ENUSA INTEGRAL SOLUTION FOR INTERGRANULAR STRESS CORROSION CRACKING ON EARLY 17X17 PWR DESIGNS

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ABSTRACT

Currently, there are several fuel assemblies (FA) affected worldwide by intergranular stress corrosion cracking (IGSCC) of the sleeves that connect the top nozzle to the guide tubes. After identification of the first assemblies susceptible of being affected by IGSCC, ENUSA has developed multidisciplinary actions to mitigate the impact in the strategy for dry storage and transportation. The first action consisted of a detailed analysis of historic records of the susceptible population. The analysis allowed differentiation of FA groups having different probabilities of being affected by sleeves IGSCC, concluding in different spent fuel management solutions: high-resolution four faces inspections of assemblies having low probability of being affected and design, licensing and installation of the ESPIGA, a conditioning device that fastens the FA to its top nozzle and guaranties handling by normal means. As a result of these actions, majority of the initial susceptible population is being handled by normal means, dry stored and may be transported to the Spanish centralized interim storage facility (ATC, Spanish acronym). Altogether, the described actions conform an integral solution to the IGSCC issue, reducing significantly time and number of operations necessary for dry storage management.

1. Introduction

In the past, episodes of top nozzle detachment from the skeleton was observed in early 17x17 PWR designs during ordinary FA handling in the spent fuel pool (SFP) at several nuclear power plants (NPP). Early 17x17 PWR designs, the top grid sleeves are welded to the top nozzle plate. The fuel bundle was attached to the top nozzle by mechanical bulge joints between the top grid sleeves and the guide tubes. In all top nozzle detachment cases, the fuel bundle separated from the top nozzle due to cracking of the sleeves that connected the top nozzle to the guide tubes. Root cause analysis performed in the past revealed that the primary cause of the top nozzle detachments was intergranular stress corrosion cracking (IGSCC) of the sleeves in the bulged regions occurred in the spent fuel pools (SPF) (reference 1). Currently, there are thousands of FAs affected worldwide by this phenomenon. Extraordinary handling limitations in SFP were applied as a precautionary measure, increasing considerably the number of operations and time needed for handling the FAs.

Regarding spent fuel dry storage and transportation, FA retrievability is a requirement in Spain. Currently, the SFPs are close to their full capacity and dry storage casks are being loaded and placed in the corresponding independent spent fuel storage installation (ISFSI). After some years of dry storage at the ISFSIs, the casks will be transported to the centralized interim storage facility (ATC, Spanish acronym), illustrated in Figure 1. Once the casks arrive to the ATC from each NPP, the FAs will be moved from the transportation cask to the storage canisters, where will be stored another 100 years.

