TOOLS AND TECHNIQUES

Evaluation of the Structural Integrity of a Boiling Water Reactor Core Shroud with an Irregular Distribution of Circumferential Cracks: Elasto-plastic and Plastic Analysis

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Abstract Three asymmetric cracks were postulated at the circumferential horizontal weld H7 of a boiling water reactor type 5 core shroud after 25 years of operation. They were arranged in an irregular distribution with different depths. Unstable crack propagation can be induced when an earthquake and a loss of coolant accident take place. In this paper, a ductile failure analysis has been reported. It has been done following an elastoplastic analysis and a plastic limit load analysis. The crack conditions after 30 and 60 years of operation were evaluated. The results show that the core shroud will keep its structural integrity during sixty years under normal conditions of operation. On the other hand, its operational life is reduced five years under failure conditions. In general terms, the methodology, which has been developed, can be applied for any number of circumferential cracks located in the same cross section. Fast and reliable outputs can be obtained. It can be applied in any moment of the life of the plant, to support the decision on "Use as is", "Mandatory Repair", or "Estimation of the remaining life."

Introduction

In the case of Boiling Water Reactors (BWRs), cracks along the circumferential welds of the core shroud have been identified during inspections in some Nuclear Power Plants (NPPs) in planned outages. They have an irregular shape and unsymmetrical distribution (Fig. 1) [1, 2]. It is important to evaluate the structural integrity of such core shroud or determine its remaining life. Unfortunately, a numerical evaluation is quite complex in most of the cases. The generic letter 94-03, issued by the United States Nuclear Regulatory Commission (USNRC) [3] states that: the core shroud is susceptible to intergranular stress corrosion cracking (IGSCC).

During the operating life, normal, upset and emergency conditions of operation could take place. An undesirable combination could be developed when an earthquake and a loss of coolant accident (LOCA) are combined. The bottom of the core shroud would be under tension and bending, and some cracks on the circumferential welds would be loaded under Fracture Mode I. As more hours of operation are accumulated, the material of the core shroud is more exposed to a fission process, and the material becomes brittle.

A nuclear power plant (NPP) must operate with an adequate level of safety during its extended life of

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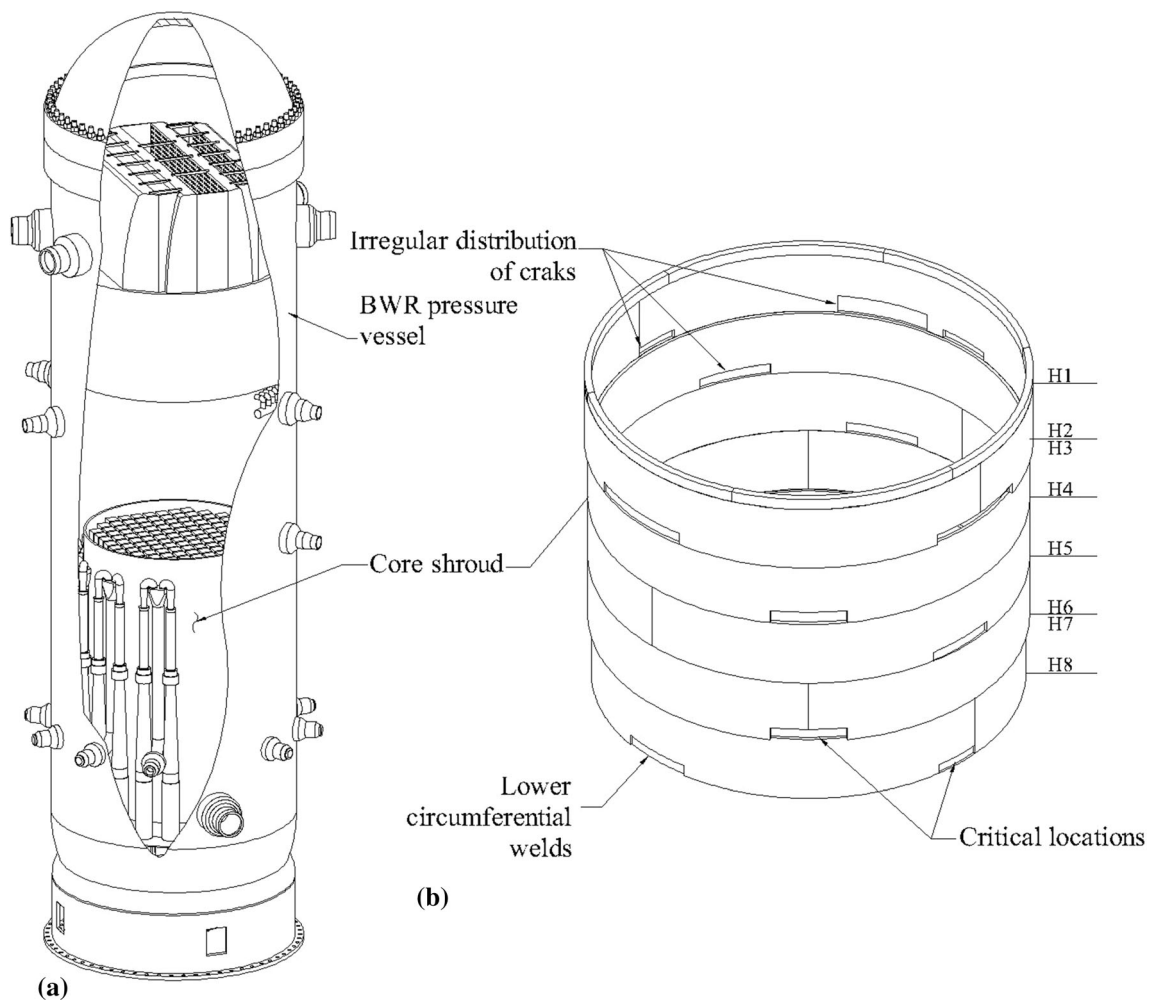J Fail. Anal. and Preven. (2022) 22:956–967

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Fig. 1 (a) BWR-5, (b) localization of the horizontal weld of the core shroud

operation or in a power up rate. Guidelines and recommendations have been established, based on accumulated experience, for a proper management of aging of nuclear reactors [4, 5]. Besides, periodic inspections have been established in [6]. However, if a defect becomes relevant, a Time Limited Aging Analysis (TLAA) is required. An evaluation of the brittle and ductile failures is required to establish a performance scenario of the core shroud.

