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Core Verification System

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Nuclear Energy Institute's Top Industry Practice (TIP) Awards highlight the nuclear industry's most innovative techniques and ideas.

This was a 2012 NEI Process Award Winner.

The team members who participated included: David Kelly, Exelon Outage Services Sr. Manager; Nathan Neal, Exelon Site Reactor Services Manager; Martin Wolfe, Exelon Site Reactor Services Manager; John Bramblet, Newton Labs President and CEO; Barry O'Brien, Newton Labs Director of Software.

Summary

Following completion of core reloads at pressurized water reactors (PWR), an inspection is performed to verify that all the fuel is in proper alignment, ensuring there are no problems encountered when installing the Upper Internals or Reactor Plenum. Previously this inspection has been performed using binoculars or underwater cameras. While this binocular inspection or camera examination is most often accurate enough to avoid incident, misalignment has resulted in stuck or damaged fuel assemblies and prolonged outages of up to 3 months. Within the 265 PWRs worldwide, 10 documented events involving damaged or stuck fuel assemblies have occurred, including four in the last two years.

After two years of work, we have developed a revolutionary system that will change and improve the way nuclear operators ensure that the fuel assemblies will not be damaged when with the upper internals/plenum are lowered after a refueling. This system, known as the NM200E Core Verification System, uses a camera head deployed from the refueling mast coupled with proprietary computer vision algorithms to accurately measure the positions of all fuel assemblies and compare them with ideal positions (supplied by the reactor operators). The result is detailed, accurate measurements of all S-Hole locations, allowing reactor personnel to determine if there will be any issues with the installation of the upper internals.

Locations of S-holes, not gaps, are the critical measurements when it comes to installation of the upper internals. The NM200E marks a significant improvement over traditional gap measurement based mapping techniques. Its software enables the precise global mapping of fuel assembly S-hole positions, including any degree of misalignment or top nozzle rotation. The legacy video method merely gauges the relative nozzle gap variations, limiting the operators to inferring the actual positions of the S-holes.

There were three significant challenges to overcome when developing this technology. The first is the difficulty in producing precise measurements underwater. What is routine practice in air becomes a major engineering challenge underwater. Second, and especially true for PWRs, are the thermals coming off the hot core. Viewing these thermals with a camera creates blurred and distorted images that look similar to a mirage in the desert, again making measurement difficult. Finally, the high radiation dose field of the nuclear core can burn out most camera systems. Designing a camera system that can operate over sustained periods of time in high radiation would be critical.

Exelon Nuclear and its technology partner, Newton Labs, set out to overcome these challenges. The resultant NM200E Core Verification System uses advanced computer vision algorithms to accurately measure S-Hole position to +/- 0.050", an unheard of underwater tolerance prior to this development.

To test the system, a PWR fuel core quadrant was accurately mocked up at Newton Labs and used extensively in development. After the prototype system was completed, the team moved to the Byron Fuel Pool to test the device in a realistic environment using spent fuel assemblies. This effort was enlightening and provided data on two environmental characteristics that had yet to be incorporated into the prototype system. First, the thermal distortion that the spent fuel bundles produced did blur the images significantly, and second, the dark oxide build-up on the top nozzles made s-hole detection difficult, highlighting the need for increased lighting.

The next major engineering challenge in the project was overcoming the image distortion caused by the heat energy produced by the fuel bundles, known as thermals. To account for this thermal distortion, the team developed improved software that successfully mitigates this distortion and allows for accurate measurements in its presence.

Since the location of thermals in a reactor core depends on the placement of old and new fuel bundles, it was necessary to develop software algorithms that could compensate for every condition; from virtually no thermals to situations where the entire image was distorted.

