13th international Conference on CANDU Fuel
Holiday –Inn Waterfront Hotel
Kinston, Ontario, Canada, 2016 August 15-18

CANDU FUEL:
Evolution towards Optimal Performance

Vision Based Smart System for Reliable Nuclear Fuel Pin Manufacturing

***N. V. Satish Kumar, S. K. Pathak, Dr. D. S. Setty, G. Kalyanakrishnan, Dr. N. Saibaba**
Nuclear Fuel Complex, Department of Atomic Energy, Hyderabad, India
*E-mail: nvsatish@nfc.gov.in, *Phone: +91-40-27184484

ABSTRACT-The performance PHWR fuel bundle depends on the quality of resistance weld joints and individual components of the bundle. Stringent quality inspection techniques are followed, which includes visual and dimensional inspection of all resistance welds and bundle components to avoid defective components being converted to final bundle form in production stream. An automatic vision based tube inspection system is now being introduced at NFC, which identifies and separates acceptable and defective fuel tubes by carrying out multiple quality checks on a single unit. The details of the inspection system, its reliability and advantages are described in this paper.

1. Introduction

Nuclear Fuel Complex, the world's largest producer of PHWR fuel bundles, carries out various specialized operations to manufacture of high quality fuel bundles for nuclear reactors. The manufacturing activity involves loading of sintered UO_2 pellets into Zircaloy-4 appendage resistance welded fuel tubes and encapsulating them with Zircaloy-4 end caps on both the sides through resistance welding process. The fuel pins thus formed are then made into 19-element and 37-element fuel bundles (figure 1). In fuel assembly plants, a variety of components of PHWR fuel bundle like fuel tubes, appendages viz. spacer pads & bearing pads, end caps, end plates are quality inspected manually in very large numbers on a daily basis for carrying out uninterrupted production activities [1]. For obtaining reliable resistance weld joints, it is very important to have precise geometry and dimensions for the individual components. Accordingly, various Zircaloy-4 parts such as, fuel tube, appendages and end caps are subjected to 100% stringent manual inspection and the defective components are filtered out. However, carrying out manual inspection with precision and consistency is a very difficult task considering manual fatigue and the quantity of the components being handled every day.

Figure 1: PHWR fuel bundles (a) 19-element for 220 MWe reactor, (b) 37-element for 540 and 700 MWe reactors

In order to ensure zero defective components entering into production stream and to improve the reliability of quality inspection, an automatic vision based tube inspection systems is now being introduced at NFC. The system is designed to identify and separate defective tubes by checking variations with respect to the tube diameter, tube end chamfer, outer surface defects like dents, pits etc. on the outer diameter of the Zircaloy-4 fuel tube.

The unit also carries out other tasks like carrying out multiple tasks like checking the orientation, axial location & number of appendages on fuel tube. The defect images are captured by the cameras and processed; afterwards decision making algorithm embedded into the system identifies and separates out acceptable components from defective ones.

2. Quality Criterions for Tube Inspection

The Zircaloy-4 fuel tubes are fabricated from machined ingots using forming operations and brought to desired sizes after wards by using pligering route at NFC. The appendages are punched out from Zircaloy-4 sheets using suitable dies and blanks. The individual tubes and appendages are inspected at other locations for ensuring product quality.

(a) (b) (c)

Figure 2: (a) End Caps for 19-element PHWR fuel bundle; (b) Appendages for PHWR fuel bundle; (c) Appendage welded 19-element PHWR fuel tube

Ends of the tubes are chamfered using special form tools to achieve 60° included chamfer angle. The end chamfer helps in achieving higher current density during resistance welding processes. At fuel assembly plants, after fuel pellet loading, small end caps are resistance welded on either side of fuel tubes for encapsulation. The weld quality is highly dependent on the quality and nature of end chamfer of fuel tubes and weld rejects can be minimized by stringent quality control in tube inspection stage. As per quality requirements specified, the chamfer must be equal distance from the edge of the tubes (ID and OD). Apart from this, it is to be ensured that the chamfer at the ID surface is uniform and does not have any damages. The split line at the chamfer and the tube surface should not have irregularities.

Appendages are welded on the surface of fuel tubes using resistance welding technique. The orientations, axial location, inter distance and numbers of appendages are to be checked on each type of element. The inner surfaces of fuel tubes are graphite coated using colloidal graphite solutions, followed by vacuum baking at 360°C, for increasing the thermal gap conductance. It is to be ensured that no major coloration (may come from graphite coating operations), surface marks, scratches or dents are present on the tube surface [2].

