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REMOTE INSPECTION AND WELDING OF DIFFICULT TO ACCESS REHEATER PIPES IN ADVANCED GAS COOLED REACTORS IN THE UK

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ABSTRACT

The UK's Advanced Gas-Cooled Reactors (AGR) include reheater systems to re-energise exhaust steam from the high pressure turbines to improve the performance of intermediate or lower pressure turbines further down the line. These systems are included in the reactor's planned monitoring and maintenance programmes. Each reheater has bundles of stainless steel pipes connected into tube sheets, if a damaged tube is identified, it must be repaired safely, reliably and quickly. The reheater tube sheets lie at the base of a long narrow tube and the tube sheet diameter is twice that of this header tube which makes the tube sheet relatively inaccessible.

A system was required to remotely; identify a leak, clean the leaking tube ends, and insert and weld a plug to isolate the tube from the steam circuit at both inlet and outlet.

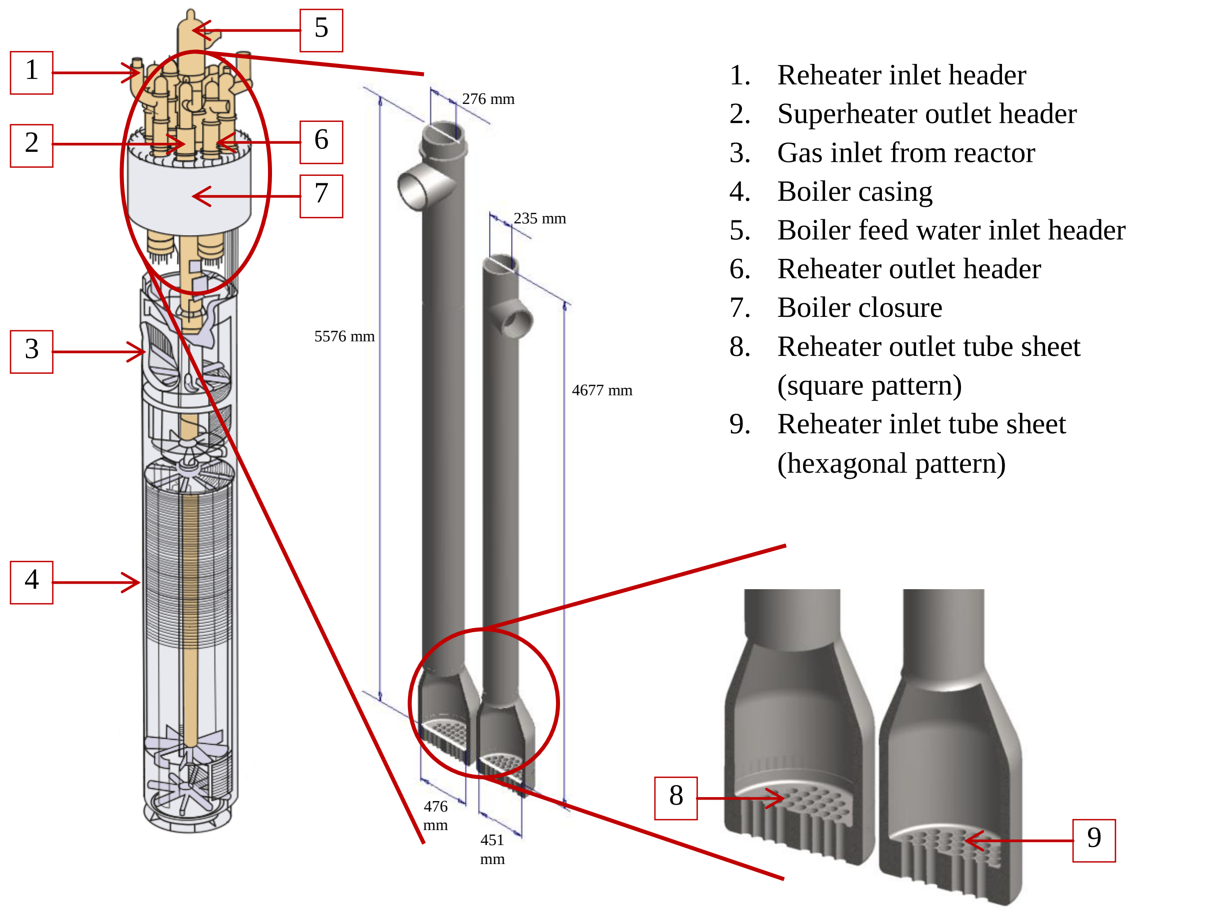
James Fisher Nuclear has developed a bespoke, remote inspection and repair manipulator. The deployment head is compatible with different tools to sense gas leaks, clean the leaking tube, insert and weld the plugs. The system can be lowered through a narrow penetration to the tube sheet, locked into position, and, using several actuated joints, perform all operations.