In a previous paper [7], the brittle behavior of a BWR-5 core shroud was evaluated. In the case of this paper, a ductile failure analysis was carried out. The circumferential cracks on the core shroud are on the same cross section and in any azimuth. They have different lengths and depths. A methodology, which can provide fast and reliable outputs, have been proposed and any number of cracks can be evaluated simultaneously.

Statement of the Problem

The BWR-5 core shroud was made with type 304 stainless steel. Its average diameter and thickness are 4.57 m (180 in) and 3.80 cm (1.5 in), respectively. The fracture toughness of the material K_{Ic} is 164.83 MPa·m$^{1/2}$ (150 ksi·in$^{1/2}$).

Three asymmetric cracks at the circumferential horizontal weld H7 have been postulated after 25 years of operation. They have an irregular shape. It was considered that one of them is through thickness and the other two are part through thickness (Fig. 2, Table 1). Regarding the last two cracks, neutron radiation and a low quality of the water chemistry would promote their propagation, in such way that they will become a through thickness crack after five years of operation. Therefore, it is important to determine the time when the safe conditions will be lost. Unfortunately, a numerical evaluation is quite complex in most of the cases.

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It must keep in mind that a nuclear reactor produces energy from nuclear fission, which generates atoms, neutrons, and energy. So, the materials located near the nuclear core receive some quantity of neutrons or nuclear fluence. In relation with the problem at hand, the core shroud has received a neutron fluence of 4.5E+20 n/cm^2 (6.98E+19 n/in^2) after 30 years of operation and it will be 1.21E+21 n/cm^2 (7.81E+21 n/in^2) after 60 years.

All this information is useful in the determination of the safe conditions. It can be defined as the condition when the structural integrity is maintained. In this way, the component can fulfill its safety function. Some safety factors are stated by the industrial codes. It is in accordance with the type of installations to be designed or inspected.

Elastic Plastic Fracture Mechanics (EPFM) Analysis

For those materials with a high toughness, they will not have a catastrophic failure. Their R curve grows, as the J curve increases with the crack propagation. In metals, such increase is associated with the development and coalescence of microvoids [8].

The J-R curve describes the fracture behavior of a ductile material. The slope dJ_R/da is associated with the relative stability of the propagation of a crack and it is related with the Tearing Modulus (T_{mat}), which is an adimensional parameter.

$$T_{\mathrm{mat}} = \frac{E'}{\sigma_F^2}\frac{dJ_R}{da} \tag{Eq 1}$$

where E' is the Effective Young Modulus for plane stress or plane strain, J_R is the strain energy release rate for the material, σ_F is the flow stress and a is the crack length.

The J_R curve is evaluated in function of the crack propagation with the following relationship:

$$J_R = C(\Delta a)^n \tag{Eq 2}$$

C and n are constants that depend on the material. They were obtained from a simple average of the values reported in the NUREG/CR-6826 [9] and the NUREG/CR-7027 [10] (Table 2). It was done for the evaluations after thirty and sixty years of operation.

Under this consideration, the following equation was obtained for the evaluation of the T_{mat} of the material. In this case, E´ is the effective modulus of elasticity and it depends if plane stress or plane strain takes place and σ_F is the flow stress.

$$T_{\mathrm{mat}} = \frac{E'}{\sigma_F^2}\left(\frac{dJ_R}{da}\right) = \frac{E'}{\sigma_F^2}\left(Cn(\Delta a)^{n-1}\right) \tag{Eq 3}$$

The applied tearing modulus was calculated with the following relationship.

Fig. 2 Crack configuration at the circumferential weld H7 of a core shroud (cross section)
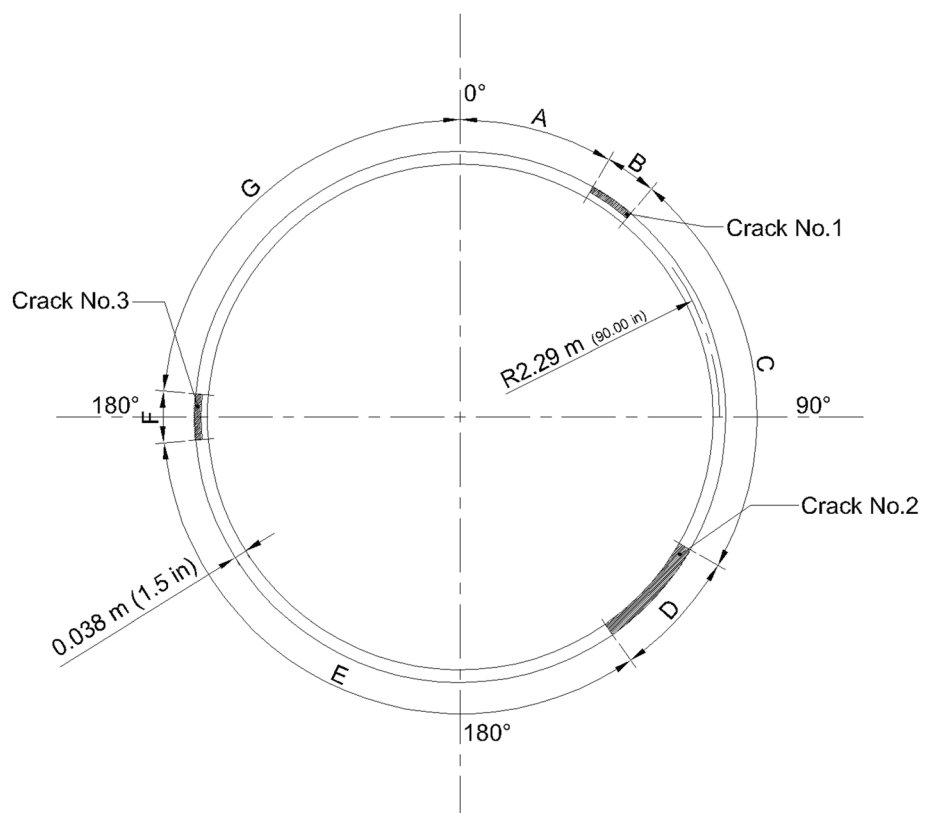
Table 1 Configuration of the cracks through the period of evaluation

