Under Sodium Ultrasonic Imaging System for PFBR

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Abstract

Under Sodium UltraSonic Scanner (USUSS) has been developed to detect the growth and protrusion of Fuel Sub-Assemblies of PFBR, submerged in liquid sodium by using the ultrasonic imaging technique during reactor shut-down when liquid sodium is at 180^{0}C. The imaging is carried out prior to every Fuel handling operation. Electronics Division, BARC has designed and developed an 8-Channel Ultrasonic Imaging System (UIS) which consists of 4 downward viewing and 4 side viewing ultrasonic transducers alongwith pulser-receiver, signal processing electronics hardware and software. An automated mechanical scanner developed by IGCAR houses sodium immersible transducers to image the fuel Sub Assemblies. The system has been successfully tested with dummy protruding and grown FSAs, submerged under liquid sodium. Such ultrasonic imaging systems are not available to India from international market. The USUSS developed indigenously has all the features available in similar systems developed by other countries.

After every imaging campaign, the mechanical scanner containing ultrasonic transducers is stored in the Argon filled storage-pit. Before every campaign of USUSS, it is necessary to check the healthiness of the sodium immersible and contaminated ultrasonic transducers, as the under-sodium scanner is decontaminated once in five years. For this purpose, a novel Non Contact Ultrasonic Inspection System (NCUIS) has been designed and developed by Electronics Division, BARC to check the functionality of the high-temperature and contaminated transducers of USUSS, using air-coupled ultrasonic technique.

Introduction

PFBR is a sodium cooled pool-type nuclear reactor which has sodium-submerged 181 Fuel Sub Assemblies (FSAs). During normal operation of the reactor, the temperature of liquid sodium is more than 550^{0}C. Due to high temperature, prolonged irradiation and flow of liquid sodium, there is a possibility of growth and protrusion of hexagonal shaped FSAs. As ultrasonic imaging technique only can be used for visualisation inside the optically opaque liquid sodium at 180^{0}C, an automated Under Sodium UltraSonic Scanner (USUSS) has been designed & developed for detection of growth and protrusion of in-core FSAs. Ultrasonic Pulse-Echo (PE) mode and C-Scan imaging technique have been used for this application. Sodium-compatible 5MHz ultrasonic transducers are employed for downward viewing operation for detection of growth in FSAs which are located underneath the scanner and 1MHz transducers are utilised to scan in sideways i.e. in lateral direction for detection of protrusion of FSAs. The scanning is carried out before every fuel handling operation so that Large and Small Rotatable Plugs of Prototype Fast Breeder Reactor (PFBR) can be rotated safely.

Core-plenum is a general level of all the in-core FSAs of PFBR. Detection of growth and protrusion of FSAs is to be carried out with reference to this level. For detection of growth in FSAs, maximum distance between the core-plenum and the front face of DVTs would be 100mm with minimum detection of growth to be 5mm. Therefore to meet this requirement, optimum frequency found out by experiments for DVTs is 5MHz. Similarly, to detect minimum 50mm protrusion of FSAs at a distance of 5m in sodium, optimum frequency found out by experiments for SVTs is 1MHz.

After completion of imaging campaign, the mechanical scanner is taken out of reactor vessel and stored in the Argon filled storage-pit. Before starting of every campaign of USUSS, it is necessary to check the health of all the ultrasonic transducers. These transducers, which have residues of sodium and are contaminated, are checked using air-coupled ultrasonic technique which does not require any liquid or solid couplant. The transducers are checked by pairing each of them with corresponding air-coupled transducers and each pair works in Transmit-Receive (T-R) mode. 16-Channel ultrasonic instrumentation designated as Non-contact Ultrasonic Inspection System (NCUIS) has been designed and developed for this purpose. Following description provides details of both the systems as well as their configuration, calibration setup and test results.

Under Sodium UltraSonic Scanner (USUSS)

System Description: Under Sodium Ultrasonic Scanner of PFBR comprises of Instrumentation & Control (I&C) H/W, system S/W and automated mechanical scanner. The I&C hardware of USUSS has been configured into 19” Control & Drive Panel and Ultrasonic Imaging System (UIS) Panel. The system software performs automated data acquisition, display, storage and analysis of 1D,2D,3D data/ images. Fig. 1 shows schematic block diagram of I&C of USUSS.