This paper describes the design and development of the system through to manufacture, testing, delivery, demonstration and training.

INTRODUCTION

Coiled tube boilers are used in nuclear applications, one variety are pod boilers, used in a number of power stations (AGR) in the UK, shown by Ruffell (2015) in Figure 1. There are eight of these per reactor. The pressure barrier of a pod boiler is formed by a cylindrical pressure vessel mounted with its axis vertical (4). Feed water (5), superheated steam (2) and reheated steam (1,6) systems enter / leave the boiler through headers that penetrate the concrete closure (7) at the top of the pod. The feed water (5) and superheated steam headers (2) have tube sheets that are located above this concrete boiler closure. Removing a section of header allows manual access to the tube sheets for servicing / repair. The reheater inlet (9) and outlet (8) tube sheets, however, are located over 2500mm below the top of the concrete boiler closure. Servicing of these therefore requires the headers to be opened and a remotely operated machine to be deployed, the internal diameter of the largest header tubes are less than 280mm.

James Fisher Nuclear (JFN) has designed, built and successfully commissioned (including personnel training) a system for repairing the reheater tube system within these pod boilers. This remote handling system is known as the Reheater Tube Plugging System or RTS.



1. Reheater inlet header
2. Superheater outlet header
3. Gas inlet from reactor
4. Boiler casing
5. Boiler feed water inlet header
6. Reheater outlet header
7. Boiler closure
8. Reheater outlet tube sheet (square pattern)
9. Reheater inlet tube sheet (hexagonal pattern)

Figure 1. (left) Pod boiler by Ruffell (2011); (centre) Reheater inlet and outlet header; (right) Tube sheets

SYSTEM REQUIREMENTS

The customer required a system to identify a leak within a pod boiler reheater circuit, clean the leaking tube ends and then insert and weld a plug to isolate the tube from the steam circuit at both inlet and outlet. Specific requirements of the RTS included the following:

1) Deployable remotely on plant, considering space constraints.
2) Detect CO_2 leakage.
3) Prepare tube ends for welding.
4) Insert and weld a plug.
5) Able to plug both inlet and outlet tube sheets.
6) Simple, quick and intuitive set up and operation.
7) Remote camera views sufficient to facilitate operations.
8) Automation of repetitive tasks.
9) Able to be stored for long periods and deployed at short notice.
10) Operational life of 20 years.
11) Able to be recovered in the event of a failure.
12) Able to operate in low radiological conditions in temperatures ranging 18-50°C.

To validate the designed solution, and provide operator training, JFN were required to provide and run tests using a mock-up facility representing the plant configuration within the customer works.

DESCRIPTION OF THE SYSTEM

The RTS has been designed as a long cylindrical shape (Figure 2), consisting of a Tool Body and Tool Mount, able to be deployed through reheater inlet and outlet headers. The system is housed within a Deployment Unit which can be mounted above the reheater inlet or outlet headers, allowing the RTS to be lowered to the respective reheater tube sheets. Different Tool Heads can be mounted onto the Tool Mount to sample CO_2, clean tubes for welding, insert a plug and weld the plug.

