ADVANCED VACUUM SIPPING FOR SPENT FUEL CLASSIFICATION

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ABSTRACT

ENUSA is collaborating with the Spanish nuclear industry in classifying spent fuel with the best available technology to prepare dry cask loading. To identify the integrity of nuclear fuel assemblies, ENUSA has developed with Dominion Engineering INC a high-sensitivity vacuum sipping system, SICOM-INCAN, devoted to identify leaking fuel assemblies that have been stored for long term.

SICOM-INCAN SIPPING started its commercial use in 2015 and several campaigns have been set during these years at Spanish nuclear plants. This portable equipment is easily adaptable to any nuclear power plant lay-out and consists of an advanced detection unit, a process unit, and a canister.

As a main result of the preliminary tests and the following campaigns, the developed in-can sipping system has shown a high sensitivity and accuracy in detecting leaking fuel assembly due to the detector's effectiveness and the high vacuum achieved around the assembly.

1. INTRODUCTION

In 2015 ENUSA started to classify the integrity of the fuel assemblies at the nuclear power plants, as a part of a master plan to characterize fuel assemblies stored at the spent fuel pools in Spain (this characterization plan, apart from integrity, includes other inspections such as corrosion oxide layer or spalling). During the last four years, some of the Spanish nuclear power plants have started to use dry cask storage to obtain more space at the pools. For this reason, ENUSA developed a new equipment called SICOM-INCAN SIPPING that has been added to the SICOM family (inspections systems used to measure different properties of the fuel assemblies or fuel rods) intended to verify the integrity of the fuel assemblies prior to dry cask loading. The development began in 2013 and the equipment was qualified in a nuclear power plant during a blank test, detecting Krypton-85 (^{85}Kr) injections and several known leaking fuel assemblies (Reference 1). Since the project started, three campaigns have been performed, having inspected around 200 spent fuel assemblies with high accuracy and stability.

SICOM-INCAN SIPPING is a portable device prepared to inspect fuel assemblies of different designs, both BWR and PWR. The equipment consists of an underwater pump station and a canister, where the fuel assemblies are introduced, and outside the water a process unit and detection unit. The pump performs a suction inside the canister, creating a pressure decrease in the liquid phase to favor the exit of fission gases from the leaking rods. These gases are separated from the water by means of a high efficiency separation system, to be later analyzed in the equipment detection unit.

Additionally, the process unit can be configured to operate in fuel handling manipulator crane over the reactor cavity with another specific γ-detection unit to detect fuel failures during core download (Online

Mode). At both *In-Can* and *Online* modes, the response of the detection system is adequate, due to the efficiency of the process unit to extract the fission gasses and their optimized detection units.

2. DESCRIPTION OF THE TECHNIQUE AND THE EQUIPMENT

SICOM-INCAN SIPPING is a nuclear fuel characterization device which is property of ENUSA and TECNATOM. This sipping system operates on the principle that the pressure inside of a leaking fuel rod will equilibrate to that of the surrounding water. If one or more leaks are present, fission gasses from within the fuel rod(s) will exit the cladding when there is a reduction in ambient water pressure. The reduction in ambient water pressure is accomplished either by increasing the elevation of the fuel (for Online sipping) or by placing the fuel in a sealed canister and applying a vacuum to the canister volume (for Vacuum sipping). With an analytics method on a sample of these gases using spectrometry and signal shape, the result of the integrity can be confirmed. On the other hand, if there is not damage on the fuel rod, no fission gases will escape, and no leaking rods will be detected.

The principal components of the equipment are:

A **sipping canister** where the fuel assembly is introduced for the inspection. It consists of a series of flanged spool sections bolted together with an articulated lid at the top and baseplate on the bottom. During a sipping campaign, the fuel assembly is inserted through the opened lid.
This sipping canister contains pressure transducers to control the vacuum level and thermocouples to guarantee the safety of the fuel assembly inside of the canister during the vacuum process.

The equipment contains also an **underwater pump** that draws water out the top of the sipping canister lid once the sipping cycle is initiated, entraining any fission leak out from defected fuel rod. The underwater pump provides flow through the system during sipping operations and pumps it up to the process unit. A mixture of low-pressure water and bubbles from the sipping canister is pressurized within the pump station and then flows to the process unit for liquid/gas separation.

The **process unit** extracts dissolved gases from the water stream entering the unit and sends the extracted gases to the detection unit. Instrumentation throughout the unit provides real-time monitoring of the ongoing process. This unit consist of a water loop and a gas loop connected by a liquid-gas separator.