Ultrasonic Imaging System: The Ultrasonic Imaging System comprises of 8-Channel Ultrasonic Pulser-Receiver unit, Industrial PC with high speed PCI digitizer and system S/W and HV & LV DC power supplies. The pulser-receiver unit sequentially excites the ultrasonic transducers of USUSS using high voltage square wave tone-burst pulser; receives the reflected echo signals for each channel; amplifies and multiplexes them. The multiplexed echo signal is fed to PCI based 100MSPS, 8 Bits Digitizer located in PC. The software acquires, stores, processes and analyzes the data. The data acquisition is synchronized by generating suitable trigger signals within the pulser-receiver unit and the multiplexed trigger signal is connected to the Digitizer. Configuration of pulser-receiver

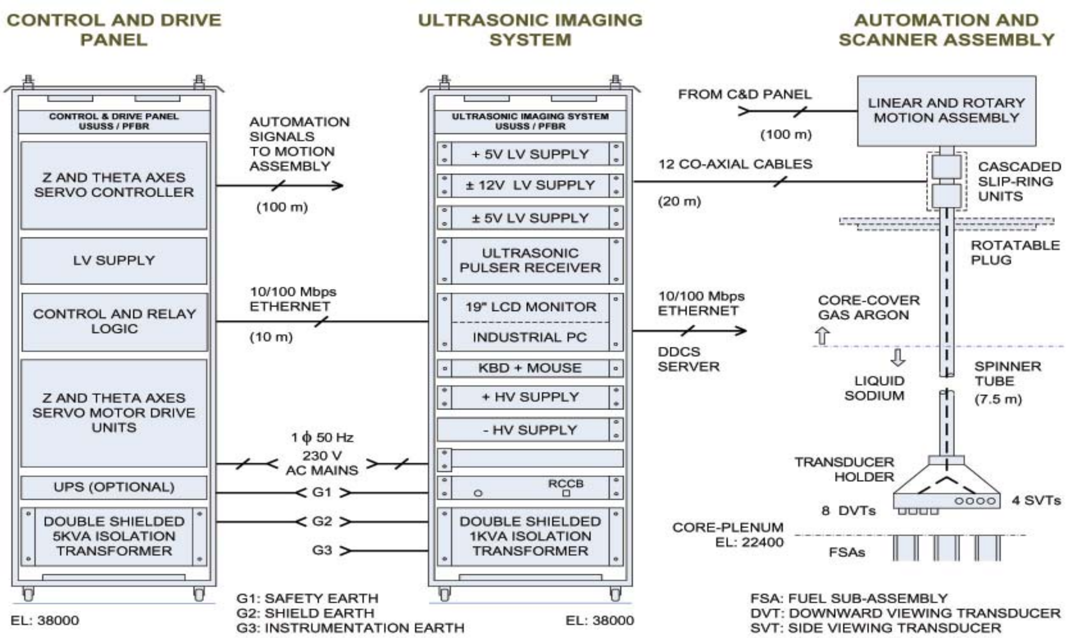

Fig.1: Schematic Block Diagram of I&C of USUSS for PFBR

Fig.2: 8-Channel Ultrasonic Imaging System

for deciding the no. of cycles in the tone-burst, frequency of excitation signal, receiver (amplifier) gain, band-pass filter selection, total channels etc., is achieved using RS232 interface between UPR unit and PC. Pulser-receiver diagnostics are performed to check availability of all LV DC power supplies, delivery of trigger commands, checking of active channels, checking of initial ringing of transducer/ reflected echo and filter settings etc. Fig.2 shows the photograph of 8-Channel Ultrasonic Imaging System. The system hardware has been qualified for Environmental compliances as per IS 9000 standards and EMI/EMC compliances as per IEC 61000 standards.

The Control and Drive (C&D) panel houses electronics hardware for controller of vertical (z) and rotational (θ) movements of the mechanical scanner. PC receives the Z and θ values from C&D panel over Ethernet.

Automated Mechanical Scanner and C&D Panel: 2-axes automated mechanical scanner has been designed and developed by IGCAR. Lower part of the scanner has 7.5m long spinner tube welded to a conical shaped transducer holder at the bottom-most position, containing 4 Downward Viewing Transducers (DVTs), 3 Side Viewing Transducers (SVTs) and 3 Spare DVTs. By imparting linear (Z) and rotary motion (θ) to the spinner tube, transducers are manoeuvred for imaging of FSAs. Upper part of scanner has Z & θ motors, ball-screws, Gear-box, feedback elements and slip-ring units to avoid entanglement of co-axial cables.