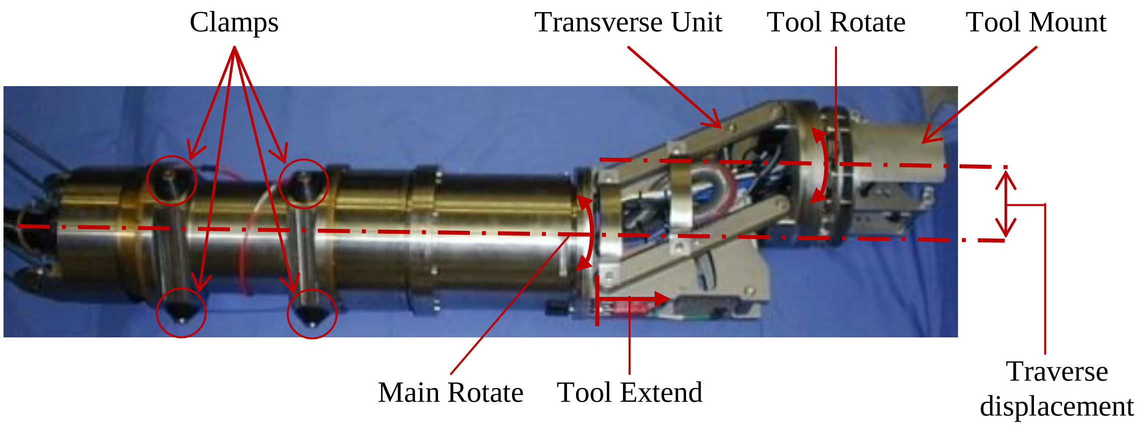


Figure 2. RTS Tool Body (Traverse Unit 'Deployed')

All cubicles are positioned above the boiler closure position. The operator interface, printer and camera display are located within an Operating Station. The Control Cubicle houses the Programmable Logic Controller (PLC), power supply, interface relays and contactors and the Welding Set houses the commercially available ARC Machines unit.

The RTS can assess every tube position within the reheater outlet and inlet tube sheets for a comprehensive circuit check. If a leak is detected the RTS is capable of plugging both the inlet and respective outlet. This problem was difficult to solve, as shown in Figure 1, the tube sheet diameter is significantly greater than the header tube diameter. This required a deployment system able to extend beyond the header tube diameter to access these locations, but still be removable during a failure scenario.

Deployment

The Deployment Unit houses the hoist for lowering the RTS into the header. It has a guarded Tool Change Station for interchanging tools on the Tool Body and can be mounted to the opened inlet or outlet header tube as required. All electrical and pneumatic services for the RTS pass through the Deployment Unit and are protected using an umbilical in the form of a flexible conduit.

Once the RTS is lowered to the tube sheet the operator is able to control movement of the Tool Body using the actuators described below:

- Pneumatically-operated clamps lock the Tool Body centrally in the header at the working position.
- An electrically-driven Main Rotate actuator allows the complete Tool Body to rotate 0-370° within the header to position tools.
- A pneumatically-driven Traverse Unit actuator extends the tool support link 109/122mm into the large diameter lower part of the header.

- An electrically-driven Tool Rotate actuator rotates the tool support link 0-185° so that, in combination with the Main Rotate, all tubes can be accessed by the tool.
- An electrically-driven Tool Extend actuator provides 0-75mm height adjustment of the tool relative to the tube sheet.

The novel motion relationship between the Main Rotate, Transverse Unit and the Tool Rotate allows the tool to access every tube end on the reheater inlet (Figure 3) or outlet tube sheet as illustrated in Figure 4.

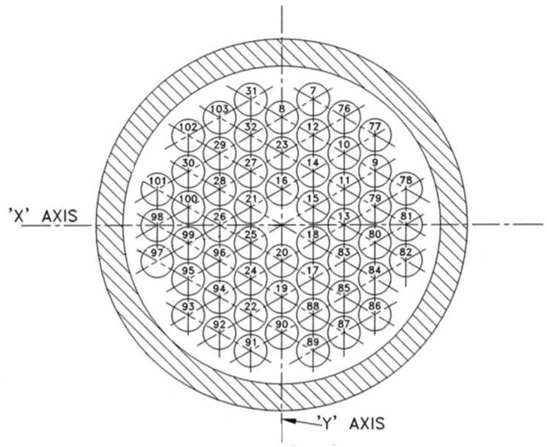


Figure 3: Reheater inlet tube sheet (hexagonal pattern)

