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

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Abstract—**The integrity of the nuclear fuel is the first of the three barriers of nuclear safety for nuclear power plants. The fuel failure rate fluctuates in the first two decades of the 21 century as modern reactor operation strategies, which usually have longer refueling cycle and higher fuel burnup, are employed to achieve the high economic benefits. Advanced fuel is designed and new reactor operation strategies are adopted to improve the reliability of fuel and achieve the zero failure rate target of the nuclear fuel during reactor operation, which was firstly proposed by the American Institute of Nuclear Power Operations (INPO) in 2006. Nuclear fuel performances are fundamentally formulated by the fuel design, the process of fuel fabrication, fuel handling and the operation of the nuclear reactors. Therefore, fuel reliability analysis and optimization involve a wide range of expertise knowledge, a long period of time, a high cost of money, and a lot of challenges. In order to improve the fuel reliability fundamentally, this paper focuses on the fuel design, fuel fabrication and the reactor operation. A commercial pressurized water reactor (PWR) is took as an example reactor. The Failure Mode Effects and Criticality Analysis (FMECA) methodology is used to analyze the influential factors and parameters of the fuel performance. Firstly, the fuel failure modes are classified based on the international collected fuel failure data. Then, two fuel failure modes, which are caused by Pellet-Cladding Interaction (PCI) and corrosion, are selected to analyze in detail. However, the corrosion analysis results are not included in the paper as the page limit. 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. Thirdly, the characteristic design, manufacture and operation parameters are examined to determine the effects on PCI and corrosion caused fuel failure respectively. The characteristic parameters include pellet and cladding design parameters, which represent the design effect on the fuel performance, pallet and cladding fabrication parameters, which indicate the influence of the fabrication process on the fuel performance, and the reactor core design conditions with the reactor hydrochemical conditions, which determine the reactor operation condition. Fourthly, the severity and probability of fuel failure caused by different key parameters are calculated. The risk priority number of key parameters can be acquired and analyzed. Through detailed analysis and research, necessary suggestions are provided to improve nuclear fuel reliability and a quality management system is constructed for the key parameters during the fuel design and manufacturing process.**

Keywords—fuel failure; fuel reliability; FMECA; quality characteristics technology

I. INTRODUCTION

The fuel element is a key critical component of the reactor, which produce not only the fission energy but also the radioactive products. The fuel integrity performs the first barrier of nuclear safety. Fuel failure might release the fission products to the primary circulation loop, which has negative impact on the plant operation cost and performance and consequently results in the radiological release to the environment. Therefore, nuclear fuel reliability relates with the safety and cost effectiveness of the nuclear power plant. The nuclear fuel reliability is formulated during the design and manufacturing process and its quality characteristics play a vital role in the safe and economical operation of the fuel assembly in the reactor. The World Association of Nuclear Operations (WANO) regards the Fuel Reliability Indicator (FRI) as one of indicators to quantitatively monitor the plant safety, reliability performance world widely, which reflects the importance of fuel reliability to the safe operation of nuclear power[1]. Improvement the reliability of fuel and achievement the "zero failure rate" was proposed by the INPO in 2006. This requirement poses a challenge to all fuel suppliers and nuclear power operators, and is also one of the ultimate goals of nuclear power operation[2]. These kinds of fuel reliability programs such as in EPRI (Electric Power Research Institute) and Westinghouse continuously improved the fuel performance. Through the early 2000s, nuclear fuel failures are decreased by incorporating plant operation limits. However, fuel failure rate increases as the nuclear industry employs the modern reactor operation strategies to pursue higher economic benefits which usually have longer refueling cycle, higher fuel burnup, higher temperature and more aggressive water chemistries. In this decade, advanced fuel design has fundamentally improve the fuel performance and fuel reliability[3][4].

Many factors and processes can lead to fuel failures. By studying the failure mechanism of the PWR (Pressurized Water Reactor) fuel, the types of PWR fuel failure can be roughly classified into the following categories: crud induced corrosion, debris, fabrication, Grid fretting, Fuel Handling, PCI (Pellet-Cladding Interaction), etc. An overview of the proportion of fuel rod failure in the world from 1994 to 2006 and from 2006 to 2010 is presented in reference [3] respectively. Among these knowns fuel failure modes, although PCI fuel failure is not the largest proportion of the fuel failure statistic, PCI failure is the most typical of fuel failures that have attracted much attention during design and fabrication of the fuel and the operation of PWR. Therefore, this paper focuses on the FMECA (Failure Mode Effects and Criticality Analysis) analysis of fuel failure caused by PCI to fundamentally study the factors and parameters influence. And it is expected that PCI induced fuel failures can be completely prevented and managed through the detailed analysis and study.