Geometry of the cracks after 25 years of operation			
A	B	C	D
1.19 m (47.12 in)	0.39 m (15.71 in)	3.14 m (123.66 in)	0.99 m (133.52 in)
E	F	G	
4.79 m (188.50 in)	0.39 m (15.71 in)	3.39 m (133.52 in)	
Location of the cracks and their depth after 25 years of operation			
Crack	Depth	Initial azimuth	Final azimuth
1	0.0254 m (1 in)	30°	40°
2	0.0381 m (1.5 in)	120°	145°
3	0.0254 m (1 in)	265°	275°
Geometry of the cracks after 30 years of operation			
A	B	C	D
1.19 m (47.12 in)	0.39 m (15.71 in)	3.14 m (123.66 in)	0.99 m (133.52 in)
E	F	G	
4.79 m (188.50 in)	0.39 m (15.71 in)	3.39 m (133.52 in)	
Location of the cracks and their depth after 30 years of operation			
Crack	Depth	Initial azimuth	Final azimuth
1	0.0381 m (1.5 in)	30°	40°
2	0.0381 m (1.5 in)	120°	145°
3	0.0381 m (1.5 in)	265°	275°
Geometry of the cracks after 60 years of operation			
A	B	C	D
0.79 m (31.42 in)	1.19 m (47.12 in)	2.39 m (94.25 in)	1.79 m (70.69 in)
E	F	G	
3.99 m (157.08 in)	1.19 m (47.12 in)	2.99 m (117.81 in)	
Location of the cracks and their depth after 60 years of operation			
Crack	Depth	Initial azimuth	Final azimuth
1	0.0381 m (1.5 in)	20°	50°
2	0.0381 m (1.5 in)	110°	155°
3	0.0381 m (1.5 in)	255°	285°

Table 2 C and n parameters for the case of interest

	30 years of operation		60 years of operation	
	C	n	C	n
NUREG CR-7027	536.54	0.22	400.30	0.36
NUREG CR-6826	541.97	0.27	382.86	0.27
This paper	539.25	0.25	391.58	0.31

$$T_{app} = \frac{E'}{\sigma_F^2}\left(\frac{dJ_{app}}{da}\right)_{\Delta T} = \frac{E'}{\sigma_F^2}\left(\frac{J_{p+inc} - J_p}{a_{p+inc} - a_p}\right) \qquad \text{(Eq 4)}$$

$a_{(p+inc)}$ is the crack length. It is a plus the radius of the plastic zone r_y and it is incremented by the remote displacement ΔT. This increment can be as less as 1%.

$$a_{(p+inc)} = a + r_y + \Delta T \qquad \text{(Eq 5)}$$

a_p is the crack length adjusted with size of the plastic zone. On the other hand, $J_{(p+inc)}$ and J_p are evaluated with $a_{(p+inc)}$ and a_p, respectively. The radius of the plastic zone is calculated with the following equations. In case of plane strain, $r_y = \frac{1}{6\pi}\left(\frac{K_I}{\sigma_{YS}}\right)^2$ or, in plane stress, $r_y = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_{YS}}\right)^2$. σ_{YS} is the yield stress.

Once that these data have been obtained, the following criteria can be considered: (1) a stable crack propagation can take place when $T_{app} \leq T_{mat}$, otherwise, (2) unstable crack propagation occurs when $T_{app} > T_{mat}$. As a result, the following safety factor can be established:

$$SF = \frac{T_{mat}}{T_{app}} \qquad \text{(Eq 6)}$$

At the initiation of operation of the reactor, Stainless Steel, which is the material of the core shroud, is ductile. However, neutron irradiation induces a brittle state as hours

of operation are accumulated. So, the yield and flow stresses are increased, and the fracture toughness is reduced. Therefore, it is important to evaluate the variation of these parameters as the material is aged. For the problem at hand, the data of the cross section of the cracked weld and the J-R curve coefficients for the core shroud material were considered.

The variation of the yield stress of a stainless steel 304, in function of the neutron irradiation, was evaluated with the equations of the Sect. 2.1.4 of NUREG/CR-7027 [10]. In this way, the variation of this stress during the operation life of the reactor is illustrated in Fig. 3. Equation 7 was considered, where d is the neutron dose.

$$\sigma_{ys} = 200 + 600\left(1 - e^{\left(-\frac{d}{3}\right)}\right) \quad \text{(Eq 7)}$$

In a similar way and in accordance with [10], the following correlation has been proposed for the estimation of the flow stress of the stainless steel as a function of the neutron fluence (n/cm^2). Figure 4 shows the estimated flow stress during the period of operation of the BWR.

$$\sigma_f = 113.67\ln(\text{neutron fluence}) - 4952.8 \quad \text{(Eq 8)}$$

The J curves, when the internal parts of a Light Water Reactor (LWR) have been irradiated, were considered. Under this condition, the J curves were developed with the data obtained with Eq 2 (Figure 5).

Under normal conditions of operation, the tension membrane stress P_m is 6.89 MPa (1000 psi), the bending stress is P_b is 17.24 MPa (2500 psi) and the safety factor is 3.0. Table 3 summarizes the evaluation of the Tearing Modulus of crack 1, which was considered as the most

critical. Table 3 was obtained with Eqs 2, 3, 4, 5 and 6. The Stress Intensity Factor (SIF) was calculated in accordance with [2].

A similar evaluation was carried out for the other two cracks. In Table 4, the safety factors are summarized for normal conditions of operation. These parameters are greater than 3.0. All the cracks can be considered safe.

Regarding the failure conditions, the safety factors are also reported in Table 4. In all these cases, it is expected that they must be greater than 1.5.