3. Automatic Inspection System

The automatic vision based tube inspection system was conceptualized at NFC as an advanced tool for replacing manual inspections at production level of fuel tubes, thereby reducing the operator fatigue. The system was envisioned to have adequate proficiency over manual operations. The overall working of the tube inspection system is made very simple. The inspection system has three (3) separate functional areas. The first functional area is the feeding area where tubes are loaded onto the machine, the second one being the inspection area and third being segregation where the tubes are separated based on acceptance and rejection criteria’s. The various sub-systems includes the following,

a) Mechanical sub-systems,
b) Smart cameras for image capturing along with suitable lenses,
c) Smart camera illumination system
d) Machine control system software
e) Computer hardware’s
f) Control panel to house PLC and other electrical/ electronic equipments.

The mechanical sub-system consists of a tube feeding mechanism, a v-guide conveyor system, rotating roller set-up, an accepted tube storage bin, an rejected tube storage bin and a third bin where tubes which can be reworked are stored (figure 4). The appendage welded tubes are fed into the feeding bucket, from which they are positioned over the v-guide conveyor. A roller system is provided which lifts up the tubes from the v-guide conveyors and rotates it by 360° so that surfaces images are acquired by smart cameras. After decision making, the tubes are sent to accepted, rejected or to be reworked tube storage bin by a special movable flap system, rack and pinion arrangement and dual stroke pneumatic cylinder. The v-guide conveyor is having a pitch of 5 cm. and has a typical linear speed of 0.3 m/min.

Total five (5) nos. of high precision, auto-focusing and high resolution cameras with suitable LED based illumination system are positioned along the conveyor for capturing the images of both the ends of tube and of tube surfaces. The two (2) end cameras are having a resolution of 1280 x 960 pixels and the other three (3) surface cameras are having a resolution of 1600 x 1200 pixels. The end face cameras and surface cameras are having focal length of 25.0 mm. and 8.0 mm. respectively. The image processing software is developed using Microsoft visual C++ and uses the camera libraries developed by camera vendor. Each smart camera can be used to retain 100 defect images, which can be retrieved at any time using connected PC system. The defect identification is based on the principles of image processing technique. The user input screens are administrator password protected so that only authorized supervisors can alter the values in future requirements. Different input screens are designed based on fuel tube type (19-element central, middle or outer, 37-element inner-1 and 2, outer 1 and 2 and central).

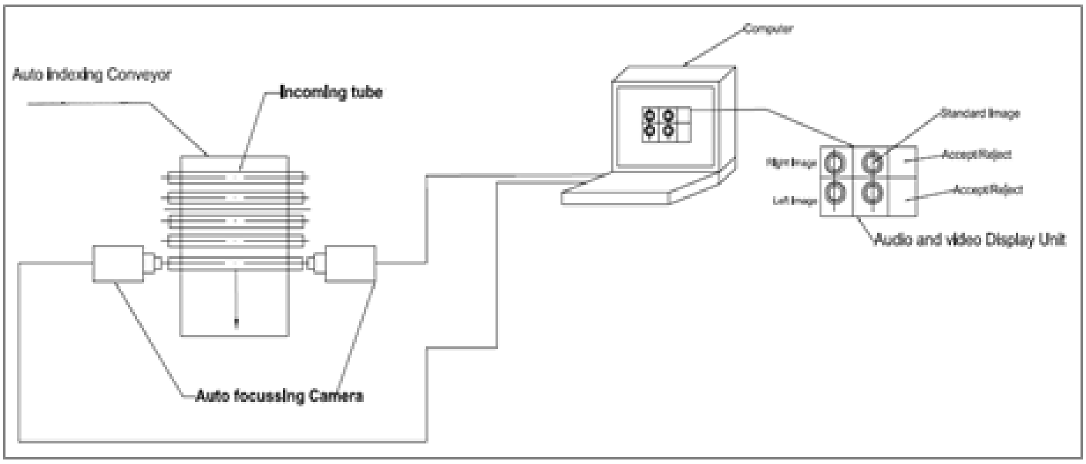


Figure 3: Overall concept of the Automatic tube inspection system

Separate window is also created for indentifying defects of plain fuel tube (without appendage welded). The system was calibrated using precisely fabricated tubes as per drawings, which were used a master components for dimensional and visual acceptance. The master tubes were used for setting acceptance values of RGB in the unit for each type of defects. Tolerances are also provided on the RGB values for each smart camera according to dimensional tolerances of components.

