0.0000	2.8700	1.2748	
	13126	0.0089	2.8611	1.2709	
Transient peak power（W/cm）	210.27	0.3644	2.5056	1.1130	Reactor Operation
	256.99	1.0103	1.8597	0.8261	
	247.03	0.8290	2.0410	0.9066	
Long-term low power operation mode	75% FP runs for 30 calendar days	0.8505	2.0195	0.8970	Reactor Operation
	75% FP runs for 90 calendar days	1.4880	1.3820	0.6139	

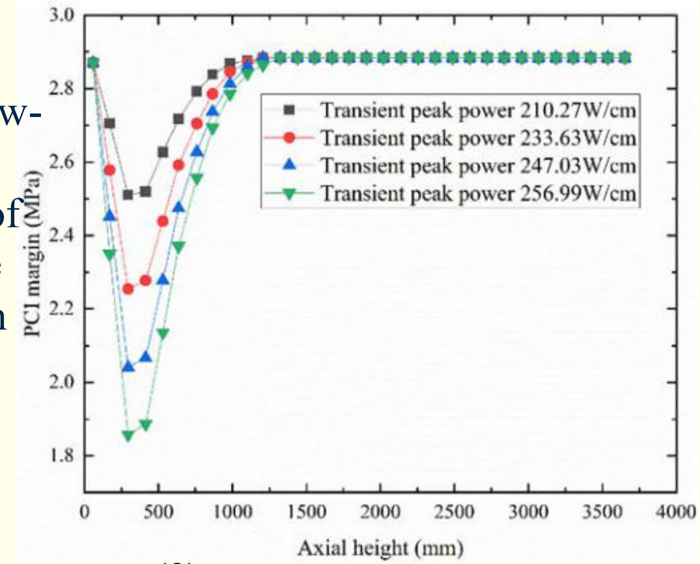
Results for PCI analysis



(1)

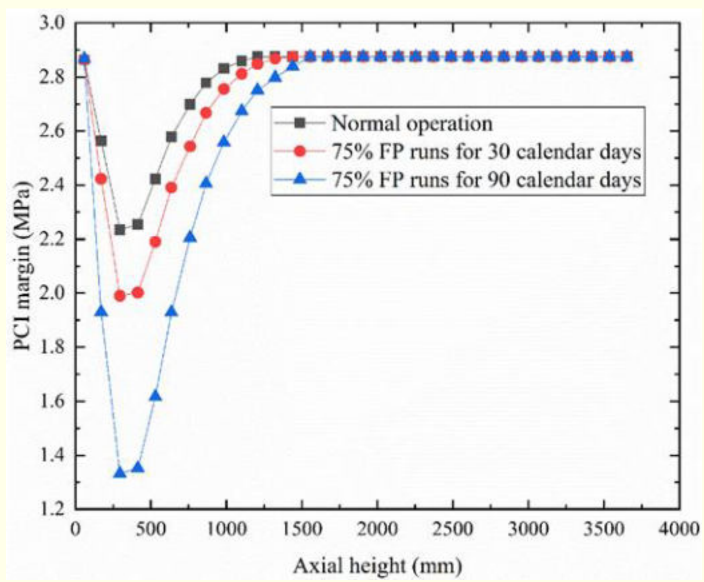
- The density of pellet has impact on the heat conduction of the fuel and causes the difference in thermal expansion between the cladding and pellets, which has a greater impact on PCI performance

- The longer the fuel rod low-power operation lasts, the greater the inward creep of the cladding and the more serious the deviation from the reference state. It can result in a smaller PCI margin



(3)

- The higher the transient peak power, the greater the expansion of the pellet after the transient occurs. Therefore, the interaction between the pellet and the cladding during the transient process becomes stronger, which results in a decrease in PCI margin



(2)