It has to be observed that the second crack is unsafe under failure conditions after 60 years of operation. Its safety factor (0.68) is lower than 1.5.

Limit Load Analysis

A plastic analysis of a thin wall cylinder with diverse cracks on a horizontal plane is not straight forward. In [11, 12], an explicit solution for a single circumferential crack through and not through thickness is presented. Rahman and Wilkowski [13] provided the explicit solution for an arbitrary configuration of circumferential cracks. Such configuration must be symmetrical with respect to the bending plane [13]. One solution would be to group the cracks. However, the results would be excessively conservative. Finally, the solution for the case of interest is presented in [14]. However, the interpretation of the theoretical basis and the solution are complex.

A methodology, which is named the "PRL method" after the first author's name, has been developed in a

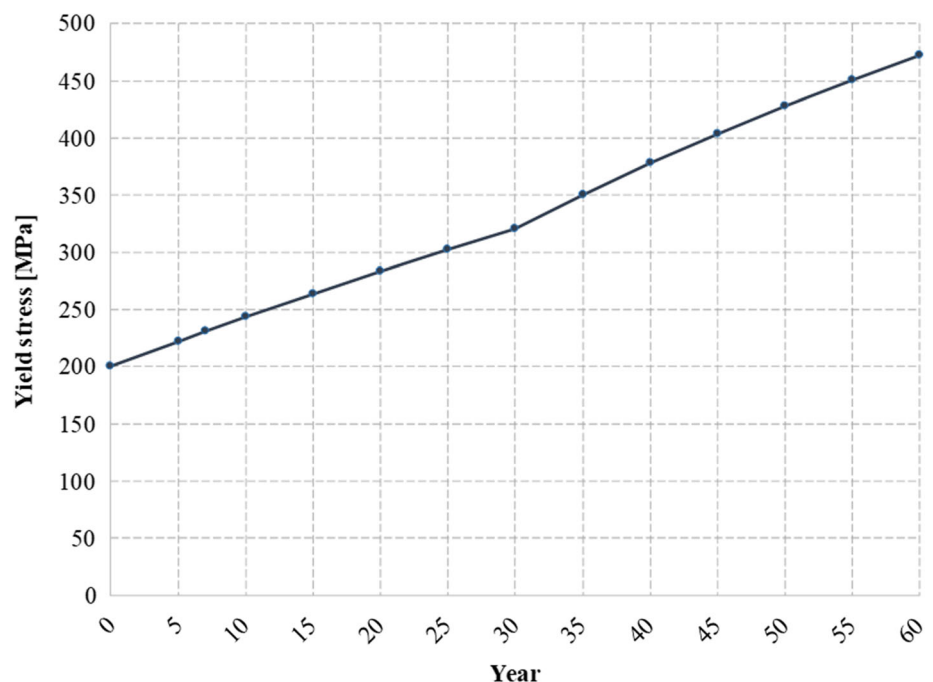Fig. 3 Variation of yield stress σ_{YS} during 60 years of operation

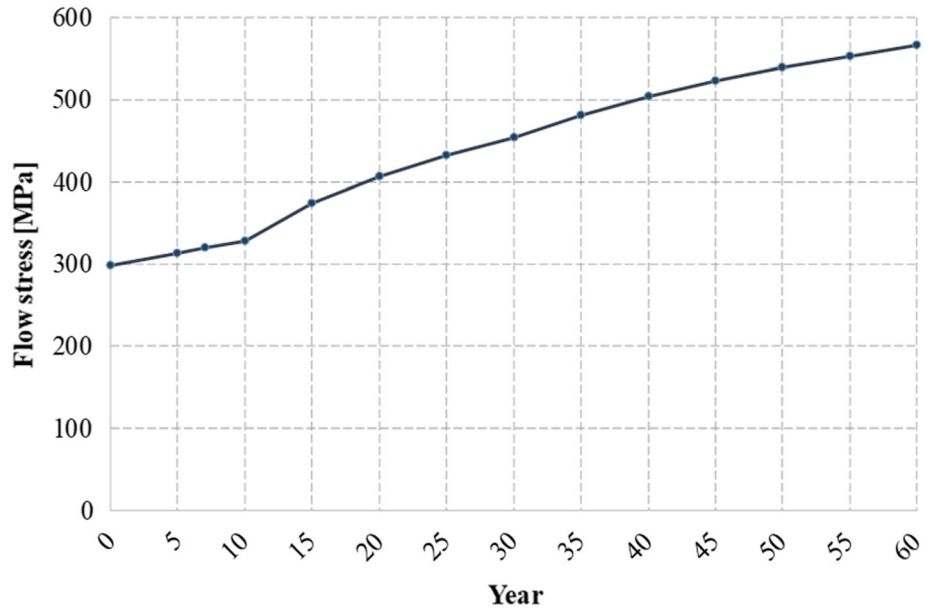**Fig. 4** Variation of flow stress σ_F during 60 years of operation
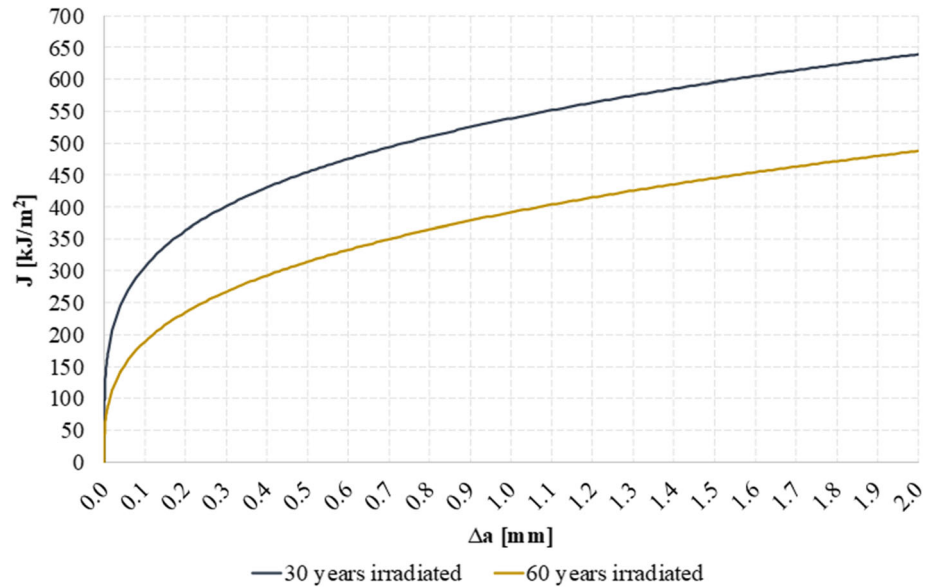

