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MECHANICAL STRESS ANALYSIS FOR A FUEL ROD UNDER NORMAL OPERATING CONDITIONS

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ABSTRACT

Nuclear reactor fuel elements consist mainly in a system of a nuclear fuel encapsulated by a cladding material subject to high fluxes of energetic neutrons, high operating temperatures, pressure systems, thermal gradients, heat fluxes and with chemical compatibility with the reactor coolant. The design of a nuclear reactor requires, among a set of activities, the evaluation of the structural integrity of the fuel rod submitted to different loads which arise during the reactor operation. This evaluation can be carried out considering all types of loads acting on the fuel rod and the specific properties (dimensions and mechanical and thermal properties) of the cladding material and coolant, including thermal and pressure gradients produced inside the rod due to the fuel burnup. In this work were evaluated the structural mechanical stresses of a fuel rod using stainless steel as cladding material and UO_2 with a low degree of enrichment as fuel pellet in a PWR (pressurized water reactor) under normal operating conditions. In this sense, tangential, radial and axial stress on internal and external cladding surfaces considering the orientations of 0^o, 90^o and 180^o were considered. The obtained values were compared with the limit values for stress to the studied material. From the obtained results, it was possible to conclude that, under the expected normal reactor operation conditions, the integrity of the fuel rod can be maintained.

1. INTRODUCTION

The design of a PWR requires, among a set of activities, the evaluation of the structural integrity of the fuel rod submitted to different loads which arise during the reactor operation. In this sense, all cladding stresses, taking into account the differential pressure across the cladding wall, thermal stresses, hydraulic vibration, fuel rod bowing spacer, grid contact and cladding ovality, must be considered in the stress evaluation. The stresses due to pellet/cladding mechanical interaction (PCMI) are excluded in the cladding stress evaluation because they are addressed in the cladding strain criterion and the no fuel melting criterion [1].

In order to address the cladding stresses and to assess the fuel rod integrity, it is fundamental to evaluate the design limits related to the applied cladding material considering the associated geometry.

Austenitic stainless steel was used for fuel rod cladding in the first PWR and other types of nuclear reactors [2]. Since, in the years 1960, stainless steel claddings have been replaced by zirconium-based alloys in commercial reactor cores by zirconium-based alloys mainly due to its lower absorption cross section for thermal neutrons, which allows zirconium-based alloys cladding material to operate with lower UO_2 degree of enrichment, and therefore lower cost than when using stainless steel as cladding material. Although this, stainless steel as cladding material in PWR's has some advantages to zirconium-alloys cladding materials. Stainless steel is less susceptible to damage during pellet cladding mechanical interaction (PCMI) than zirconium-based alloys. Stainless steel is also less susceptible than zirconium-based alloys to stress corrosion cracking generated by fission products in the fuel and the cracks formation on the cladding inner wall is less likely, and consequently stainless steel fuel rods can withstand higher concentrations of fission products. The embrittlement due to oxygen is almost ruled out, and the stainless steel mechanical strength and ductility are better than those of zirconium-based alloys, leading to a smaller cladding deformation and reduced cooling channel blockage. Also, concerning to safety requirements, the use of stainless steel cladding has the advantage of not presenting the violent oxidation reaction that occurs with zirconium-based alloys at high temperatures.

Conventional fuel performance codes enable to evaluate the thermal-mechanical behavior of the cladding just due to the axial and tangential primary membrane stresses as consequence of the differential pressure loads during the irradiation [3]. In this way, the obtained results by means of these codes are not enough to assure the rod integrity during the reactor operation.

In this paper is presented aspects of steady state behavior of the 348 type austenitic stainless steel cladding under irradiation [4], its properties, design limits, loads on the fuel rod related to out of the welding zone, and stress analyze of the fuel rod obtained by means of a CTMSP/IPEN program. The internal and external cladding temperature and internal pressure under steady state operation were obtained by means of a modified fuel performance code, which simulate the fuel performance of rods manufactured using AISI 348 cladding material.