The gas extracted is continuously analyzed at the **detection unit**. This fully experienced digital detection unit, developed by ENUSA, is provided with a high efficiency gas chamber with two redundant plannar scintillation β-detectors that determines whether β-radioactive isotopes are present in the stream. The detection unit will measure β-activity, and for integrity inspections of spent fuel, the most abundant and long-lived fission gas isotopes present in the fuel assemblies is the ^{85}Kr (Half life 10,75 years).

A specific and customized software (that includes a spectrometric system) has been developed to monitor the operational parameters (flow, pressure, temperature) and to process the radiation measurement information. During the inspection or in further analysis, the software permits discerning if there has been external ionized agents not present inside the fuel rod, external sources or any other agent outside the inspection that could threaten the reliability of the sample.

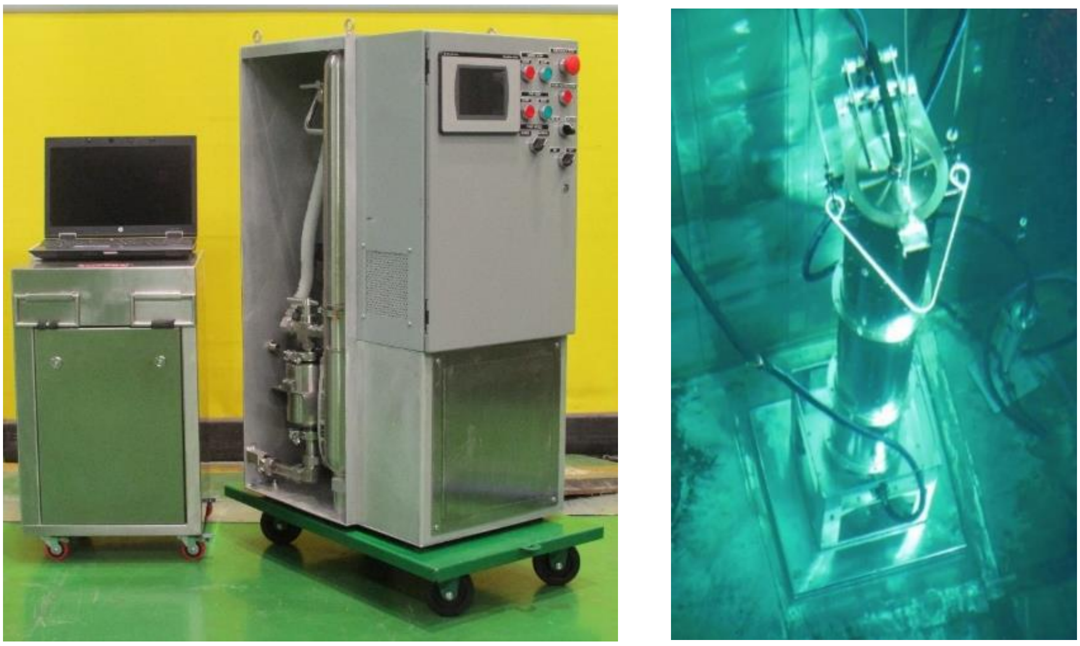

Fig 1.* SICOM-INCAN SIPPING*: Detection unit, Process unit and canister.

3. RESULTS

Three campaigns have been already performed with the SICOM-INCAN SIPPING to characterize the integrity of the fuel stored in two different unit reactors of a nuclear power plant (NPP) in Spain. All inspections have been carried out without incidences, inspecting almost 200 fuel assemblies of type AEF and MAEF with an approximate range of cooling time at the spent fuel pool of 13 and 21 years. The target population of the inspections were the assemblies classified as "uncertain" in the records of spent fuel assemblies of the NPP. There are many spent fuel assemblies classified as "uncertain" because at the beginning of operation of the NPP they did not use leaking inspection techniques if the batch of fuel assemblies suspected where of third cycle. By the radiochemistry report, once the leak appear on the primary, they identified the batch of FA suspected of having a leak and, if the report matched with a third cycle fuel assembly, they used to retire all the batch suspected and classified it as “uncertain”. Despite the fact that in the performed inspections, it was not possible to complete a full-cycle inspection, it is expected that in future inspections, the leaks predicted by radiochemistry will appear for each cycle.

The detection principle is as follows: If a background inspection is performed, that is without fuel assembly, the detection unit registers the radiation of the gases dissolved in pool water, which passes through the canister. This background signal shows during the first minutes an increase provoked by these gases being extracted on the unit process (depending on the concentration of gases on the spent fuel pool the background will be higher or lower). If the fuel assembly is not leaking, there will be no more contribution to the gases extracted from pool water (The signal would be the same as the background). Accordingly, if a leaking fuel assembly is inspected, additional extracted gases will be added to the water pool gases, increasing the cps (counts per second) registered on the gas chamber. Figure 2 shows an example of the typical profile of the inspection of a non-leaking fuel assembly with low cps background (*counts per second* detected on the detection unit). This profile show how the system accumulates the ^{85}Kr of the pool in the gas circuit during 12 minutes of a "no leak" inspection. At the beginning of the inspection, during the first 100 seconds the process unit begins to separate the ^{85}Kr dissolved in the water inside the canister, then the system accumulates and reanalyzes the extracted gas for approximately 10 minutes, when the ^{85}Kr reaches the highest level and stabilizes.