Fig. 5 Variation of the fracture toughness J_{IC} due to the neutronic radiation (for 30 and 60 years of operation)

previous work [15]. The required equations proposed in [14] have been developed and simplified. Certain number of iterations for the calculation of the α angle, which is required for the determination of the minimum or critical plastic moment, are needed. The distance between the central and the neutral axes is δ.

In this methodology, the perimeter of the circumferential is divided in simple arcs (Fig. 6). The angle of each arc is between θ_{i1} and θ_{i2} and its thickness can be from 0.0 up to the nominal thickness t_n.

The following equations have been proposed, where t_i is

the thickness of each individual arc-segment or sector of the core shroud.

$$\frac{1}{2}\left\{\sum_{i=1}^{I} \text{arc}_i\, t_i\right\} \tag{Eq 9}$$

$$\text{arc}_i = R_m(\theta_{i1} - \theta_{i2}) \tag{Eq 10}$$

The plastic moment is evaluated with the following relationship:

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Table 3 Evaluation of the Tearing Modulus of crack 1

Original length of the crack (2a=0.39 m (15.71 in))			
E´ Effective modulus of elasticity	192.31 GPa (27.892 E6 psi) Plane strain	K	$35.30 \text{ MPa} \cdot \text{m}^{1/2}$ ($32.1052 \text{ ksi} \cdot \text{in}^{1/2}$)
J	6471.79 N/m (36.9549 lb/in)	Radius of the plastic zone	1.92E-03 m (0.0757 in)
Crack length considering the plastic zone			
a	0.20 m (7.9297 in)	K	$35.50 \text{ MPa} \cdot \text{m}^{1/2}$ ($32.2641 \text{ ksi} \cdot \text{in}^{1/2}$)
J	6536.01 N/m (37.3216 lb/in)		
Original crack length incremented by 1% (2a= 0.40 m (15.8650 in))			
K	$35.50 \text{ MPa} \cdot \text{m}^{1/2}$ ($32.27 \text{ ksi} \cdot \text{in}^{1/2}$)	J	6538.40 N/m (37.3352 lb/in)
Radius of the plastic zone	1.94E-03 m (0.07651 in)		
Original crack length incremented by 1% and the radius of the plastic zone (2a= 0.41 m (16.01807 in))			
K	$35.70 \text{ MPa} \cdot \text{m}^{1/2}$ ($32.4508 \text{ ksi} \cdot \text{in}^{1/2}$)	J	6611.88 N/m (37.7548 lb/in)
Ductile Tearing Modulus (T_{app})			
ΔJ	75.8742 J/m^2	Δa	2.01E-03 m (0.079319 in)
$E´/\sigma^2$	$9.43 \text{ E-07 m}^2\text{/N}$ ($0.0065 \text{ in}^2\text{/lb}$)	T_{app}	0.035
Material Tearing Modulus (T_{mat})			
$J (a+r_y+ \Delta T)$	6611.88 N/m (37.7548 lb/in)	$J (a+r_y)$	6536.01 N/m (37.3216 lb/in)
J_{avg}	6573.95 N/m (37.5382 lb/in)	Δa	1.6223 E-8 mm (6.39E-10 in)
T_{mat}	93.3560		
SF = 2643.7 > 3.0 It is safe			

Table 4 Safety factors obtained with an elasto-plastic fracture mechanics analysis

	Normal conditions of operation	
Crack	After 30 years of operation	After 60 years of operation
1	2643.7	47.2
2	72.6	6.07
3	2647.9	43.2
Failure conditions		
1	153.90	3.26
2	5.74	0.68
3	154.10	3.19

$$M_p = \sigma_F \sum_{i=1}^{I} \text{arc}_i \, t_i \left\{ R_m \sin\left(\alpha - \theta - \frac{\text{arc}}{2}\right) + R_m \sin(\beta) \right\}$$

(Eq 11)

The angle $\alpha + \beta$ is determined iteratively until the minimum M_p is found. An efficient way to find it is to observe the configuration of cracks in which there is an angle that envelops the greatest length of cracks in tension. As the analyst makes several calculations, some degree of skill for determining the angle $\alpha + \beta$ is acquired. Regarding the case of interest, the circumferential horizontal weld H7 was divided in sections of 5 degrees as a polygon. The length of each one is 0.19 m (7.85 in).

Initially, the evaluation was performed after 30 years of normal conditions of operation. During this period, the radiation flow has been $4.50E+20 \text{ n/cm}^2$ (6.98 n/in^2). The geometrical parameters considered have been reported in Table 5.

The modulus of elasticity of the material was 175 GPa (25,382 ksi) and the Poisson ratio was 0.3. The fracture toughness was $165 \text{ MPa·m}^{1/2}$ ($150 \text{ ksi·in}^{1/2}$).

In the case of the seismic loading, it must be considered that the direction of an earthquake is unpredictable. As a result, tension and shear stresses are developed at the circumferential cracks. However, the bending moments induced by lateral loads (like earthquake, and the break of the main steam or recirculation piping) are the main concern, because they produce opening of cracks in Mode I. For this reason, the evaluation was carried out on the direction where most of the cracks were under tension. The addition of both stresses, P_m+P_b, was considered as the loading conditions. It was 24.13 MPa (3500 psi). The safety factor for the normal conditions of operations considered in the evaluation was 3.0.