The C&D panel houses 2-axes AC servo motor controller and drives, control logic and Ethernet connectivity to PC for automated imaging.

System Software: QT-based Linux (Fedora-8) system-software has been designed & developed by ED, BARC for ultrasonic data acquisition, display, processing/ analysis, automation control, UPR configuration, diagnostics and interface to Distributed Digital Control System (DDCS) server for data/image archival and fetching co-ordinates of rotatable plugs of PFBR. Image processing/ analysis includes C-Scan imaging, growth monitoring of FSAs using DVTs and detection of protrusion of FSAs using SVTs, TOF/distance measurement and comparison with base-line data/image. The system software installed in the PC of UIS, controls the overall operation of USUSS. Before initiating the imaging of FSAs either by DVTs or by SVTs, 1D A-Scan waveform data is utilised to set time gates along the time or depth axis with user selectable amplitude threshold, so as to acquire 3D C-Scan image data of region- of-interest. As H/W based passive bandpass filters have been utilised for SNR enhancement of ultrasonic signals, separate digital filtering/ processing techniques have not been applied on image data. The main goal of USUSS is to view the in-core sodium-submerged FSAs of PFBR for detection of their relative growth and protrusion with reference to core-plenum. Frequency analysis of stored data has not been at present carried out.

Under-water Test Setup for Calibration of UIS:

Under-water test set up has been fabricated and installed at ED, BARC for the calibration of 8-Channel Ultrasonic Imaging System. 10m long pipe-assembly set-up is shown in Fig. 3a. The horizontally placed pipe assembly was filled with water. A circular opening has been provided to mount the 1MHz SVT at one end of the pipe-assembly and a rectangular cut-out has been provided at the other end of pipe to place cluster of 10 FSA top-heads made of SS as shown in Fig. 3b. FSA top-heads (each 90 mm tall) and reflector sub-assemblies (3 nos. of each having 88 mm OD and 190 mm height) were placed over the flat plate resting inside the pipe.

Fig. 3a: 10 m Long Pipe Assembly

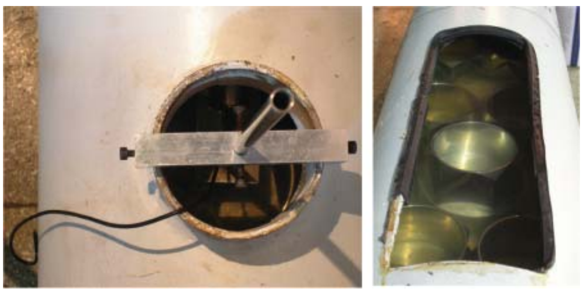

Fig. 3b: Cut-outs for Transducer and FSA Top-heads in 10 m Long Pipe Assembly

The cylindrical reflector SAs were placed behind the cluster of FSA top-heads, with reference to face of SVT. Circular discs of thickness range 5-50mm were placed under one of the FSA top-heads to simulate protrusion. Provision was made to change the orientation of protruding FSA with respect to the front face of SVT. The detection of protrusion was carried out in under-water setup where the protruding FSA was kept at a distance of ~9 m from the front surface of SVT. Cluster of nine FSAs were placed at same level and were kept between the protruded FSA and SVT to form the core-plenum. The actual height of hexagonal shaped full-length FSA of PFBR is 4.5m whereas only 90mm tall top-heads, having identical shape as the original FSA with 3mm flat annular surface at the top of FSA, have been used for calibration of 8-Channel ultrasonic imaging system. To simulate the divergence of ultrasound in sodium, 10m pipe, filled with water was selected, to match the difference in acoustic velocities. Maximum distance to be scanned in PFBR would be ~5m in sodium.

Major parameters governing the fidelity of ultrasonic images are based on the axial resolution of the transducer, digitization rate and angular/ linear step size with which automated ultrasonic images are acquired. For imaging activity carried out by DVTs, the optimum angular step size found out by experiments is 1 degree whereas, for SVTs, the angular and linear step sizes found out by series of experiments is 1 degree and 2mm respectively.