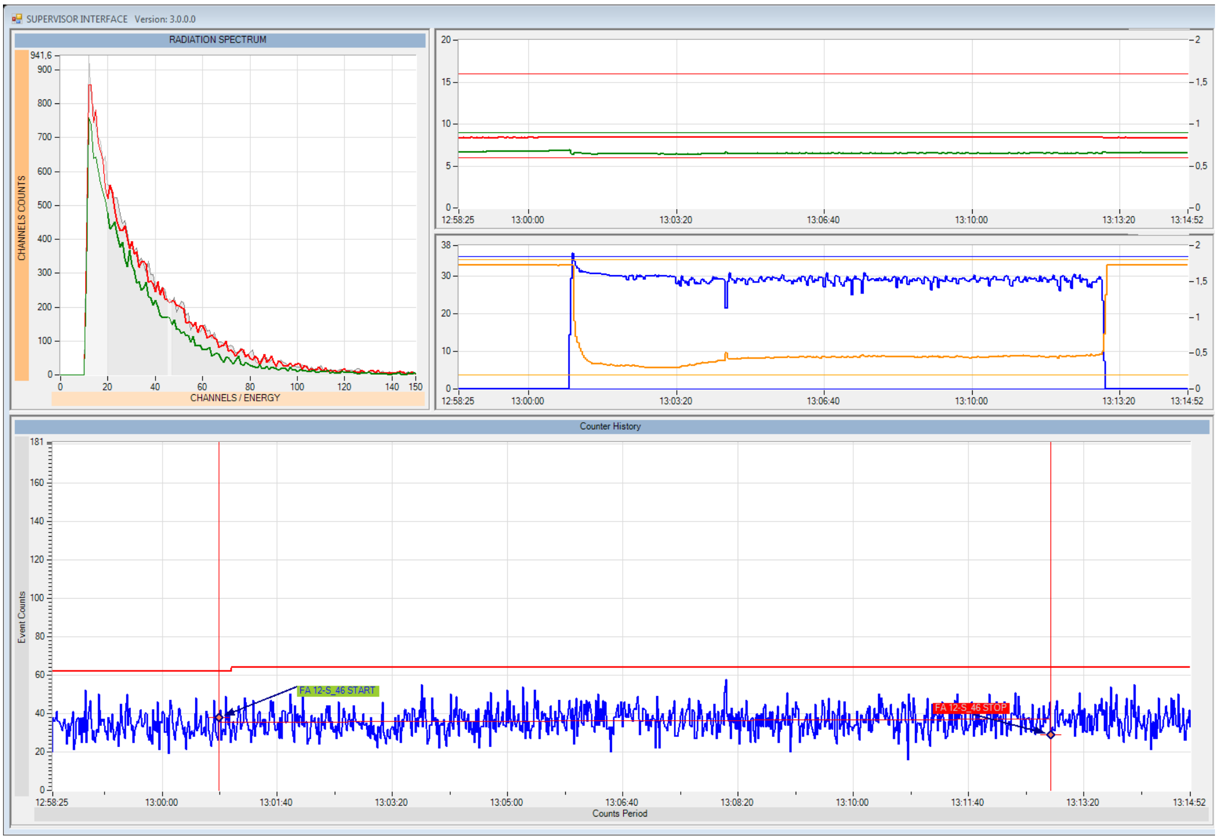

Fig 2. Example of "Non-leaking" inspection (Screenshot of the SICOM-SIPPING software showing the spectrometric figure on the upper left panel, the operational parameters (pressure, flow) on the upper right panel and the lower panel with signal registered (in counts per second (cps) vs time).

This study reveals that the equipment has shown very good stability as it is presented in Figure 3. The quantity of krypton extracted from the pool across the three campaigns tends to be stable. Although different behaviors can be seen in the figure amongst the campaigns performed, the level of activity of the ^{85}Kr dissolved in the water remained relative stable across the campaigns with a low variance from one day to another in the case of the *March 2016* campaign. Slight changes of the ^{85}Kr background were registered in *March 2016* campaign, indicating that variations on the concentration of ^{85}Kr in the pool may occur in the water sampled by the system. However, this background gradually decreased during the campaign from 80-100cps to approximately 45cps. On the other hand, the *February* and *October 2017* campaigns have been practically stable throughout the campaign.
If the assemblies inspected during that increases were leaked, a punctual increase in the cps registered during the inspection would have been noticed. This effect is observed in Figure 3, where two peaks belong to fuel assemblies characterized as "Leaking". None of these leaking fuel assemblies affected the following inspections, as it is shown on the figure.