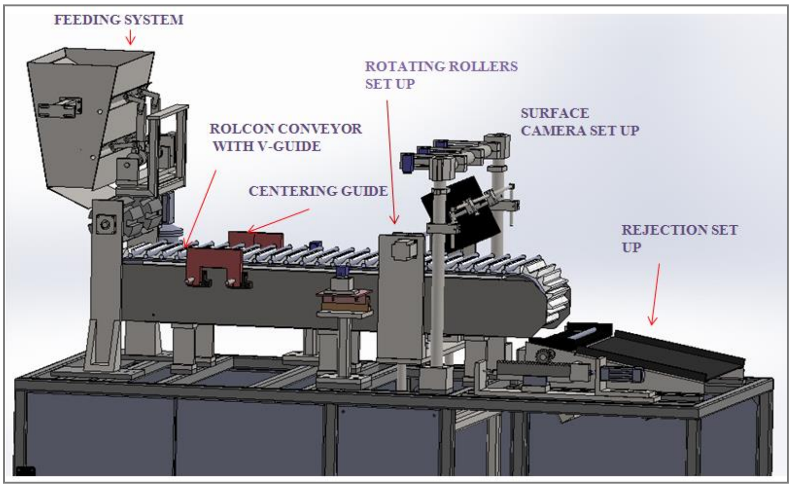


Figure 4: 3D cut-open view of automatic tube inspection system

The machine operation screen is shown in figure 5 for a trial conducted with 32 appendages welded 19-element outer tubes. The overall statistics of the run is displayed on the screen, so that operators or supervisors can analyze the possible causes of rejections and identify possible trends of defects. The automatic inspection system is capable of inspecting 5 tubes per minute by all the installed five cameras.

The report generated by the system after completion of inspection has information's such as number of inspected tubes, tubes rejected by end camera-1 and 2, tubes rejected by surface inspection cameras, date, time, month and year of the inspection. Statistical bar chart report of the nature of defect distribution in date wise manner is also generated by the system. The operators have options to take print out of the reports and also to convert the report to MS office excel format.

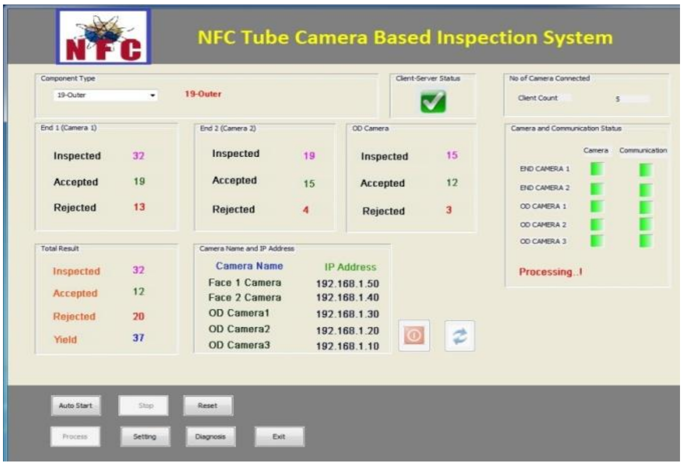
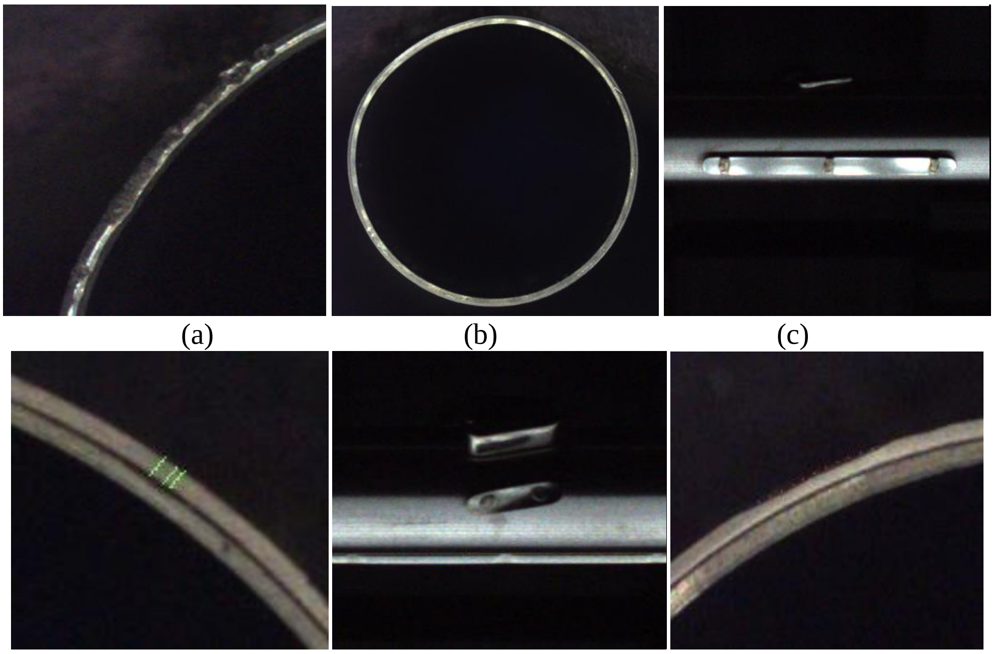