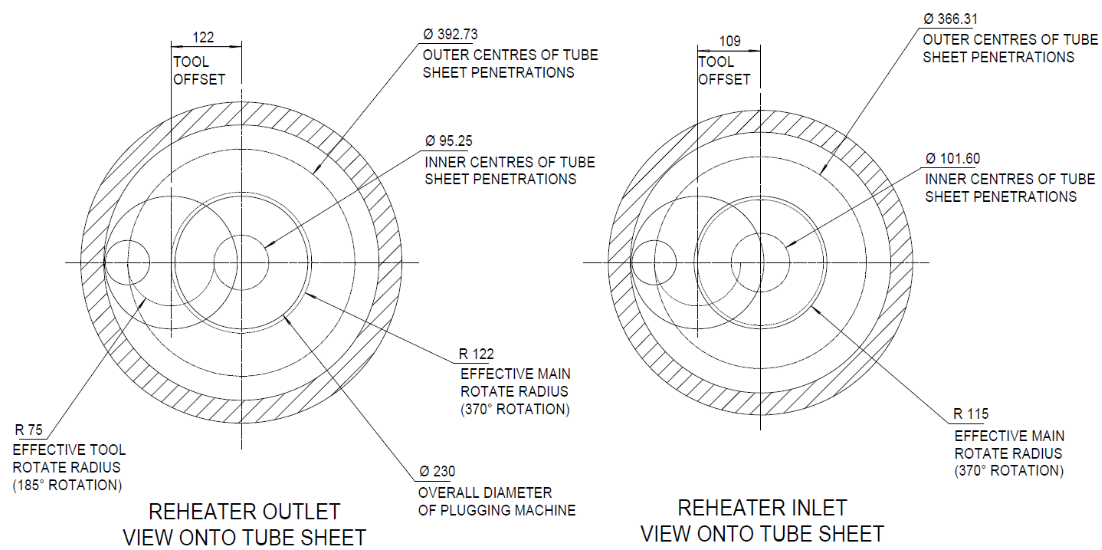


Figure 4: Motion of RTS Tool Body to manipulate tool on different tube sheets

The RTS utilises a standardised connection for tooling heads, this allows tools to be changed dependant on the task. This tool head has a sprung compliance to provide ease of tool deployment into the tube ends.

Leak detection

During operations of an AGR coiled tube boiler the steam circuit is monitored, this may indicate leakage between the CO_2 gas from the reactor and the reheater circuit. During outages these leaks can be investigated further and repaired. During an outage the RTS was required to sense CO_2 for each reheater tube circuit to confirm and identify any leaks.

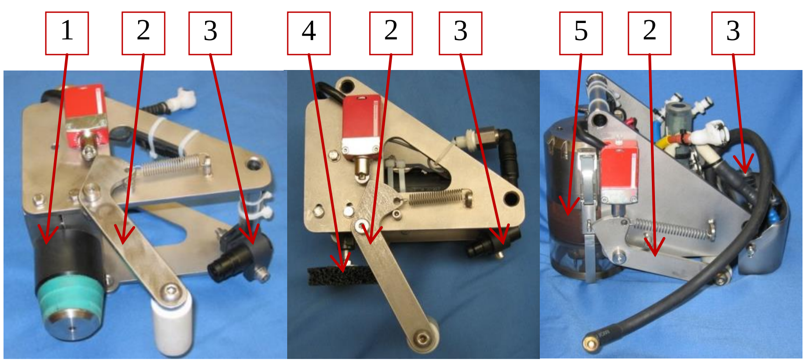
The CO_2 Sampling Tool Head (Figure 5) includes a sample tube and rubber bung. Once the RTS is deployed within the tube sheet header the sample tube is able to be inserted in a reheater tube with the rubber bung sealing the tube mouth. The gas sample is then drawn up a hose in the umbilical and its CO_2 content analysed by instrumentation within the Control Station and displayed on the Operating Station.

Preparing a tube end for welding

Once a leak has been identified within a reheater tube circuit plugs can be welded either side to isolate the steam and CO_2 circuits. The Cleaning Tool Head (Figure 5) was designed to clean the reheater tube entrance (face and bore) using a wire brush or emery pads, driven by an air-motor, in preparation for welding.

Inserting and welding a plug

The Welding Tool Head (Figure 5) comprises of a proprietary (ARC Machines) orbital weld head able to TIG (Tungsten Inert Gas) weld a plug into the mouth of a reheater tube. The welding tool has been modified to carry and insert the plug into the prepared reheater tube entrance. Due to space restrictions the rim material of the weld plug is used to form the weld, this removes the need for a wire feed. The weld head is fed from an inert gas line and closed water cooling system via the umbilical. The weld is initiated by the PLC via the operator interface and the Weld Set has been modified to feed weld data to the PLC to be recorded along with the associated tube location, time and date.



1. Bung and sample tube
2. Tube sheet contact mechanism
3. Camera
4. Cleaning head
5. Weld head

Figure 5. (left) CO_2 Sample Tool Head; (centre) Cleaning Tool Head; (right) Welding Tool Head

Ability to plug both inlet and outlet tube sheets

If a leak is detected the RTS can plug both the reheater tube sheet inlet and respective outlet. As shown in Figure 1 the inlet and outlet headers diameters, tube sheet diameters, tube sheet hole diameters and arrangement (square / hexagonal) patterns are different.