Results of Under-water Testing:

8-Channel Ultrasonic Imaging System has been tested with varying amount of protrusion ranging from 5 mm to 50 mm as well as with two different orientations of the protruding FSA by placing flat surface or the edge of hexagonal shaped FSA in front of SVT. Distinct echo signals were obtained from FSA with 25mm or higher protrusion when its flat surface/ edge was facing SVT.

The amplitude of echo signal received from protruded FSA was observed to be increasing with increase in protrusion. Fig. 4 shows a typical A-Scan waveform obtained with 50 mm protrusion at a distance of around 9 m, in water. Also, irrespective of the orientation of protruded FSA, the echo

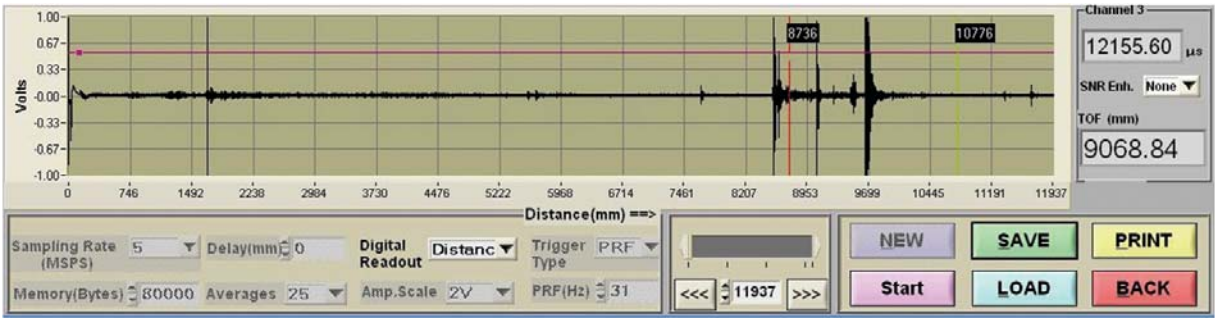

Fig. 4: Typical A-Scan Waveform Acquired for Detection of 50 mm Protrusion of FSA

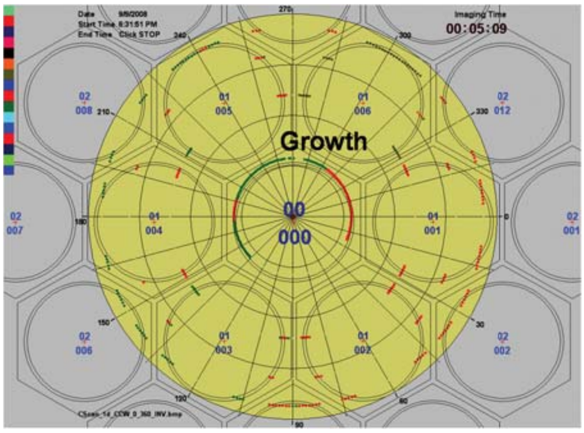

Fig. 5a: FSA Mapping using 4 DVTs

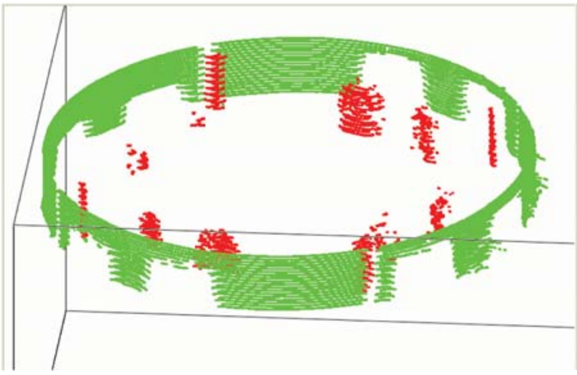

Fig. 5b: 3D Ultrasonic Image of FSAs using SVT

signals received from the cylindrical shaped reflector SAs were observed to have a trend of increase in amplitude with the reduction in protrusion from 50 mm to 25 mm.

Fidelity of echo signals was confirmed also by generating water flow of 1m/s in pipe setup and 10% reduction in echo signal amplitude was observed.