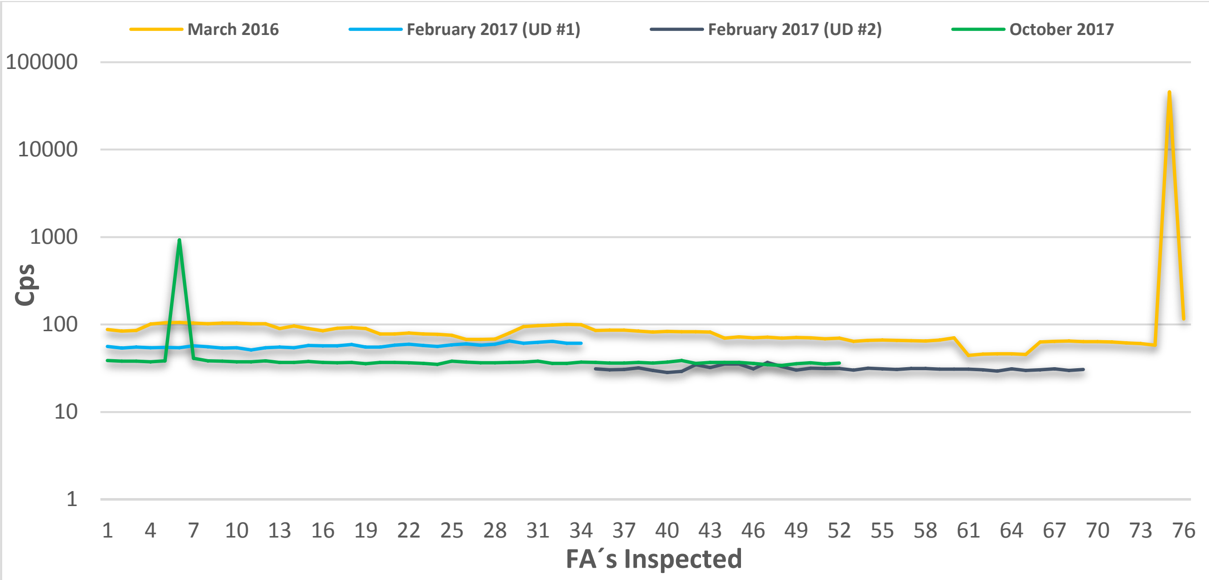

Fig 3. Overall inspections performed with SICOM-SIPPING IN CAN (Leakings FA´s on #6 (October 2017 campaign) and #75 (March 2016 campaign), more detailed on Figure 7).

Prior to the start and at the end of the inspection, operational tests with isotope Krypton-85 (^{85}Kr) were performed as a verification of the proper operation of the equipment. By means of a volume injection of ^{85}Kr corresponding to 1μCi (an activity 10 times greater than the estimated limit of detection of the equipment), this gas sample was effectively detected in less than two minutes (Figure 4). Commonly, tests are performed with 1μCi, but other amounts of ^{85}Kr can be injected to estimate the detection capacity. Furthermore, a compatibility test was performed with a dummy assembly, to verify the vertical alignment and the proper fitting of the fuel assembly within the canister.