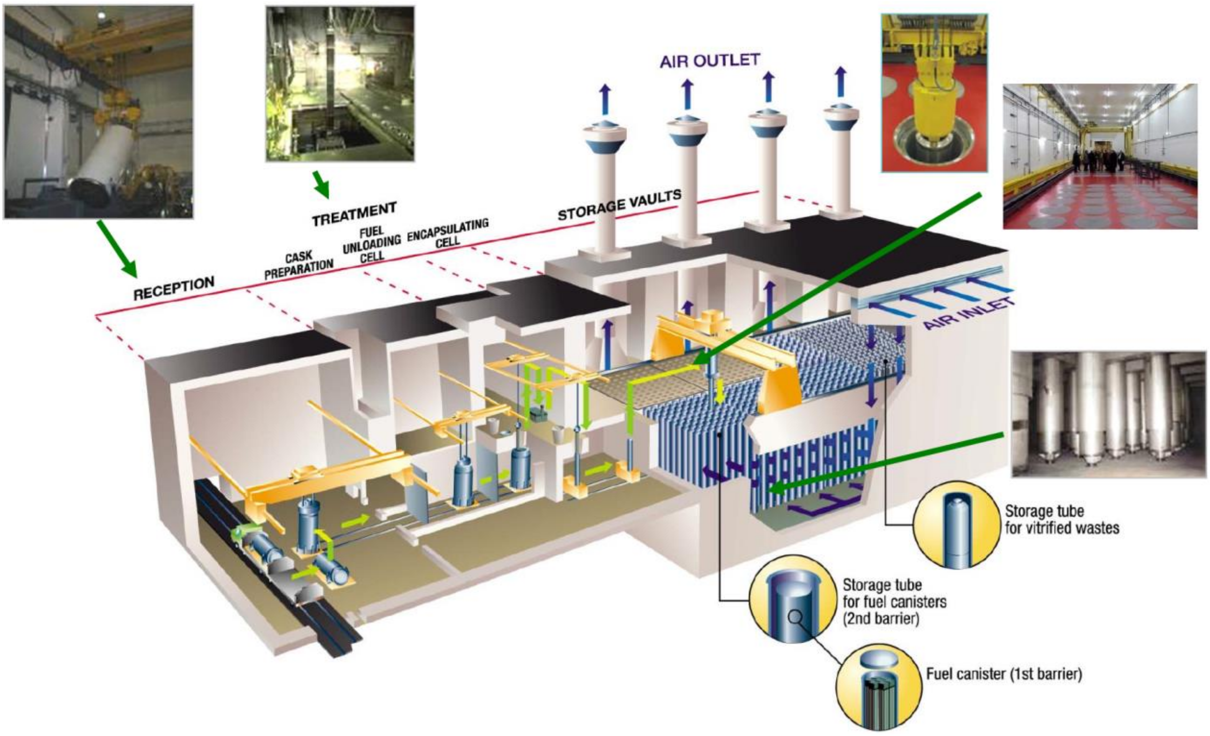

Fig. 1. Spanish centralized interim storage facility ATC (reference 2)

Since each FA need to be extracted from the transportation cask, FA retrievability after transport is a requirement in the Spanish spent fuel management strategy. If no other approaches were explored, every FA included in the initial IGSCC susceptible population should be indefinitely subjected to precautionary measures and inspections. ENUSA has carried out different actions with the objective of reducing the initial susceptible population, minimizing the necessary number of operations and time in the SFPs and in the ATC. The objective of this paper is describing these actions and how the susceptible population has been substantially reduced.

2. Description of the integral solution

1.1 Historic record analysis

The first part of the solution consisted of a detailed analysis of historic records of the initial susceptible population. The analysis focused in the sleeves material composition, SPF chemistry, irradiation history and total number of movements and inspections.

Top grid sleeves material is SS304 / SS304L austenitic stainless steels, depending on the FA design. Carbon concentration, [C], is a key parameter for SS304 / SS304L intergranular corrosion susceptibility, in such a way that the higher [C] the higher susceptibility. At certain temperatures and holding times, carbon and chromium dissolved in the austenite matrix precipitate as chromium carbides ($Cr_{23}C_6$) at grain boundaries. Due to the high number of Cr atoms in the carbide molecule per one C atom, an austenite Cr depleted zone appears around grain boundaries (reference 3). This phenomenon, known as sensitization, produces weak corrosion resistance at grain boundaries because [Cr] goes below minimum 12 wt% required to generate the chromium oxide protective layer.

In the first 17x17 PWR designs introduced in the Spanish NPPs, top grid sleeves material was SS304, which may have [C] up to 0.080 wt.% (reference 4). During the top grid manufacturing process, sleeves underwent temperatures that could cause sensitization to intergranular corrosion. Because of the first IGSCC issues, sleeves material changed to

SS304L, which have a maximum [C] of 0.030 wt.% (reference 4). Below this limit, the material does not sensitize at real manufacturing times and temperatures.
As the manufacturing process was nearly the same independently of the carbon concentration, the first part of the analysis consisted of segregation of FAs having sleeves with [C] < 0.030 wt.%. Review of the historic records related to sleeves manufacturing was necessary. The amount of FAs having [C] < 0.030 wt.% represented 25% of the initial susceptible population and were considered none-affected by IGSCC and no special handling requirements were recommended.
Other main factor affecting IGSCC is the environment. IGSCC phenomenon occurred in the SPF. At the beginning of the operation in several NPPs, not all the chemical species which could affect to the sleeves resistance to IGSCC were controlled. Particularly, the IGSCC phenomenon was related with presence of sulphates in the SFP water, which was not measured in all NPPs from the beginning of their operation.
ENUSA has revised chemical information provided by each analysed NPP. In case of clear evidence of contamination or absence of chemical records, the SFP water was considered susceptible of being affected by sleeves IGSCC. Based on the gathered information, it was possible to stablish a period when a particular SFP was susceptible of sleeves IGSCC and periods when was not.
Other types of records that have been analysed for every susceptible FA in a particular SFP during its susceptibility period are:

- Operation and reloading history: beginning and end of irradiation cycles;
- Results of all top grid sleeves visual inspections, both old and new visual inspections;
- Total number of handling movements since their first irradiation cycle until the last characterization inspection for dry storage.