The evaluation of individual stress was carried out in the elastic region considering a uniform fuel rod out of the welding region. The stress on the internal and external surfaces in the radial orientations of 0°, 90° and 180°, were also calculated.

2. STRESSES ANALYSIS

The AISI 348 austenitic stain steel has the following composition (in weight percent): C-0.08%, Mn-2.00, Si-1, Cr-17 to 19, Ni-9 to 13, P-0.045, S-0.03, Cu-0.2, Nb-0.7, Ta-0.1, Co-0.2, and Fe for balance [5]. The addition of Nb and Ta will hinder corrosion and the low percent of carbon will prevent the formation of inter-granular precipitation of metallic carbides. Properties of this material are presented in Table 1 [6].

Table 1: AISI 348 Austenitic Stainless Steel Properties

Property	AISI 348
Crystalline structure	CFC
Density (10^3 kg/m^3)	7.84
Rockwell-B Hardness	85
Ultimate strength (MPa)	655
Tens. strength at yield (MPa)	275
Maximum elongation (%)	45
Elastic modulus (GPa)	195
Poisson's ratio	0.27
Shear modulus (GPa)	77
Resistivity (µOhm.cm)	79
Specific heat (J/g.°C)	0.5
Thermal conductivity (W/mK)	19.1
Thermal expansion coefficient (10^{-6}/K)	18.5
Melting point (°C)	1400
Under irradiation creep (%) ($\varphi t = 3.10^{21}$n/cm^2)	0.045
Capture cross-section (Barn)	$3.13\sigma_c$

The geometry parameters of the studied rod as well as the coolant data are those typical of a conventional PWR.

The maximum internal pressure reached at the end of the life for the studied rod, and the internal and external temperatures of the cladding were obtained performing a fuel behavior assessment under the studied irradiated conditions using an adapted fuel performance code which enables to evaluate a single rod behavior manufactured using 348 stainless steel as cladding.

The stresses analysis and the deformations associated to the fuel rod were carried out using a CTMSP/IPEN program considering the following loads out of the welding zone during irradiation under steady state operation at full power:

- Internal and external pressure gradients;
- Radial and azimuthal thermal gradients;
- Cladding ovalization;
- Restrictions on thermal expansions;
- Differential thermal expansions;
- Axial stress considering the plenum and the spacer grid springs;
- Vibration induced by the coolant;
- Inertial forces;
- Angularity of the plugs.

The developed code considers the deviation of the tube geometry due to its non-circular shape and the lack of concentricity of the inside and outside diameters. Also, it takes in account the thermo-mechanical properties of the cladding material, such as, Young modulus, thermal expansion coefficient, Poisson´s ratio and yield strength.

In order to calculate the stresses due to the vibration induced by the coolant, the code uses the density and the dynamic viscosity of water as function of pressure and temperature.

Stress is classified as primary, secondary and bending. Primary stress is due to external loading and it is no limited by the material yield stress. Secondary stress arises from restrictions to deformation by adjacent materials and also geometrical discontinuities. Membrane stress is the average of the stress distribution of all stresses that affect the whole membrane and bending is a variable component.

In each point, the individual stress was estimated for every orientation (0^o, 90^o and 180^o) and settled with all stresses according to the following categories:
M: stress on the primary membrane;
M + B: stress on primary membrane and bending;
M + B + S: stress on the primary membrane, bending and secondary stress.
For each point, the calculated single stresses are combined to obtain the total stress in the tangential, axial and radial directions. Then, the equivalent stress is obtained applying the distortion energy theory (von Mises). In this way, the tridimensional state of stresses is reduced to one-dimensional state in order to allow comparing with the stresses values obtained by means of simple uniaxial tensile tests.

The design limits considered for the studied material are presented in Table 2.