Results for corrosion analysis

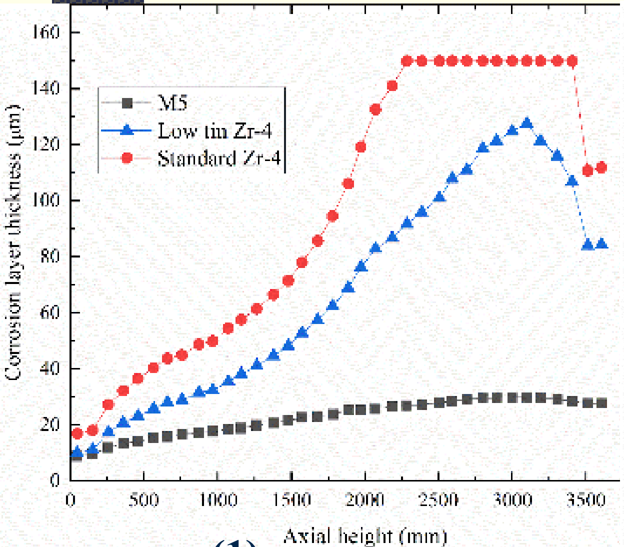
- a typical CPR1000 unit
- the strain energy density and the margin are calculated to represent fuel performance
- And the calculated strain energy density and margin under different parameters is compared with the nominal conditions

The design limit of the oxide layer thickness of the zirconium alloy cladding is 100μm in the CPR1000 plant design.

Results for corrosion analysis

Key parameters	Value	Peak oxide thickness (μm)	Margin (μm)	Margin ratio	Phase of fuel
Cladding material	Standard Zr-4	150	-50	-0.7133	Fuel Design and Fabrication
	Low tin Zr-4	127.5	-27.5	-0.3923	
	M5 alloy	29.9	70.1	1.0000	
Rod average line power（W/cm）	186	29.9	70.1	1.0000	Reactor Operation
	220	31.6	68.4	0.9757	
	90.65	14.7	85.3	1.2468	
	10% over limit，204.6	31.1	68.9	0.9829	
Fuel cycle（h）	31899.04	29.9	70.1	1.0000	Reactor Operation
	43800	41.2	58.8	0.8345	
	87600	93.5	6.5	0.0927	
	131400	150	-50	-0.7133	
Axial power distribution	Nominal axial power	29.9	70.1	1.0000	Reactor Operation
	Power peak at the top	31.3	68.7	0.9800	
	Power peak at the bottom	27.8	72.2	1.0300	
	Power peak in the middle	27.7	72.3	1.0314	
Core water flow（m^3/h）	69378	29.9	70.1	1.0000	Reactor Operation
	75132	29.3	70.7	1.0086	
	73762	29.4	70.6	1.0071	
	83253.6	28.2	71.8	1.0243	
	55502.4	30.5	69.5	0.9914	
Debris deposit thermal conductivity（W/mm/K）	No dirt	29.9	70.1	1.0000	Reactor Operation
	0.0008655	71.6	28.4	0.4051	
	0.0005	149.6	-49.6	-0.7076	
	0.02	43	57	0.8131	

Results for PCI analysis



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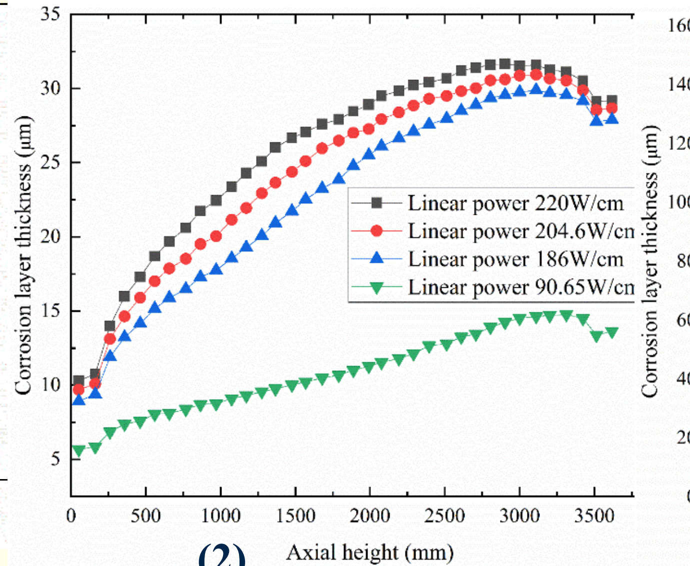