Results of Under-sodium Imaging: Prototype Ultrasonic Imaging System was tested in sodium test-vessel at IGCAR, Kalpakkam, Tamilnadu. The sodium vessel test setup comprised of 1m diameter tank containing 27 dummy FSA top-heads at the bottom-most position. 19 FSA top-heads were placed under the transducer holder and remaining 8 FSA heads were mounted along periphery of the tank at different orientations with reference to the face of SVTs. Fig. 5a shows the C-Scan image of 19 FSAs located underneath the transducer holder and detection of 5mm growth of one of the FSAs. Fig. 5b shows the 3D ultrasonic image of the setup indicating locations of tie-rods used to hold the test setup, and 8 FSAs with different orientations. The circular shaped image at the boundary shows the wall of the tank containing all the FSA top-heads.

16-Channel Non-Contact Ultrasonic Inspection System: The NCUIS is used to check the functionality of ultrasonic transducers of USUSS, without making any contact with the contaminated transducers, before every campaign of USUSS of PFBR. Instrumentation of 16-Channel NCUIS, housed in 19” rack, is based on air-coupled ultrasonics and works in T-R mode of operation. A test-jig consisting of 8 sodium-compatible and 8 Air-coupled transducers has been fabricated for testing of NCUIS. Each pair of the sodium-compatible and air-coupled transducer is placed along the line-of-sight with a known stand-off distance.

Initially, the sodium-compatible transducers were sequentially energized by a tone-burst pulser to transmit ultrasound in air and the corresponding air-coupled transducer of the same frequency was used as a receiver. The signal was amplified using programmable gain amplifier with gain more than 100dB. A-scan waveforms were recorded for off-line measurements. Subsequently, the role of each transducer within the pair was interchanged and data was once again recorded. The received signals for both the setup were (off-line) analyzed for the assessment of health of sodium-compatible and contaminated transducers for its sensitivity as a receiver, transmission capability as a transmitter and computation of frequency contents of the received signal. DVTs and SVTs are narrowband transducers and so the frequency analysis carried out on received signals was only for academic study.

The NCUIS is capable of driving four pairs of 1MHz transducers and four pairs of 5MHz transducers to check the healthiness of SVTs and DVTs of USUSS. T-R mode of inspection is used because the sensitivity of 5MHz transducers is not adequate to work in air using Pulse-Echo (PE) mode due to excessive attenuation of energy at higher frequencies in air.

Fig. 6: 16-Channel NCUIS System

NCUIS System Hardware: PC based 16-Channel NCUIS consists of 8-Channel Ultrasonic Tone-Burst Pulser with ±300V square-wave output and programmable 1-15 cycles of tone-burst; 8-Channel wideband receivers with programmable gain up to 120dB@ 10MHz (-3dB BW); 100 MSPS-8-bits PCI bus-based digitizer board located in Industrial grade PC, DC power supplies and an isolation transformer. Fig.6 shows the photograph of the system panel.

NCUIS System Software: GUI software has been developed for NCUIS. It facilitates A-Scan data acquisition, display and storage of 1D data, measurement of TOF/distance and frequency analysis of the acquired data.

Test Setup for Calibration of NCUIS and Results: The test-jig, fabricated for the purpose, comprises of four 5MHz ultrasonic transducers, representing DVTs of USUSS, facing 4 air-coupled ultrasonic transducers of same frequency with a stand-off distance of ~25 mm, as depicted in Fig. 7. Similarly 4 more 1MHz transducers, representing SVTs of USUSS, and corresponding 4 air-coupled transducers of same frequency were mounted on the test-jig with a stand-off distance of ~45 mm.

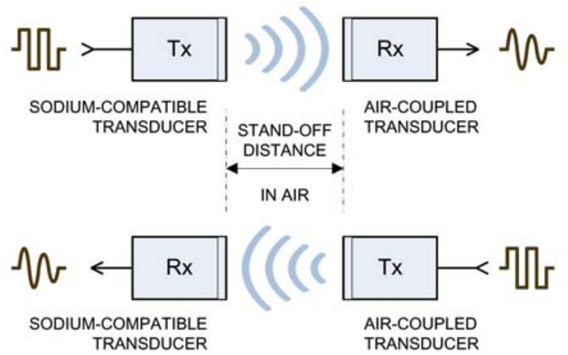

Fig. 7: Health-Checking of Sodium-Compatible Transducer as Transmitter and Receiver