The RTS is configured differently for the reheater inlet or outlet header. Spacers are included on the clamps to account for the wider diameter outlet header. A locking pin position on the Transverse Unit is adjustable to suit the alternative tube sheet patterns as shown in Figure 4.

During every deployment the RTS is orientated against a known feature at the tube header. When lowered to the tube sheet a “tool home” operation is carried out to position the Tool Body with respect to a specific tube bore. Position feedback sensors are integrated into the system to measure depth in the header of the Tool Body, Tool Extend height, Main Rotate angle and Tool Rotate angle. By setting the RTS home position within the tube sheet, along with positional feedback, motion to any particular tube face can be automated.

Simple, quick and intuitive set up and operation

Mechanical and electrical set up of the RTS is designed to be as simple as possible. All cabling and hoses between the Deployment Unit and associated cubicles use simple and unique connectors preventing incorrect wiring. Once the Deployment Unit is attached to the reheater header and power is provided the operators can follow the operator interface prompts to deploy and use the system.

Operator familiarity was expected to be poor due to infrequent usage hence the operator interface and control characteristics needed to be straight-forward. The optimum method of identifying and navigating the tube plate patterns was determined after several design reviews.

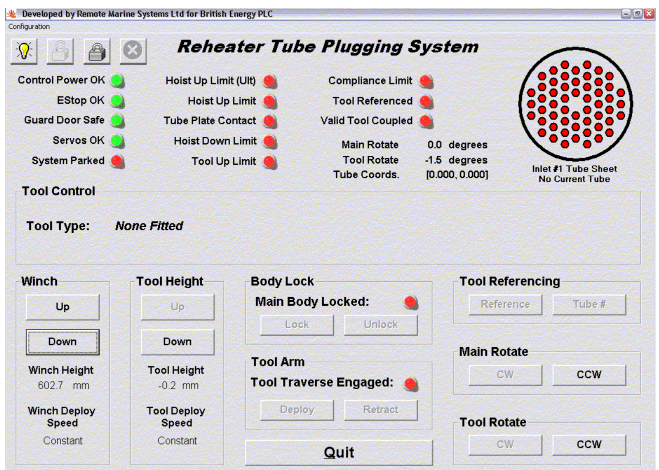


Figure 6. Typical operator interface screen

Camera Systems

There are two discrete camera systems on the assembly, the Deployment Unit camera and the tube sheet camera. The Deployment Unit camera along with a light is positioned to view the Tool Head, facilitating the initial tool home operation.

The tube sheet camera was required to be as compact as possible. As the camera positions relative to the tube sheet were bounded, a camera with a good depth of field negated the requirement for a high level of zoom. Considering this miniature pinhole type, cameras and lights are mounted onto the Tool Body (Figure 5) to observe location and operation of the tools.

The camera control system allows the operator to view the camera footage on the Operator Station display while driving the manipulator as shown in Figure 7, adjust the system light levels and optimise the settings of the deployment tube camera.

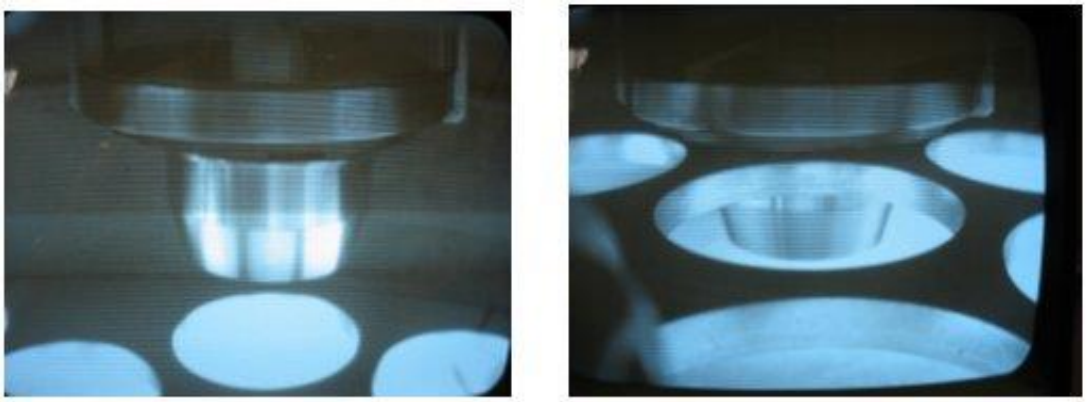


Figure 7: Tube sheet camera view of the plug before (left) and during (right) insertion in test facility.