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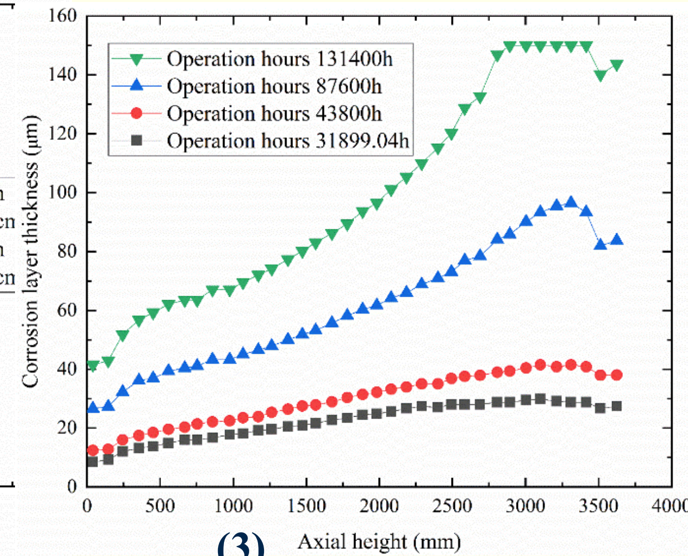

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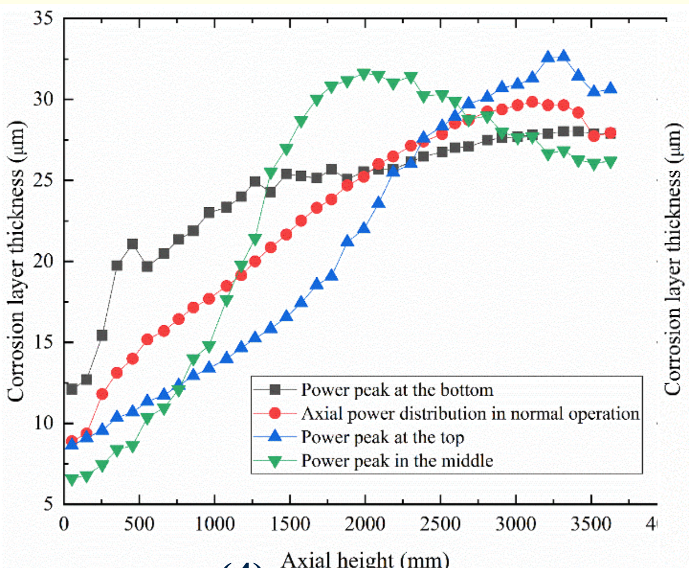

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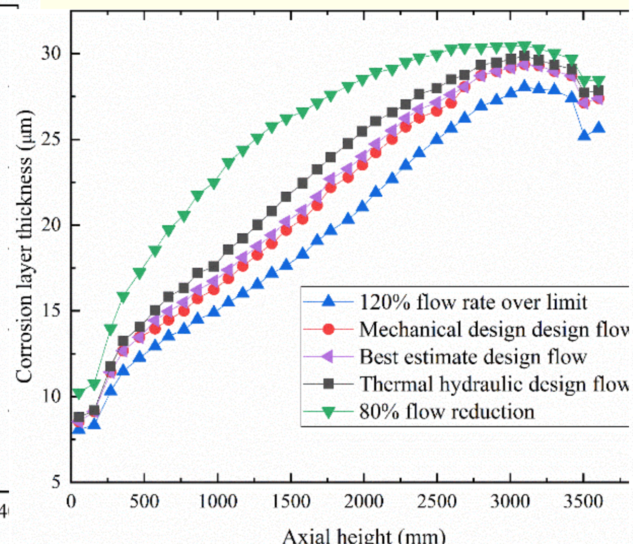

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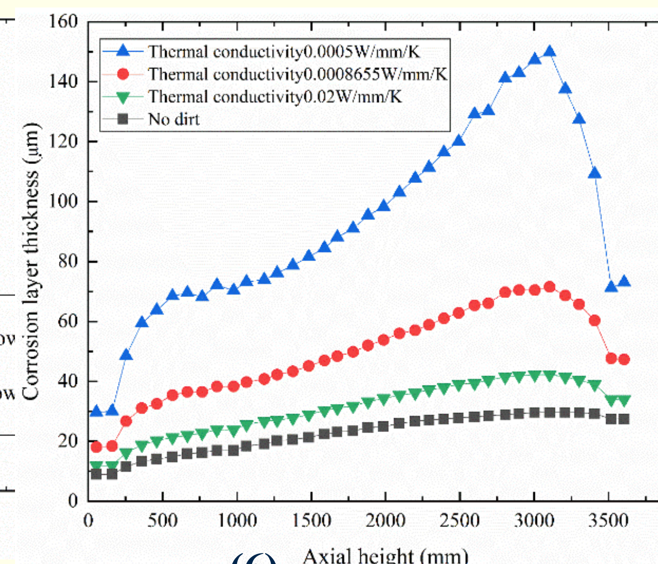