Regarding the plastic analysis parameters, the shape factor, which is the ratio between the Plastic Moment and the First Yield Moment, was considered. Besides, the Plastic Section Modulus of the cross section with any crack was 0.20 m^4 ($48.35E3 \text{ in}^4$). The plastic moment of the

Fig. 6 Graphical representation of the methodology developed by PRL
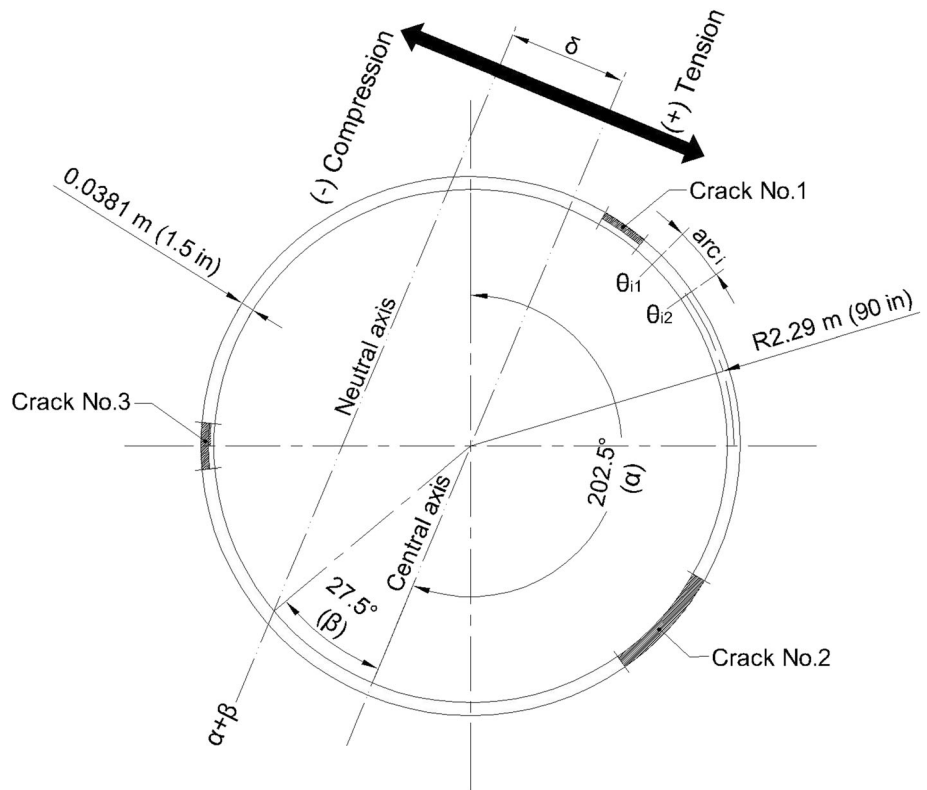
Table 5 Geometrical parameters of a core shroud

Thickness	0.0381 m (1.5 in)	Circumference	14.363 m (565.4867 in)
Mean radius	2.286 m (90.0 in)	Cross-sectional area	0.547 m^2 (848.23 in^2)
Interior radius	2.267 m (89.25 in)	Inertia moment	0.182 m^4 (435570.1 in^4)
Exterior radius	2.305 m (90.75 in)	Elastic modulus of section	0.620 m^3 (37857.522 in^3)

Table 6 Results of the limit load analysis

α	202.5°	$\delta + R_m$	3.341 m (131.5574 in)
M_p	318.02 MN • m (2.8147 E9 lb • in)	$\alpha + \beta$	230.0°
β	27.5°	P_b (calculated)	512.63 MPa (74351 psi)
δ	1.055 m (41.5574 in)	Safety factor	21.529

Table 7 Parameters considered in the evaluation of the strength of the remaining material ligament

Cross-sectional area	0.547 m^2 (848.23 in^2)	P_m	6.89 MPa (1000 psi)
Remanent cross-sectional area	0.478 m^2 (742.20 in^2)	P_b	17.24 MPa (2500 psi)
σ_F Flow stress	297.85 MPa (43200 psi)	P_m+P_b	24.13 MPa (3500 psi)

Table 8 Results of the limit load analysis

Considering P_m	7.88 MPa < 452.87 MPa (1142.86 psi < 65683 psi)	Safety Factor 57.47
Considering P_m+P_b	27.58 MPa < 452.87 MPa (4000 psi < 65683 psi)	Safety Factor 16.42

The safety factor is greater than 3.0. Therefore, the core shroud can maintain its integrity after 30 years of operation.

An additional evaluation was carried out, in which the remaining material ligament was considered. Parameters

cracked cross section was 318.02 MN·m (2.81 E9 lb·in). The results have been reported in Table 6.

Table 9 Results of the limit load of the evaluation for 30 and 60 years of operation

Normal conditions of operation after 30 years of operation		
Plastic Moment (M_p)	Plastic stress (P_b)	Safety Factor
317.49 MN · m	513.87 MPa	21.5 >3
(2.81 E9 lb · in)	(74531 psi)	
Strength of the remaining material ligament	Safety Factor	
	57.47 >3	
	The membrane stress was considered for the uncracked thickness	
Failure conditions of operation after 30 years of operation		
Plastic Moment (M_p)	Plastic stress (P_b)	Safety Factor
317.49 MN · m	513.87 MPa	15.2 >1.5
(2.81 E9 lb · in)	(74351 psi)	
Strength of the remaining material ligament	Safety Factor	
	38.31 >1.5	
	The membrane stress was considered for the uncracked thickness	
Normal conditions of operation after 60 years of operation		
Plastic Moment (M_p)	Plastic stress (P_b)	Safety Factor
315.23 MN · m	508.02 MPa	21.3 >3
(2.79 E9 lb · in)	(73682 psi)	
Strength of the remain ligament	Safety Factor	
	62.6 >3	
	The membrane stress was considered for the uncracked thickness	
Failure conditions of operation after 60 years of operation		
Plastic Moment (M_p)	Plastic stress (P_b)	Safety Factor
315.23 MN · m	508.02 MPa	15.0 >1.5
(2.79 E9 lb · in)	(73682 psi)	
Strength of the remain ligament	Safety Factor	
	41.8 >1.5	
	The membrane stress was considered for the uncracked thickness	

Table 10 Safety factors evaluated under normal conditions of operation

Years of operation	Safety factor	Plastic analysis	Fracture mechanics	
			Elasto-plastic	Elastic
30	3.0	21.5	72.6	2.9
60	3.0	21.3	5.9	2.0

are shown in Table 7, and the results have been reported in Table 8.