Automation of repetitive tasks

A PLC system is used to facilitate some automation of repetitive tasks while maintaining ultimate control with the operator. This reduces the risk of damaging equipment, records results, clearly indicates the expected process to the operators and reduces the time taken to complete the task. Each of the tube sheets in the reheater circuit are known to be distinct, therefore heuristic algorithms use a database of tube coordinates and associated parameters to control the tool-tip(s). This allows significant reduction in the time taken to analyse every tube and reduces the likelihood of moving to the wrong tube after tool change and re-deployment.

Able to be stored for long periods and deployed at short notice

The Deployment Unit was designed to store, transport and deploy the RTS on existing reheater headers, this optimises space and reduces deployment time, essential on plant outages. To ensure the equipment is fully functional at short notice periodic testing rehearsals are specified in the operations and maintenance manuals.

Operational life of 20 years.

To ensure spares availability and technical support for the intended 20 year life of the machine, where ever possible in the design, standard, commercially available, components were selected considering obsolescence. A comprehensive spares list is provided with the complete system.

Recovery in the event of a failure

Failure of any drive does not prevent the RTS from being recovered, in all cases back up or recovery methods are available.

To reduce the chance of failure the design employed a heavy duty commercially available hoist unit with a lifting capacity rated to greater than the mass of the items to be hoisted. Additionally the system utilises a four fall rope arrangement effectively quadrupling the lift capacity. In the event of hoist motor failure, recovery can be facilitated by lifting the free end of the cable. This end is fitted with a suitable lifting feature at its termination.

In the unlikely event of a hoist cable failure during raising / lowering operations the machine will fall to the tube sheet. Recovery of the machine from the header can be achieved by using the tensile cable embedded in the umbilical.

Failure of the main body clamps will not cause a drop of the machine as the hoist cable will support the load. Operation of the clamps requires air pressure to extend and retract. If the air supply failed whilst the clamps are extended, then the clamps will relax. Due to the arrangement of the mechanism, subsequent lifting of the main body will further release the clamps allowing retrieval.

The tool Traverse Unit deploys the Tool Head into the bell of the reheater header as shown in Figure 8, therefore this poses a risk of jamming the system during a failure. To reduce this risk the mechanism is pneumatically driven; if the air supply to this mechanism fails the ram will relax. If the mechanism does not fully retract then, when lifted, its profile allows the reducing diameter of the header pipe to encourage the mechanism to retract sufficiently for recovery. This is not anticipated to cause damage to either the internal of the header or the plugging machine.

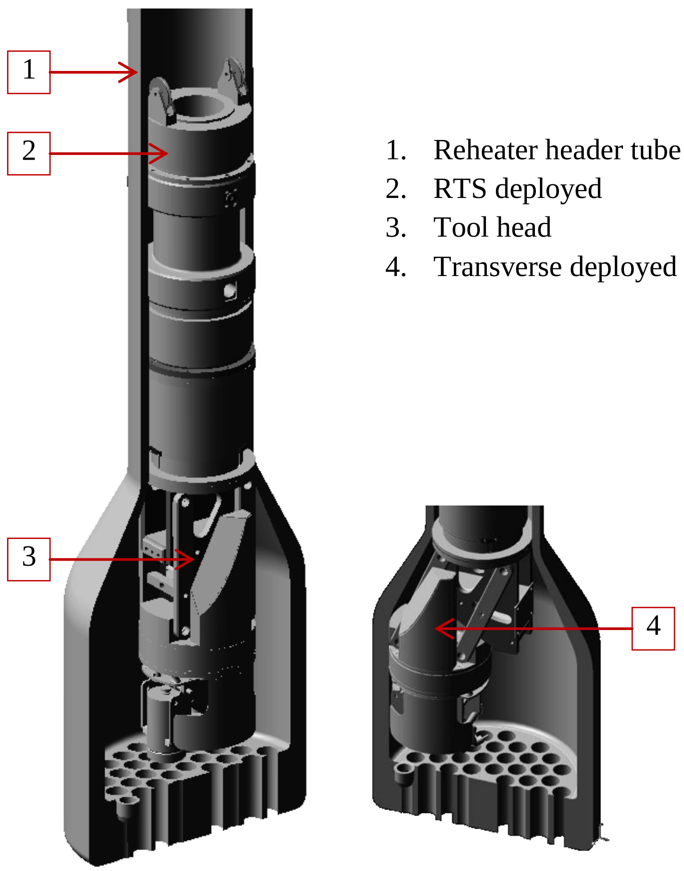


Figure 8. Sections showing Tool Head before (left) & after deployment (right)