Given all the compiled information, it has been possible to differentiate FA groups having different probabilities of being affected by sleeves IGSCC, concluding in different spent fuel management solutions. After this analysis,

- 25% were directly considered none affected by IGSCC and, subsequently, no special handling measures were necessary afterwards.
- 28% of the initial susceptible FA population had very low probability of being actually affected. High-resolution four faces inspection was recommended. In case of observing no corrosion indication, this population would be considered none-affected.
- For the remaining 47%, some of the FA can not be moved from their SFP location because they have shown clear corrosion indications during the visual inspections. For these FA, a conditioning solution was proposed and it is described later on in the manuscript.

1.2 High-resolution inspection

ENUSA developed an advanced high-resolution visual inspection equipment in order to detect small sized corrosion indication on the top grid sleeves. The sleeve inspection equipment was specifically designed by ENUSA to optimize this activity. A scheme of the equipment is shown in Figure 2. The equipment is made of a platform with a mobile frame for displacement of a very high-resolution subaquatic color camera, which as particular feature, has a mirror which makes possible the indirect recording of the fuel assembly image maximizing the protection against radiation by its shielding casing. This structure is placed on the top of the spent fuel racks and close to the position where the fuel assembly is inspected. In order to decrease the weight in the racks, the structure has tanks full of air that decrease the submerged weight of the equipment. Once the fuel assembly is lifted enough to have vision to the sleeves area, a gear motor moves the frame making the inspection of one of the sides. The resolution and camera zoom allows to identify the damages in the area of sleeves. During the sleeve inspection two equipment are used to perform inspection in two faces simultaneously, reducing the time that FA is suspended with fuel handling tool.

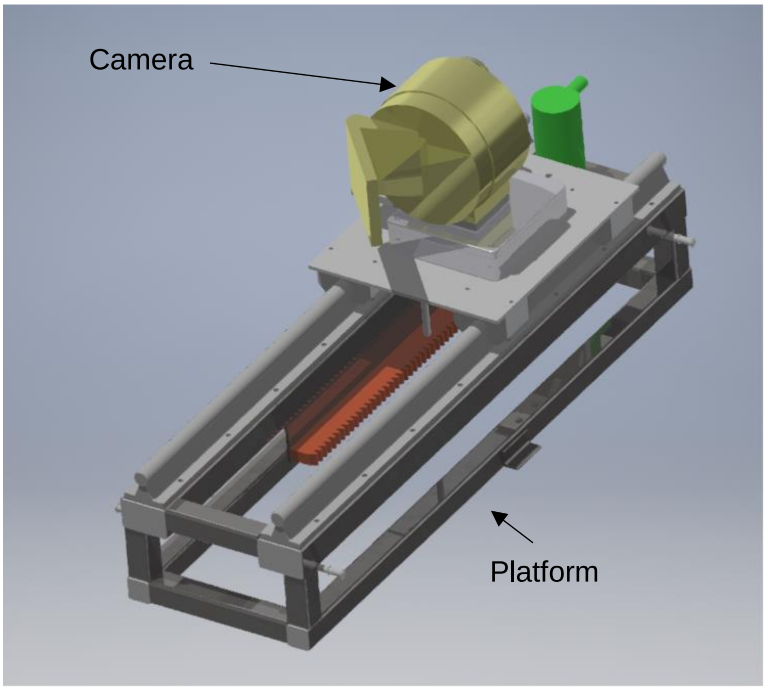

Fig. 2. Sleeves high-resolution visual inspection equipment

The corrosion indications can be either small pits or even well-developed cracks in the bulged area. As recommended after the previous analysis, a detailed four faces inspection was performed to the 28% of the initial susceptible population having very low probability of being affected by IGSCC. During the inspection, no corrosion indications were observed in any FA. These results allowed ENUSA to declare this big FA group as none-affected and, subsequently, no special handling measures were recommended afterwards.

1.3 ESPIGA device

In the case of FA showing corrosion indications or even having significant probability of being affected by IGSCC, any handling could result in top nozzle detaching from the fuel assembly when the fuel assembly is lifted. In this cases, to solve the situation, ENUSA has developed a special device named ESPIGA (reference 5). Many FAs are being conditioned with ESPIGA device and, as a result, safely handled using the standard handling tools with no limitations. Once the FA is conditioned, it is classified as undamaged for dry storage and transport.

ESPIGA device is a structural component designed to support the weight of the fuel assembly complying with the design criteria for 17x17 12-ft assemblies. The device consists of two rods (inner and outer bars) and two nuts (see a short prototype in Figure 3). The rods are introduced through the instrument tube and fixed to the top and the bottom nozzles.