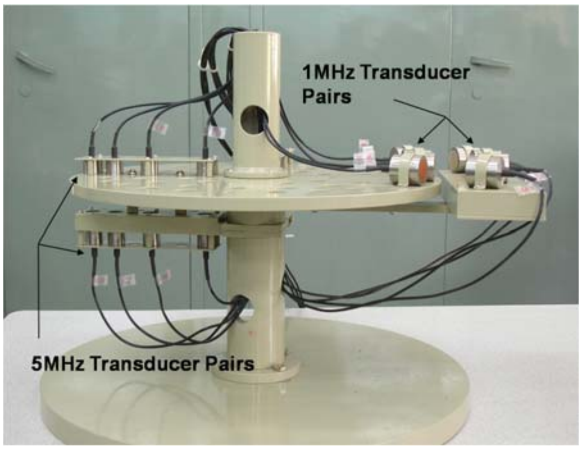

Fig. 8: Test-Jig for Calibration of NCUIS

The test-jig has been designed and manufactured by Workshop of ED, BARC and the photograph of test-jig is shown in Fig. 8.

NCUIS Test Results: The NCUIS system was connected to the transducers, mounted on the test-jig, using 20m long cables. The cables were routed through two slip ring units to simulate the actual connections of USUSS transducers of site. The received signals for 1MHz and 5MHz sodium-compatible transducers were recorded. Fig. 9a and Fig. 9b show the signals obtained from the 1MHz and 5MHz SVTs and DVTs respectively.

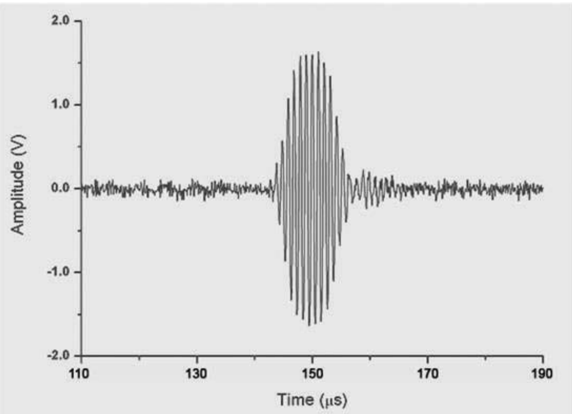

Fig. 9a: Signal received by 1MHz SVT

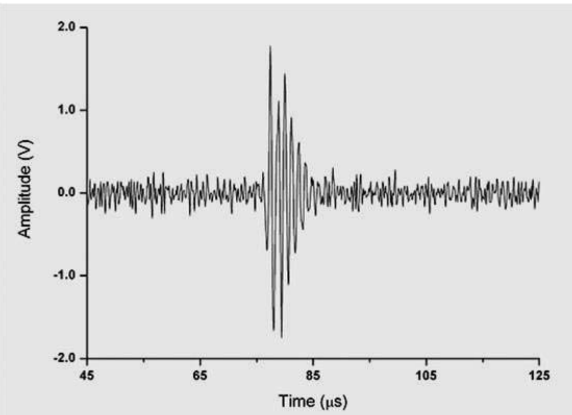

Fig. 9b: Signal received by 5MHz DVT

Conclusion

Two innovative systems namely, UIS and NCUIS have been designed and developed for USUSS of PFBR. The main function of UIS is to perform under-sodium ultrasonic imaging of PFBR core for detection of growth and protrusion of FSAs. Using sodium test vessel setup, 5MHz DVTs, 8-Channel UIS and an automated USUSS, 5mm growth of FSAs was detected. Using under-water 10m long pipe set-up, UIS and 1MHz SVTs, 25mm FSA protrusion was detected in water at a distance of 9m which is equivalent to ~5m in sodium. NCUIS is mainly intended for checking functionality of contaminated transducers of USUSS in the storage-pit area.

The pulse-echo technique based 8-Channel Ultrasonic Imaging System of USUSS has been completely tested using under-water test set-up at ED, BARC, Mumbai as well as in under-sodium test vessel at IGCAR, Kalpakkam, Tamilnadu for detection of growth and protrusion of dummy Fuel Sub Assembly top-heads.

The Non Contact Ultrasonic Inspection System, based on air-coupled ultrasound and working in T-R mode, has also been tested at ED, BARC. Both the above systems have been delivered to BHAVINI, Kalpakkam, TN.

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