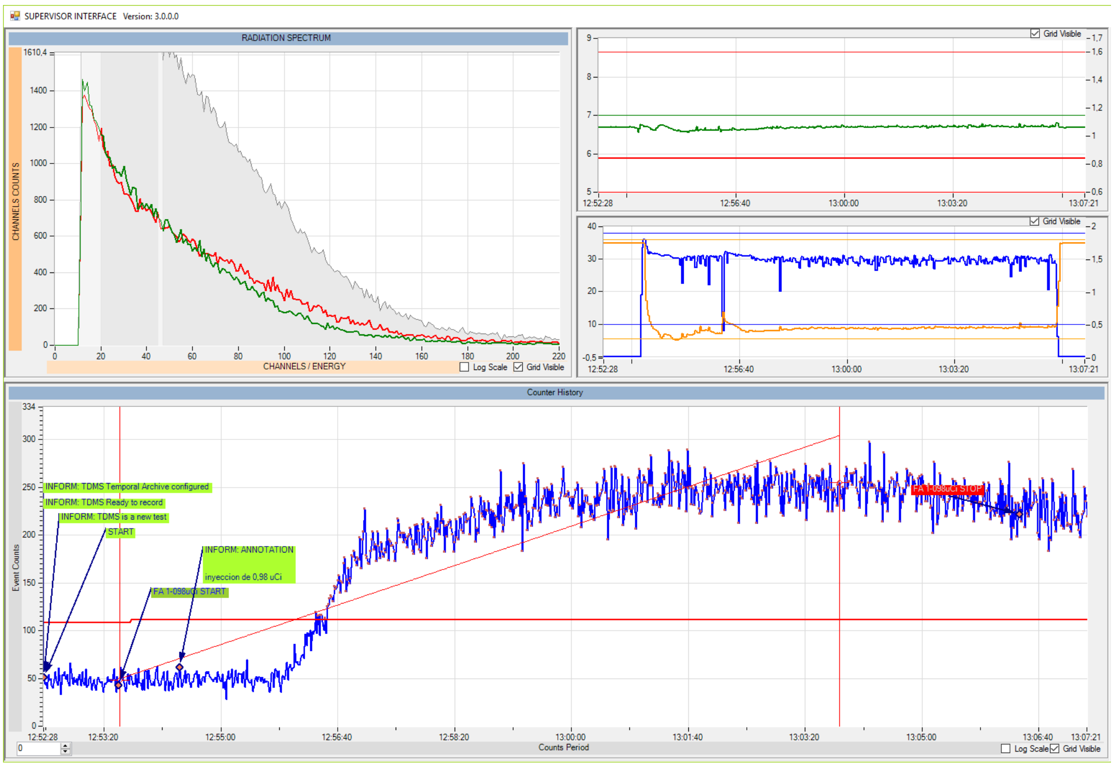

Fig 4. Screenshot of the SICOM-SIPPING software showing operational leak test with ^{85}Kr (1μCi) (In the upper left panel ^{85}Kr energy spectrum is shown; In the lower panel the ^{85}Kr signal is represented versus time, increase of signal is due to the detection of the injection test).

All operational tests performed during the three campaigns are illustrated on Figure 5. It is likely that there is a good proportionality of the test made with ^{85}Kr. The maximum cps reached during 1µCi test performed with ^{85}Kr is distributed at the same range of cps. It is worth noting, however, that some improvements have been made on the detector's parameters and all these tests were performed during different campaigns with the same gas sample. Although there has been strict control of every use of the sample over the years, as the syringe used was not accurate, it is possible that the quantity of gas activity during the latest tests was different from expected. Accordingly, depending on the procedure of the injection the result was a different type of cps increase. For example, if the ^{85}Kr was injected before achieving the maximum vacuum, the signal shape was not the same as if the injection was performed after achieving the maximum vacuum at the canister.

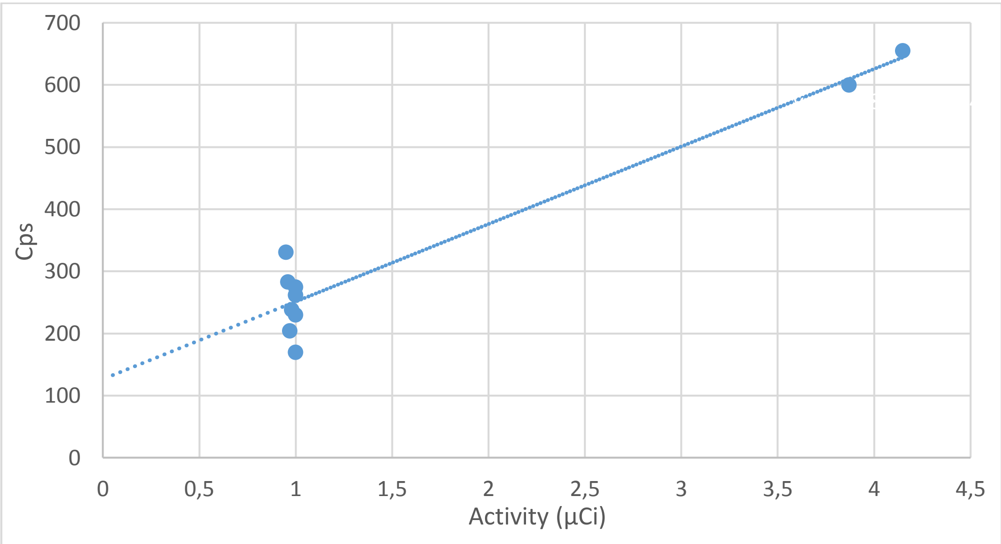

Fig 5. Maximum cps registered during ^{85}Kr injection test

Among the 199 fuel assemblies inspected, six leaking fuel assemblies were found (the first four fuel assemblies were inspected during the blank test; two were inspected during the commercial campaigns). Usually, during these leaking inspections, a considerable increase of cps was observed after 75 - 100 seconds of inspection. Despite the characteristics of the leaks (one of the fuel assemblies presented a severe failure), the vacuum generated by the equipment was able to extract enough fission gases to detect the leak clearly, demonstrating a high sensitivity and reliability of the equipment.