As indicated in this calculation, the revision with the membrane stress P_m is enough for the evaluation of the safety factor. It was 57.47. However, it is more conservative to make this evaluation with the membrane P_m and bending P_b stresses. In this case, the safety factor was 16.42. In both cases, they were greater than the allowable value 3.0. Therefore, the core shroud will maintain its integral safety with this arrangement of cracks.

In the next step, it was evaluated the structural integrity after 30 and 60 years of operation. Table 9 summarizes the results.

Discussion of the Results

Evaluation of the Structural Integrity of the Core Shroud Under Normal Conditions of Operation

The main interest is to obtain a projection of the structural integrity up to sixty years of normal operation. It was observed that crack 2 is the most critical. The following analysis was made around it. Table 10 summarizes the safety factors which were considered for this purpose and were graphed in Fig. 7. Cracks grow during the lifetime. So, after 30 years; the safety factor decreases from 2.9 to 2.0. The safety factors were calculated from the general relationship "Applied/Material Threshold." They were compared against the "Safety Factor Minimum Values"
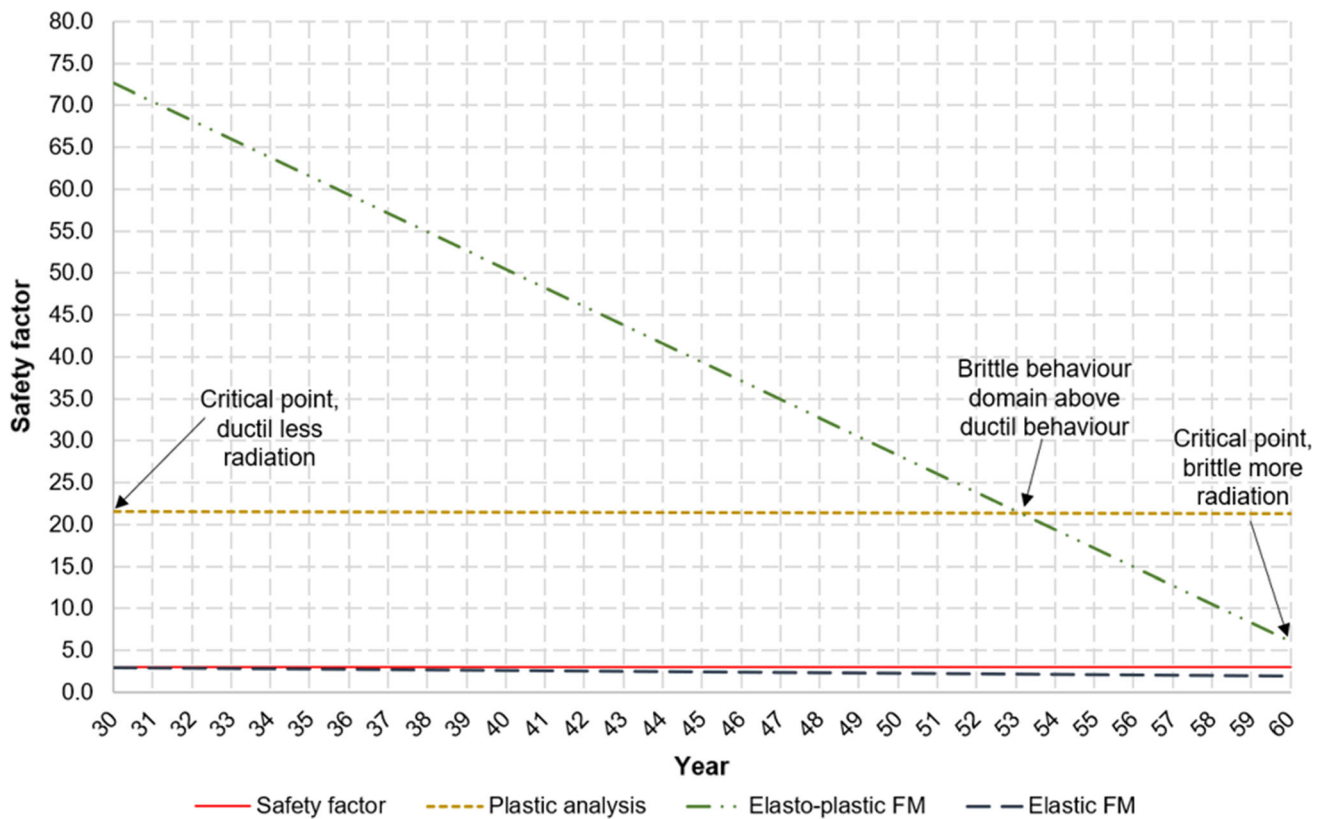
Fig. 7 Projection of structural integrity of the core shroud under normal conditions of operation

Table 11 Safety factors evaluated under failure conditions of operation

Year	Safety factor	Plastic analysis	Fracture mechanics	
			Elasto-plastic	Elastic
30	1.5	15.2	5.7	2.0
60	1.5	15.0	0.7	1.4

taken from the industrial codes like ASME for each operation condition (normal, accident).

In accordance with Fig. 7, the ductile behavior predominates under normal conditions of operation after thirty years of operation. However, the material is brittle after 53 years. Safety conditions are maintained during the whole life of operation of the core shroud in normal conditions.

Since the point of view of the Fracture Mechanics, the safety factor of 3.0 is exceeded, after 30 years of operation. This situation takes place during the subsequence 30 years. On the other hand, the results of the EPFM fulfil the requirements of such safety factor. It can be said that the cracks and the non-cracked section are simultaneously critical. However, cracks will play an important role as time goes on. The neutron irradiation will develop the embrittlement of the material.

In accordance with these results, the structural integrity of the core shroud, under normal conditions of operation, will be maintained along the sixty years of operation of the BWR plant.