Figure 5: Operator screen in automatic tube inspection system

Several trials were conducted initially to optimize the RGB values so that false acceptance of defected tubes are completely eliminated and false rejections of manually inspected tubes are reduced. Typical defects which are identified and captured using the system are shown in figure 6. Some of the trials were conducted using specially generated defects for validating the system operations.



(a) (b) (c) (d) (e) (f)

Figure 6: Typical tube defects captured in automatic vision based tube inspection system (a) End chamfer damage; (b) Tube ovality, (c) Reverse welded appendage (bearing pad); (d) End chamfer out defect; (e) Reverse welded appendage (spacer pad); (f) End chamfer defect

The finer end defects and surface marks are generally very difficult to be observed by human eyes due to their extremely small sizes. With the help of this automatic system, such defects are now identified with less efforts, which will help in reducing overall process rejects for further processes in fuel fabrication. As the false rejection is not yet fully eliminated, the tubes rejected by the system will be inspected afterwards manually by quality personnel's. During routine quality inspection, the operators are needed to select the tube type, take the unit to its home position and can start the system for automatic tube inspection. The user-interface of the system is easy to operate and flexible enough to modify based on future requirements for further improvements in the inspection process. An administration user name and password can be used for re-defining the RGB tolerances, which can be done by the supervisors.

The user input screen has three levels of authentication controls namely a) system administrator, b) operator, c) system Maintenance. The administrator has access to user name and password control, defect level setting and bypassing, report conversion and taking report print out of tube inspection runs. The operator has access to only test running page with data entry fields for shift of operation, date, name of operator, tube lot number and quantity of tubes. The system maintenance login page is exclusively dedicated for system developers.

4. Equipment Reliability

The automatic inspection system is equipped with several interlocks to ensure operator and product safety. Function logics of the system are done using PLC programming in the unit. The system is having alarm facility to detect placement of faulty tube type (such as outer-1 is selected on operator screen, whereas 19-element outer tubes are fed). The connection status of smart cameras is indicated on the operator screen with a color code. Before running for different tube types or during fresh start, the system is to be brought back to home position every time. This ensures that proper sequence of operations is followed during inspection. The end chamfer defects are more critical compared to surface defects, as chamfer damages affect the subsequent end cap resistance welding process. For this purpose, the inspection sequence logic is programmed in such a way so that, tubes identified with end chamfer defect/ damages are not inspected in the surface defect identification system, which thereby reduces the overall inspection time.

To ensure operator safety, the movable parts of the system are enclosed and fitted with suitable interlocks. The system has an emergency stop button to terminate all operations in any point of time. The inspection status can be recalled when the system is again turned on and further inspection operations can be resumed. The tube collection bins are having capacity of 150 tubes each and automatic indication occurs on operator screen when the bins are over 90 percent full of its total capacity. The system has been tested with same defect types multiple times for ensuring repeatability and is now fully fine-tuned for daily routine quality inspection process at NFC.

5. Conclusions

The feature, reliability and advantages of an automatic vision based PHWR nuclear fuel tube inspection system is discussed. The system is capable of inspecting and identifying different tube defects such as the orientation, axial location & number of appendages, checking the tube diameter, tube end chamfer, surface defects like dents, pits etc. on the outer diameter of the tubes. The system is fitted with high resolution smart cameras, enabling it to capture very fine end chamfer damages, which are very difficult to identify with naked human eyes. The embedded logics in the system helps in sorting acceptable, rejected and to be reworked tubes based stringent quality criterions. Overall the unit reduces the dependency on manual inspection techniques, reduces human fatigue and completely eliminates the possibilities of false acceptance of faulty or damaged tubes. The incorporation of the unit in routine inspection reduces the possibility of rejections in the successive operations and will help in improving recovery in fuel fabrication stream.

References

[1] U. C. gupta, R. N. Jayaraj, Meena R, V. S. Sastry, C. Radhakrishna, S. M. Rao, K. K. Sinha, "Nuclear Fuel Fabrication-Developing Indigenous Capability", Proceedings of the 5th international conference on CANDU fuel, 21-25 Sep, 1997, Toronto, ON (Canada).
[2] Quality control instructions for quality assurance, NFC/QCI/63/19 & 37, issue no.2, 5th April, 2007