After the observation of the cps increase over the background, as well as the cps slope and the shape of the spectrometry, the fuel assemblies were classified as a "leaking fuel assembly". If a leaking fuel assembly is found, β-activity signal versus time show a clear and visible cps increase indicative of the existence of fission gases from the fuel assembly (Figure 6). The increase may be slow or fast (examples can be seen in Figure 7), but finally, there will be remarkable differences between the background and the fuel assembly inspected. A deep analysis on the fuel assembly report may be done paying attention to the curve of the energy spectrum (upper left panel in Figure 6) which indicates whether the sample contains ^{85}Kr, and the cps signal increment from the start of the inspection to the maximum cps registered (comparison of different cps signal increments of fuel assemblies identified as leakers is shown in Figure 8). This variation of cps shows a specific slope that depending on the background and the variation of cps during the inspection can determine a leaker.

Amongst the 199 fuel assemblies inspected during these campaigns, none of them has been identified as "doubtful", which shows the accuracy of the equipment.

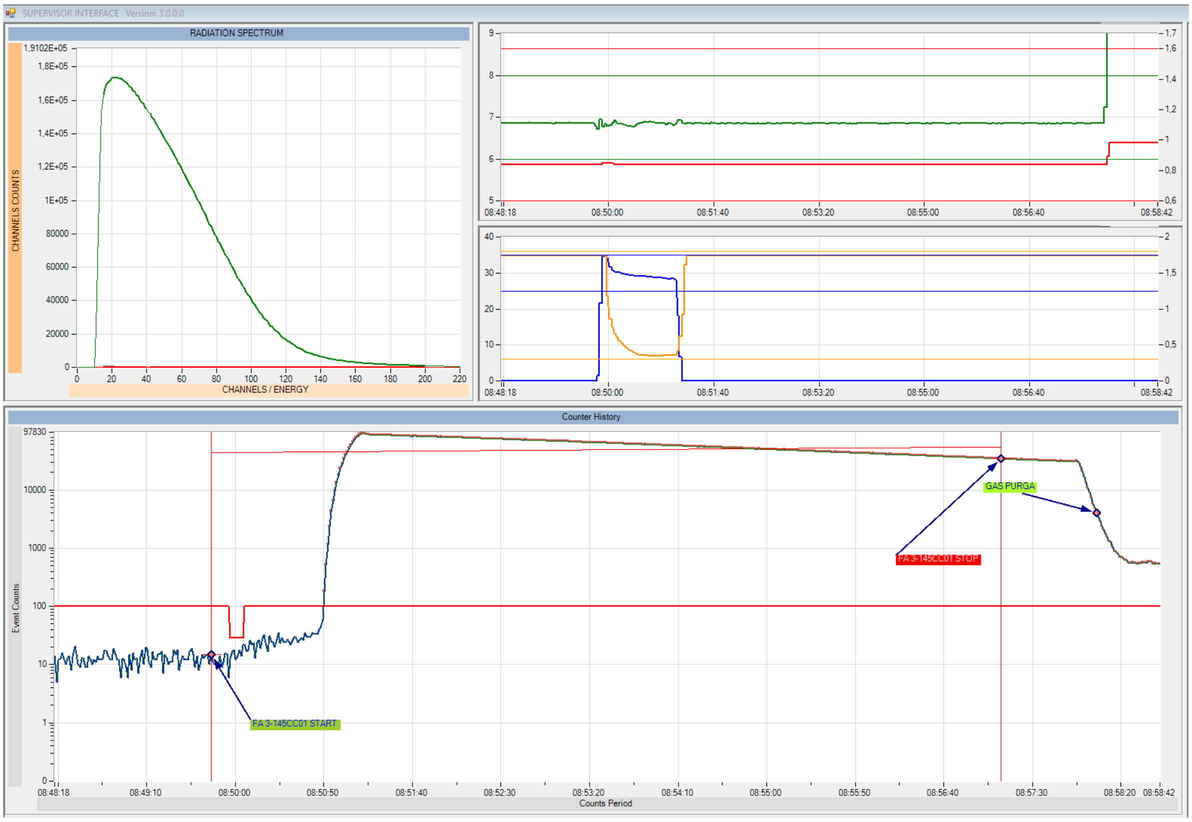

Fig 6. Screenshot of the SICOM-SIPPING software showing example of "Leaking" inspection (FA #5)