This paper analysis the PCI caused fuel failures using the FMECA[6] methodology for a commercial PWR, which tries to fundamentally prevent the PCI fuel failures by improving the fuel design, fuel fabrication and reactor operation. The impacts of different parameters of design, fabrication and operation on the fuel performance are calculated respectively. Based on the calculation results, the quantitatively indicators for different parameters are analyzed, which indicate the parameter effect on the fuel failure. Through detailed analysis and research, necessary suggestions are provided to improve nuclear fuel reliability and a quality management system is constructed for the key parameters during the fuel design and manufacturing process as well as the reactor operation period.

II. Analysis of Influencing Factors for PCI induced Fuel failure

The PCI caused fuel failure is observed not only during the large or rapid power changes but also in the low stress with highly corrosive conditions which are caused by pellet cladding gap heat transfer degradation[7]. Although the PCI propensity is reduced as the improvement of the cladding and the reactor operation strategy, it is important to understand the conditions that can lead to PCI phenomenon to completely avoid PCI failure. 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. 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[8].

By considering the mechanism for PCI induced fuel failure and the CPR1000 plant operation experience, the underlying fuel characteristic parameters are selected. These characteristic parameters includes the parameters related to the fuel design, fuel fabrication and reactor operation. 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.

The performance calculation for the fuel rode includes characteristic parameters of pellet and cladding design parameters, which represent the design effect on the fuel performance, pallet and cladding fabrication parameters, which indicate the influence of the fabrication process on the fuel performance, and the reactor core design conditions with the reactor hydrochemical conditions, which determine the reactor operation condition. The concrete underlying factors and parameters which have heavy impact on the PCI margin include the followings:

- 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.

This paper takes a typical CPR1000 unit refueling fuel management plan as an example to analyze the influence of the above factors on PCI. During the fuel performance calculations, the strain energy density and the margin are formulated. And the calculated strain energy density and margin under different parameters is compared with the nominal conditions and the PCI margins for different key parameters are shown and summarized in Table 1.

Table 1 PCI margin for different key parameters

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
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	
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	

III. FMECA RESULTS FOR PCI

Effect Severity Ranking (ESR) is used to characterize the severity of the effect of failure influencing factors on the corresponding fuel failure mode. The specific severity evaluation process is as follows: sort out the characteristic parameters that affect the failure mode performance, and then determine the failure mode's severity according to the characteristics of each parameter's influence on the failure mode, as shown in Table 2.

Table 2 PCI-induced fuel failure FMECA analysis severity (S)

Influence	Influencing	Judgment criteria：	Level

	factors	Severity of impact on fuel failure caused by PCI	
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

The frequency of failures is used to characterize the possibility of failure occurrences. Eliminating or controlling one or more failure causes/mechanisms through design changes is a possible way to reduce the failure frequency. The national standard has clear requirements on the probability of failure level for occurring probability ranking (OPR): OPR is to assess the possibility of a certain failure mode actually occurring. According to the study of the fuel failure mechanism caused by the failure mode and the feedback of the power plant operation experience and the reference of the international fuel failure data, the order of the probability of each failure mode is shown in Table 3 respectively for the PCI induced fuel failure.

Table 3 Probability of fuel failure caused by PCI (O)

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	1×10^{-2} $<P_m\leq1\times10^{-1}$	3
Medium	Core power Primary circuit pressure Flexible operation	10^2/RY ≥Theoretical Frequency≥ 1/RY	1×10^{-4} $<P_m\leq1\times10^{-2}$	2
Low	Transient peak power	1/RY ≥Theoretical Frequency≥ 10^{-2}/RY	$P_m<1\times10^{-4}$	1

The purpose of the hazard analysis is to comprehensively analyze the effects of each failure mode, the severity and its probability of occurrence, and then comprehensively evaluate the effects of all possible failure modes in the failure of the fuel cladding. In this paper, the Risk Priority Number (RPN) is used to rank each of the failure mode resulting in the fuel failure either by corrosion or PCI. The RPN value of a failure mode is equal to the product of the severity level (ESR) of the failure mode and the occurrence frequency level (OPR) of the failure mode: RPN=ESR×OPR. The higher the RPN number, the more harmful it is[5]. From the analysis of the severity of fuel failure in the previous section, it can be seen that fuel defects and flexible operation are the most important factors affecting PCI induced fuel failure, and the difference of cladding materials and cycle period are the most important factors affecting the corrosion induced failure of fuel. The sequence of the RPN value of each failure mode is shown in Table 4. Although it is not shown in this paper, the full FMECA table is compiled for the PCI induced fuel failure and in the full FMECA table, the items includes the failure modes such as the fuel fabrication defect, the ESR and the failure mechanism for each failure mode, the OPR and the preventive measure, the inspection for each failure mode that is current in effect, the RPN and recommended improvement measures for each failure mode.

Table 4 Sequence table of RPN value of PCI induced failure

Failure mode	Severity (S)	Probability of occurrence (O)	RPN	Order
Fuel 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

Based on the FMECA analysis results of key factors for the fuel failure, the Plato analysis method can be used to determine the importance of key quality characteristic parameters. The severity and frequency level of each failure mode can be calculated. The method can be employed to analyze other fuel failures.

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