Complicating the development of thermal mitigation algorithms was the issue of lighting. Since old fuel bundles are virtually black compared to the shiny new fuel bundles, the lighting would need to be significantly increased to get the fine details of the fuel assembly. This was especially true of the old fuel bundles, as their dark oxide layer build up made them virtually black to the camera under normal lighting conditions. This resulted in the development of a very high intensity LED light array. However, since the light would then produce extreme reflections on the shiny new fuel bundles, the algorithms were improved to operate in such a high contrast lighting environment.

The final major engineering challenge of the project rested in designing equipment capable of withstanding not only the underwater condition and the heat present in the water, but also enduring a relatively long life in a high radiation environment. The trade-off engineers faced was determining the distance to place the camera from the top nozzles. The closer to the fuel the camera gets, the higher the radiation levels get but the less thermal distortion is present. The opposite is true as well; place the camera farther from the fuel and the radiation levels are lower, but the thermal activity is higher.

Because the thermal mitigation algorithms proved to be so effective, the camera head was then able to remain at a relatively far distance above the fuel assembles (~5 feet). This meant that the camera head would be exposed to smaller levels of radiation, prolonging the life of the system by orders of magnitude. In addition, since the camera head did not have to be designed for extremely high levels of radiation, its production cost was dramatically reduced.

Remarkably, during testing the prototype unit was placed within a foot of the spent fuel assemblies in the reactor core in a very high radiation field and still produced clear images without damage to the equipment. The device created such superior images even under those extreme radiation fields that the camera head was used to read some serial numbers during one of the deployments after lowering it close enough to the fuel assemblies.

Both the user interface and system output have been designed to provide simple operation and easily interpreted results to the refuelling crew and reactor engineering. A live image overlaid with the computer vision results is displayed, along with a color-coded map of the core to easily identify areas of concern.

Before performing a mapping, actual plant design data is input into the system. This includes fuel assembly and baffle wall shapes, along with ideal gap specifications and the planned reload pattern. While the system is currently configured for Westinghouse 4 loop PWRs, it has the potential to be modified for use at any PWR. Currently Exelon is in the process of updating the system to be used at TMI. The necessary test data was acquired at TMI during their outage in November of 2011.

The system has been put to the test during both the 2010 and 2011 outages at Exelon's Byron and Braidwood Nuclear Stations. The NM200E was able to accurately measure the location of the fuel assemblies and deliver that information to both the refuelling crew and the outage/engineering personnel, as well as permanently store the data for later review. The system's ability to overcome the known issues of thermals, the differential between old and new bundles was outstanding. Since the correct placement of fuel assemblies is a constant concern for the industry, this extremely accurate system is a welcome addition to the current tools for determining fuel assembly placement.

Safety Response

The most significant safety feature of this tool is that it ensures the fuel assemblies are placed properly in the reactor core. If the fuel assemblies are not properly positioned in the core, fuel damage may occur. This has recently happened at one US facility as well as multiple times by EDF in France in the last three years. While the existing methods used at Exelon since 1994 have been effective in ensuring the gaps and misalignments in the fuel are acceptable, they rely on visual inspections only and do not determine the actual placement of the fuel in comparison to design locations. Due to the recent issues in the industry, several utilities are now requiring that actual fuel gap checks are performed. While this process is much more accurate and thorough than simple visual checks, it still relies on an individual manually obtaining the data. The NM200E system performs these measurements automatically and much more efficiently. This tool helps to prevent a much more significant issue from occurring, such as fuel or reactor component damage. Recovery from such damage is complicated, risky, dose intensive and very time consuming. The dose savings from using this tool on an ongoing basis is not significant, but can still save approximately 50 mrem per outage. The savings from a major recovery could be several rem.

Transferability

The existing tool is configured for Byron and Braidwood cores but the software is currently being reconfigured for use at TMI. It can be configured for any PWR core shape and size, and eventually will support any PWR fuel type. A variation of this tool (3D underwater laser scanner) has also been used to gather as built dimensions for performing modifications in BWR reactors. This will help to reduce outage extensions by gathering more accurate as-built dimensions.

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