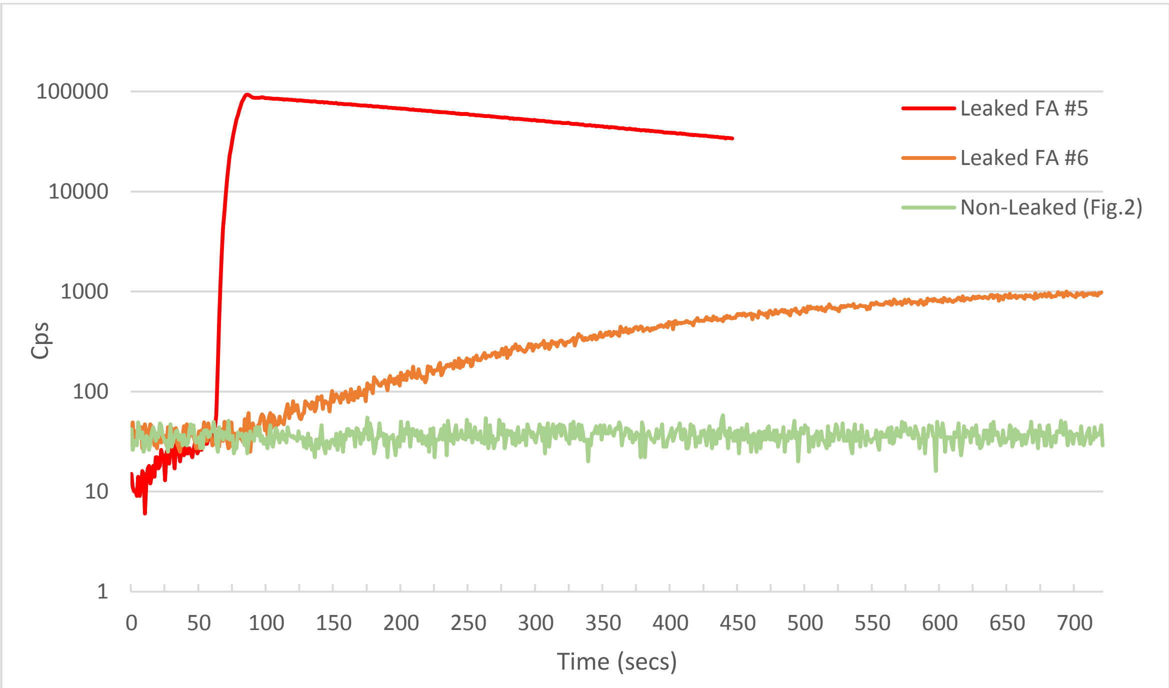

Fig 7. Cps registered during inspection of leaked fuel assemblies and comparison with a non-leaked fuel assembly