Table 2: Stresses Design Limits for 348 Stainless Steel

CATEGORY	DESIGN LIMIT [MPa]	
	Yield Stress	Stress at Break
M	162	215
M+B	243	301
M+B+S	486	430
Material Limit	180	430

The obtained results for the fuel rod loads under steady state irradiation at full power considering the nominal values for the rod geometry are presented in Tables 3 and 4. Two conditions were evaluated: the rod with the geometry considering the nominal values at hot power and the rod taking into account the tolerances associated to geometric values and 10% of over power and over pressure at end of life, both considering the region out of the welding zone of the end plugs.

Table 3: Stresses Analysis Out of the Welding Zone at 0^o, 90^o and 180^o, considering nominal geometric values and full power

CATEGORY: M+B+S							
		Internal surface			External surface		
	Directions	0^o	90^o	180^o	0^o	90^o	180^o
Stress (MPa)	Tangential	-171,35	-121,55	-162,92	13,55	-35,76	6,10
	Radial	-5,63	-5,63	-5,63	-13,80	-13,80	-13,80
	Axial	-107,97	-91,40	-101,12	36,73	18,67	26,90
	Equivalent	144,83	104,17	137,25	43,81	47,43	35,25
	Tangential	-171,35	-121,55	-162,92	13,55	-35,76	6,10
	Radial	-5,63	-5,63	-5,63	-13,80	-13,80	-13,80
	Axial	-107,97	-91,62	-101,12	36,49	18,43	26,66
	Equivalent	144,83	104,23	137,25	43,61	47,21	35,04
	Yield Stress	486	486	486	486	486	486
	Stress at break	430	430	430	430	430	430
	Project Limit*	430	430	430	430	430	430

*Design Limit: 270% of yield stress and 100% of stress at break

Table 4: Stresses Analysis Out of the Welding Zone at 0^o, 90^o and 180^o, considering tolerances associated to geometric values, and 10% of over power and over pressure

CATEGORY: M+B+S							
		Internal surface			External surface		
	Directions	0^o	90^o	180^o	0^o	90^o	180^o
Stress (MPa)	Tangential	-189,44	-134,43	-189,44	14,89	-40,11	14,89
	Radial	-5,75	-5,75	-5,75	-15,20	-15,20	-15,20
	Axial	-110,25	-102,54	-126,54	45,49	21,49	29,20
	Equivalent	159,58	116,07	161,69	52,56	53,68	39,25
	Tangential	-189,44	-134,43	-189,44	14,89	-40,11	14,89
	Radial	-5,75	-5,75	-5,75	-15,20	-15,20	-15,20
	Axial	-110,25	-102,74	-126,54	45,27	21,27	28,98
	Equivalent	159,58	116,13	161,69	52,37	53,47	39,09
	Yield Stress	486	486	486	486	486	486
	Stress at break	430	430	430	430	430	430
	Project Limit*	430	430	430	430	430	430

*Design Limit: 270% of yield stress and 100% of stress at break

In all cases studied, the loads induced by the coolant flow are very low and can be neglected during the reactor operation.

The results presented in Table 3 show that the equivalent stresses calculated in all directions are lower than the values considered as design limits for the 348 stainless steel. This indicates that under steady state operation at full power the fuel rod will preserve its integrity even considering the worst case associated to the geometric tolerances and 10% of over power and over pressure. New assessments shall be carried out in order to evaluate the effects on the material due to the welding process of the end plugs.

3. CONCLUSIONS

In condition of steady state operation of a typical PWR, the individual stresses which are classified in categories and settled with equivalent stresses were compared with values of the design limits. In this typical PWR, the major contributions, for the equivalent stress, are the internal and external pressure on the fuel rod and also its temperature which affect the strength of the rod material and also contribute for the evaluation of the equivalent stress. The obtained results have shown that despite of the different loads acting on the fuel rod, the limit values for stress of 348 stainless steel are not reached and, consequently, the rod integrity is preserved under the expected normal reactor operation conditions.

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