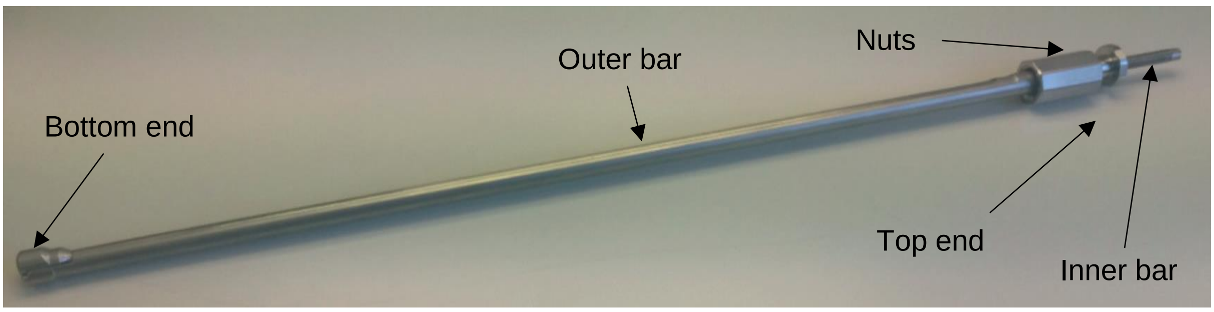

Fig. 3. ESPIGA device prototype

The outer rod is a round bar with a through hole along the length with an enlarged bottom end and a threaded top end. The inner rod is also a round bar with an enlarged bottom end and a threaded top end. This inner rod is placed into the through-hole of the outer rod.
ESPIGA device is designed to fulfil the following requirements:

- installation in the rack position without moving the fuel assembly,
- compatible with core components after installation,
- allow uninstallation,
- support different hot and cold conditions related to the Spanish spent fuel management strategy:
  - storage in the reactor spent fuel pool;
  - storage in a dry spent fuel storage facility in site, ATI in Spanish;
  - transport and storage in a centralized temporary storage (ATC in Spanish) for periods up to one hundred years.

In order to ensure the ESPIGA performance under these demanding conditions, a specific corrosion resistant alloy has been selected for its excellent mechanical properties at both low and high temperatures even after long periods of time (100 years).
ESPIGA is installed into the fuel assembly following the next steps. First, in order to allow the installation of the device into the instrument tube, the top nozzle instrument tube plug is drilled. The diameter of this hole is slightly higher than the instrument tube diameter. The machining method used is electrical discharge machining (EDM), shown in Figure 4. The EDM equipment includes a suction system to remove the very fine particles produced during hole drilling.

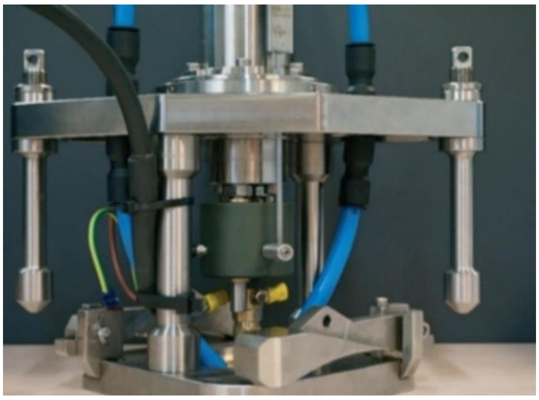

Fig. 4. Electrical discharge machining (EDM) equipment, used to drill the top nozzle plate

Once the hole is drilled, ESPIGA device is introduced through the instrument tube. For this step, the two rods of the device are positioned so that the inner rod is located inside the outer rod with the enlarged bottom ends aligned. When the device bottom ends are located below the bottom nozzle adapter plate, the rods are turned so that the bottom ends get a higher cross section (Figure 5).

Fig. 5. ESPIGA bottom end through the bottom nozzle plate at the instrumentation tube hole

This relative positioning of the two rods is fixed with a nut. After that, the positioning of ESPIGA device against the fuel assembly is performed by lifting the device up to the bottom end is in contact with the bottom surface of the bottom nozzle. Then the second nut is turning against the top surface of the top nozzle as shown in Figure 6.

Fig. 6. ESPIGA top end on the top nozzle plate at the instrumentation tube location

ENUSA carried out several tests to demonstrate the feasibility of the ESPIGA installation and to verify its structural behavior. These tests were at the ENUSA fuel manufacturing facility in Juzbado (Salamanca) and by blank tests performed in some SFPs of Spanish NPPs. The results showed that ESPIGA device accomplishes all the design requirements.