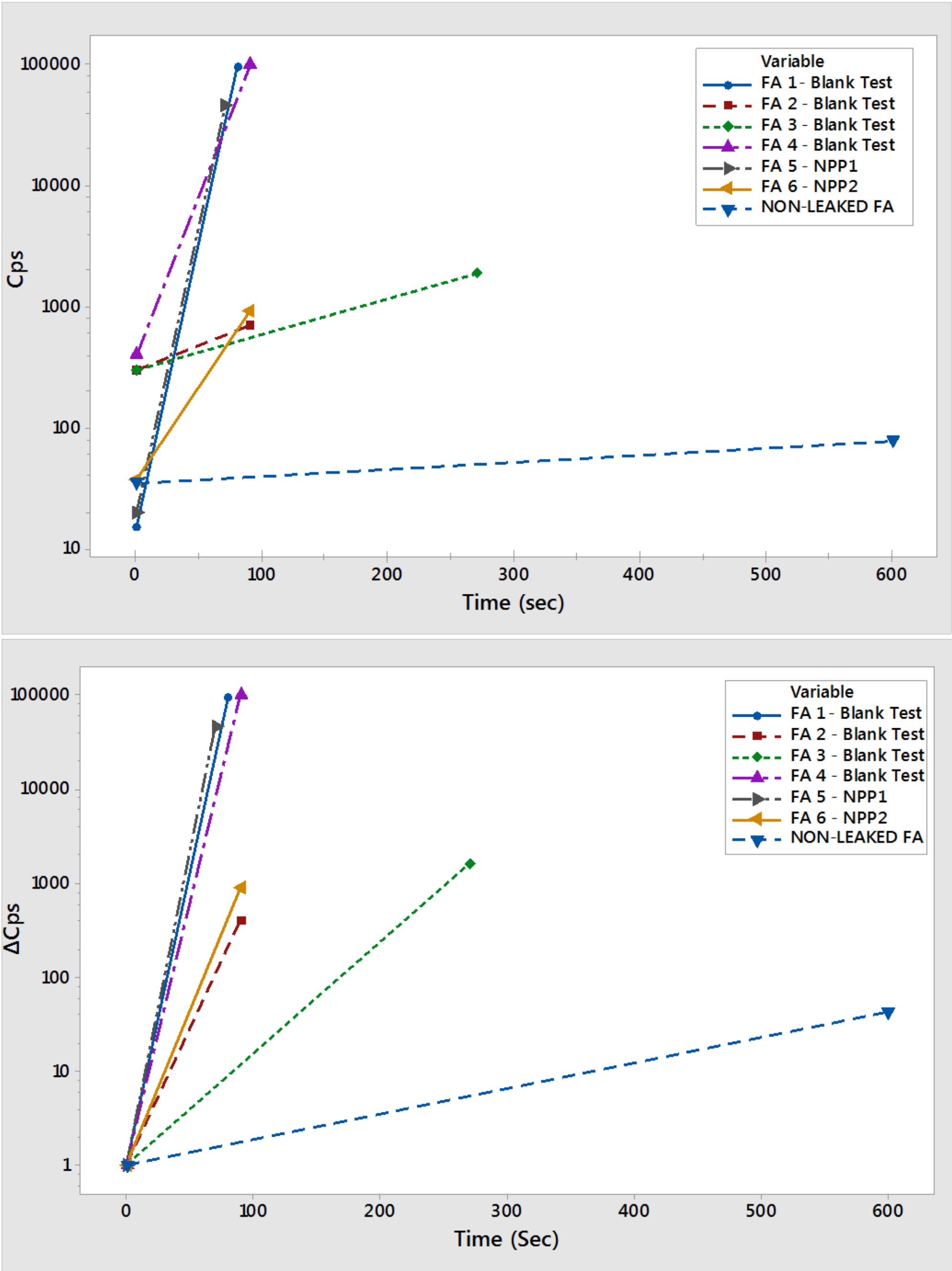

Fig 8. Increase of cps in leaking fuel assemblies with non-leaking fuel assembly in blue as a reference. (Log scale). Upper figure with the slope since the start of the inspection to the maximum cps reached. Lower figure with the Cps variation at the time of maximum cps reached.

The detection system does not intend to be a quantitative one but a qualitative way to evaluate the integrity. Before and after the campaign there are verification test that will give an approximation of the quantity of the gas extracted of the leak. Based on the ENUSA experience on Sipping campaigns it is not directly associated the type of failure with the gas remained and/or extracted from the rod. That means that fuel assemblies with big leak confirmed by visual inspection (secondary hydriding, broken rods…) where it could be expected that the gas remaining in the rod would be very low have shown high gas removal during sipping inspection (Figure 6 shows an example of a significant leak confirmed by visual inspection). On the other hand, there are experiences (On line mode) of small leaks with diverse kind of behaviors that makes difficult to get a pattern to identify the kind of leak on the rod. When more experience is gained on In Can Sipping inspections, it could be evaluated if it is possible to establish some correlation between detector responses and leak size.

4. CONCLUSIONS

The SICOM-INCAN SIPPING equipment has shown its capacity to characterize the integrity of the fuel assemblies stored at the spent fuel pool. Moreover, it is a device adaptable to inspect fuel assemblies online during the fuel core unload.

This capacity is based on the high efficiency of the extraction of dissolved gases during the inspections (it is possible to measure a minimum of 175 cps/µci Kr-85 injected as observed on the verification tests (Fig.5)), thanks to the high pressure drop around the fuel assembly during the process of vacuum, the effectiveness of the process of separation of gases from the liquid phase, and the adequate sensitivity of the designed detection system.

As a result of the three campaigns, we may conclude also that the detection unit has shown high stability during inspections, with no unexpected changes in the cps registered between inspections. The leaking fuel assemblies and the ^{85}Kr test performed did not affect the course of the campaign and the software is capable enough to determine the integrity of the fuel assemblies.

After the SICOM-IN CAN SIPPING inspection for leaking fuel assembly detection, the leaking fuel rod will be identified with SICOM-UT system in future inspections.

Some interesting future projects to consider, would be to identify the kind of leak according to its cps path. This challenging field research would improve the interpretation of the results although a great number of tests with leaking fuel assemblies will be needed.

Furthermore, according to the operation of the equipment and the experience, a reduction in the inspection time from the actual 12 minutes will be possible and it will be analyzed to optimize the plant activities without compromising the reliability of the system.

As a final conclusion, this new SICOM is a reliable characterization device in the nuclear market prepared to afford the incoming challenges.

REFERENCES

1. De Tena-Dávila et al. "Results during the first commercial campaign with SICOM-SIPPING IN CAN" 42 Annual Meeting of the Spanish Nuclear Society. Santander 2016.