Evaluation of the Structural Integrity of the Core Shroud Under Failure Conditions

Table 11 summarizes the results of the evaluation of crack number 2, and Fig. 8 shows the projection of the structural integrity of the core shroud under failure conditions.

As the material is aged by the radiation mainly, brittle behavior is expected after 55 years of operation. During the last five years of operation, cracks are relevant. Alternatively, the plastic criterion is achieved during the sixty years of operation.

Under the scope of these analyses, the core shroud will keep its structural integrity during the first 55 years of operation. However, it will not reach the desired 60 years
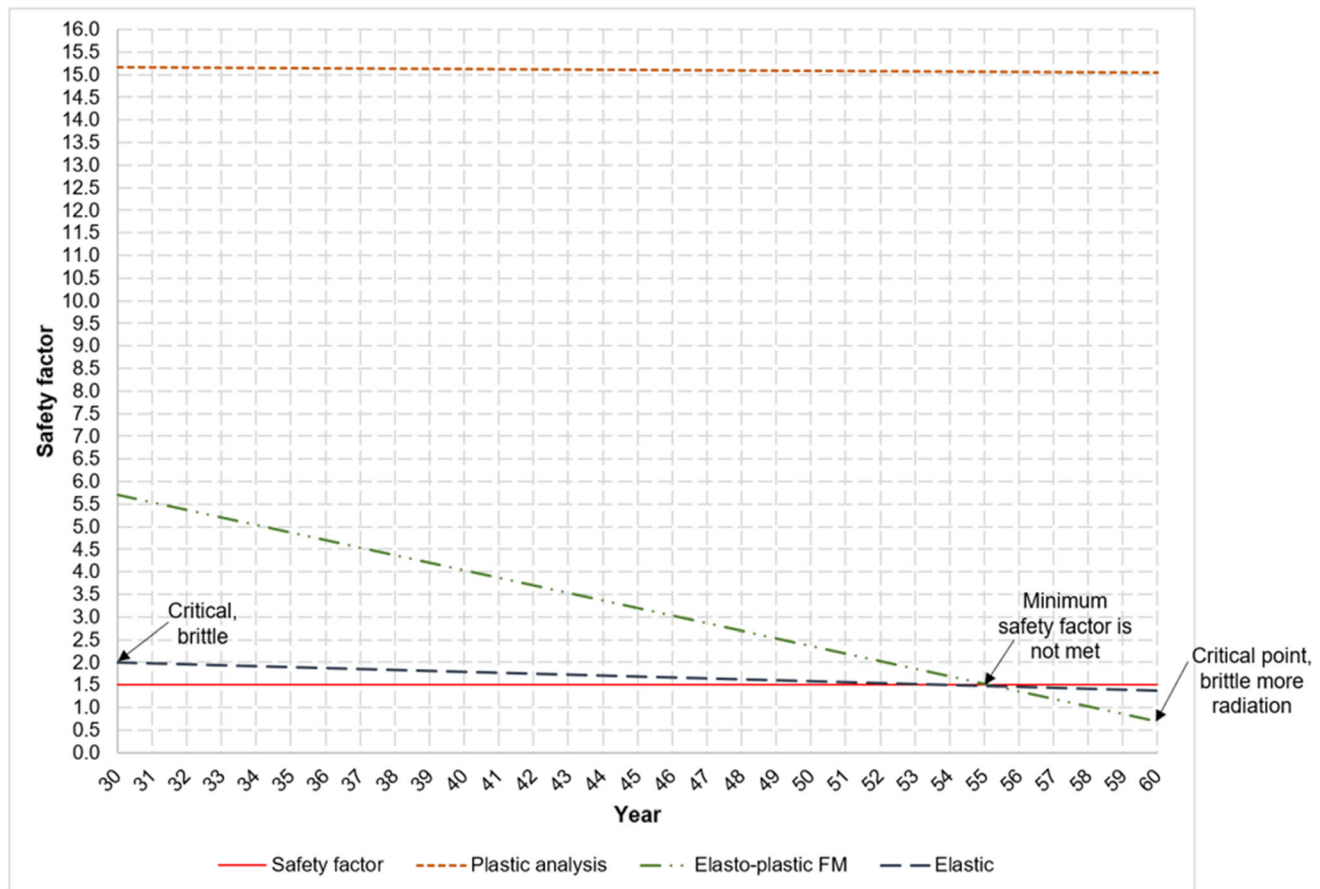
Fig. 8 Projection of structural integrity of the core shroud under failure conditions of operation

of operation. Therefore, it is advisable to take administrative and economic previsions after 55 years of operation. In this way, this internal component must be repaired or replaced to maintain the required levels of safety.

Conclusions

The remnant life of a core shroud was estimated with the guidelines of the 10 CFR 54 [16]. It is related with the renewal of the operating license for NPPs. In other words, this evaluation can be considered as a Time-Limited Aging Analysis (TLAA).

A general methodology, which evaluates the random distribution of cracks along the circumferential welds of a core shroud, was proposed. Fast and reliable outputs can be obtained, and the results can support the decision on "Use as is," "Mandatory Repair," or "Estimation of the remaining life."

For the problem at hand, the results show that the core shroud will keep its structural integrity during sixty years of operation, when it is operated under normal conditions.

However, its operational life is reduced five years under failure conditions. It must keep in mind that this component has the safety function to maintain the geometry and cooling of the nuclear core.

Initially, the stainless steel is ductile by nature. Nonetheless, as hours of operation are accumulated, the neutron irradiation of the material increases. As a result, the material becomes brittle. It is advisable to introduce in the calculation, the properties of the materials of the core shroud, which are determined experimentally. The accuracy of the results can be increased.

Statement, the conclusions and opinions stated in this paper do not represent the position of the National Commission on Nuclear Safety and Safeguards, where the co-author P. Ruiz-López is working as an employee. Although special care has been taken to maintain the accuracy of the information and results, all the authors do not assume any responsibility for the consequences of its use. The use of mentions of countries, territories, companies, associations, products, or methodologies does not imply any judgment or promotion by all the authors.

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