ESPIGA device is an ENUSA trademark, already patented with grant date November 2015. It represents an ENUSA development for spent fuel conditioning that ENUSA has performed and offers to the nuclear industry in order to solve the IGSCC top grid sleeves issue for storage and transportation.

Currently, the device is being successfully installed in many FAs in different Spanish NPPs. Once ESPIGA installation campaigns end, another 36% of the initial susceptible population, composed by the most affected assemblies, handled by normal means to complete their characterization, stored and transported to the Spanish ATC.

3. Conclusions

From the time when first FAs susceptible to IGSCC were identified, ENUSA has developed multidisciplinary actions to mitigate or cancel the impact of IGSCC in dry storage and transportation management. These actions include:

- Detailed analysis of historic records;
- Four faces high-resolution inspections and;
- Design, licensing and installation of ESPIGA device.

As a result of these actions, 89% of the initial susceptible population may be handled by normal means, dry stored and transported to the Spanish centralized interim storage facility (ATC). Altogether, the described actions conform an integral solution to the IGSCC issue, reducing significantly time and number of operations necessary for dry storage management. Figure 7 summarizes the reduction of the FA initial susceptible population after ENUSA actions completion.

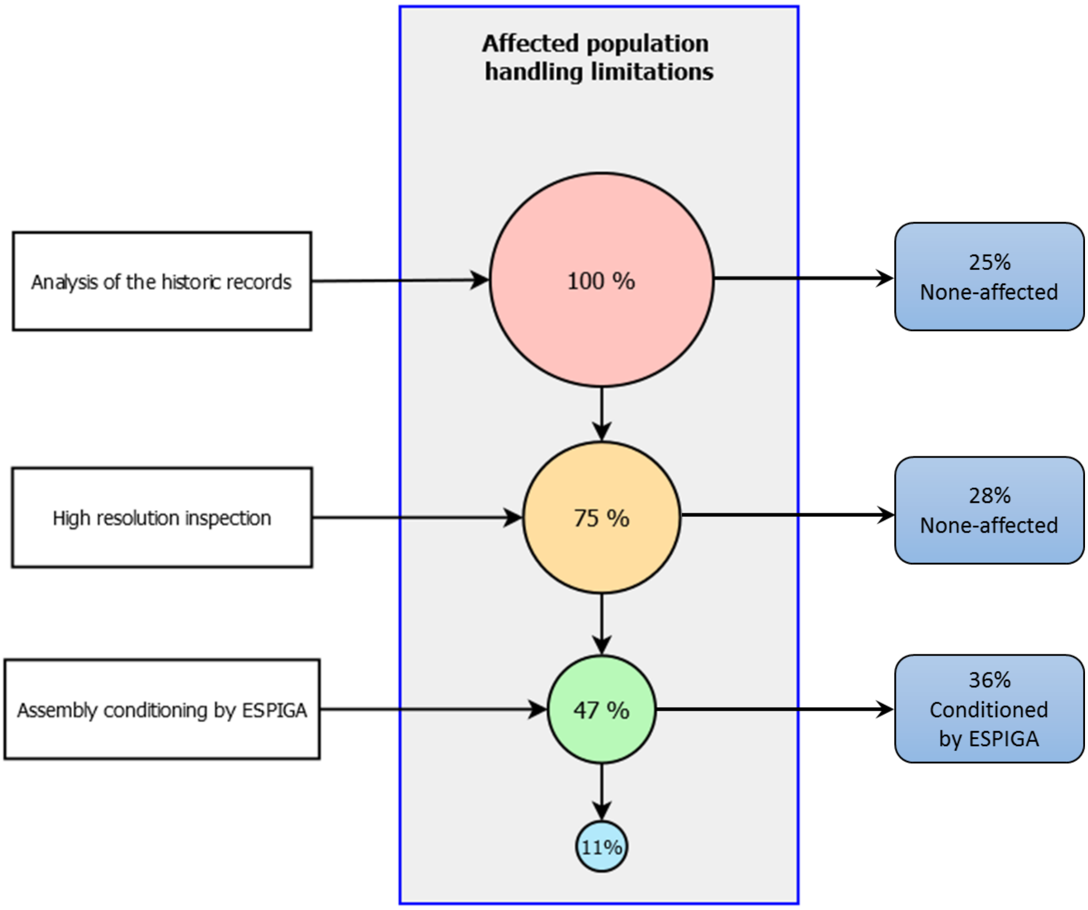

Fig. 7. Effect of different actions on reduction of the initial susceptible population

2 References

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