(6)

Effect Severity Ranking

Influence	Influencing factors	Judgment criteria：Severity of impact on fuel failure caused by PCI	Level
Very high	Fuel fabrication defect	Affect the force of the cladding and directly affect the PCI	4
	Flexible operation	Make the fuel rod deviate from the reference operating state, indirectly affect PCI	
High	Transient peak power	Affects the expansion of pellets in transient process and indirectly affects PCI	3
Medium	Core power	Affect the transient power step and indirectly affect PCI	2
Low degree	Primary circuit pressure	Affect the force of the cladding and directly affect the PCI	1

Effect Severity Ranking

Influence	Influencing factors	Judgment criterion: the severity of the influence on the corrosion failure of the cladding	Level
Does not meet the requirements of safety	Cladding material	Potential failure consequences affect the operation of the cladding	7
Very high	Fuel cycle	Directly affect the oxidation corrosion rate of the cladding	6
High	Dirt deposit	The thermal conductivity of fouling directly affects the heat transfer performance of the cladding	5
Medium	Hydrogen concentration	Directly affect the oxidation of the cladding	4
Medium low level	Axial power shape	Affect the local corrosion position of the cladding	3
	Average linear power density	Indirectly affect the corrosion performance of the cladding	
Low	Core flow	Indirectly affect the corrosion of the cladding	2
Almost no effect	Core side flow	Directly affect core flow rate and indirectly affect cladding corrosion	1

Occurring Probability Ranking

Probability of failure	Influencing factors	Frequency of occurrence	Probability of failure P_m	Level
High	Fuel defect	10^4/RY≥Theoretical Frequency≥10^2/RY	$1\times10^{-2}<P_m\leq1\times10^{-1}$	3
Medium	Core power Primary circuit pressure Flexible operation	10^2/RY≥Theoretical Frequency≥1/RY	$1\times10^{-4}<P_m\leq1\times10^{-2}$	2
Low	Transient peak power	1/RY≥Theoretical Frequency≥10^{-2}/RY	$P_m<1\times10^{-4}$	1

Occurring Probability Ranking

Probability of failure	Influencing factors	Frequency of occurrence	Probability of failure P_m	Level
Very high	Fouling deposition	The thermal conductivity of the fouling on the surface of the fuel rod cladding will decrease with the accumulation of corrosion products	0.930	5
High	Cladding material	Cladding materials with poor corrosion resistance are still widely used in reactors, and this mode has a high probability of occurrence	0.831	4
	Cycle Time	The design cycle time of some reactors far exceeds that of commercial pressurized water reactors	0.634	3
Medium	Axial power shape	Theoretical Frequency≥1/RY	0.268	2
Low	Core flow	1/RY≥Theoretical Frequency≥10^{-2}/RY	0.028	1

FMECA hazard analysis

Failure mode	Severity (S)	Probability of occurrence (O)	RPN	Order
Fuel fabrication defect	4	3	12	1
Flexible operation	4	2	8	2
Transient peak power	3	1	3	4
Core power	2	2	4	3
Primary circuit system pressure	1	2	2	5

Failure mode	Severity (S)	Probability of occurrence (O)	RPN	Order
Cladding material	7	4	28	1
Cycle Time	6	3	18	1
Dirt deposit	5	5	25	1
Dissolved hydrogen concentration	4	1	4	4
Boron lithium coordination curve	4	2	8	2
Axial power shape	3	2	6	3
Average linear fuel rod power	3	1	3	5
Core flow	2	1	2	6
Core side stream	1	1	1	7

Part 4

Conclusion

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Conclusion

- Using FMECA, the key characteristic parameters related with fuel reliability are analysis by Fuel performance calculation. A quality management system is constructed for the key parameters in the design and fabrication process.
- The detailed analysis and calculation process are elaborated in detail for the PCI and corrosion induced fuel failures. The method can be employed to analyze other fuel failures.

  The following conclusions can be made for the PCI and corrosion induced fuel failures:
- (1) Fuel design and fabrication defects are the most important factors affecting PCI failure. Flexible operation, core design, and thermal-hydraulic design are external factors that affect PCI failure.
- (2) The cladding design and fabrication is the key cause of fuel corrosion failure. Water chemical conditions, core design and thermal hydraulic design are external factors that affect fuel corrosion failure.

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Thanks for your attention

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