Environmental requirements

During the selection of materials for the RTS design, environmental conditions such as the working environment temperature range of 18-50°C, low radiological dose and contamination levels were considered. The RTS was not required to be easily decontaminable.

SYSTEM OPERATION

The Deployment Unit is designed to house and deploy the RTS. When coupled to the opened reheater header, via an adapter, the RTS is lowered to the tool change station where one of a range of tools can be mounted. Electronic identification is used by the control software to display specific tool commands from the operator interface. The deployment head is then lowered until the feedback from the tube sheet contact mechanism provides a hoist stop instruction before the tool contacts the tube sheet. The deployment head is locked into the small diameter portion of the header tube, these are driven outwards simultaneously to centre and secure the deployment head.

Initially the CO_2 Sample Tool Head is navigated to each of the tubes at the tube-sheet through the Main Rotate, Transverse Unit, Tool Rotate and Tool Extend.

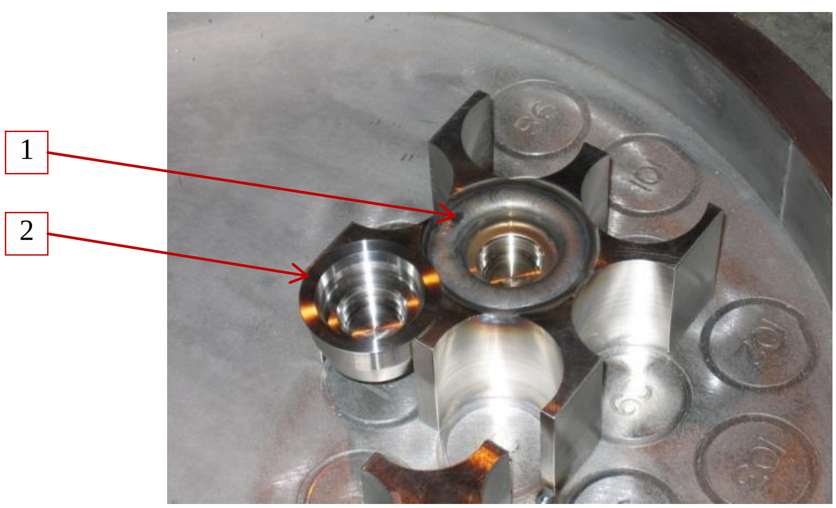
The second phase of operations requires the operator to release the locking clamps and retract the deployment unit to the tool-change station and replace the gas detection tool with a pneumatic cleaning tool. By lowering the deployment unit, and locking in place once more, the operator is able to clean residue and the oxide layer from the suspect tube. The tool camera(s) enable a visual inspection for checking the level of effectiveness of the cleaning process. Finally, following tool replacement with the proprietary weld head, the operator is able to redeploy the machine and arc weld a plug to the cleaned tube. A weld inspection camera is employed by the operator for visual inspection of the finished weld.

Despite the level of automation, the operator retains ultimate control of the system through the bespoke operator interface. Interlocks are present in both software and electrical circuits to ensure that the system performs all tasks demanded of it, whilst remaining safe and recoverable.

TRIALS, TESTING & TRAINING

Weld Approval

Weld approval trials were successfully conducted using blocks of appropriate stainless steel machined to represent sections of the header tube sheets and specially designed weld plugs (Figure 9), the required parameters for the welding controller were determined. A number of these trial welds were conducted and each one sectioned and etched to confirm correct weld penetration leading to an accepted 'weld recipe'.



1. Successfully welded plug
2. Unwelded plug

Figure 9. Welded and unwelded test weld plugs

Factory Acceptance Testing

Full factory acceptance tests were successfully conducted utilising mock-ups of the inlet and outlet header tubes. These mock-ups have the same geometries at the top and bottom as the on-site designs, but were made of mild steel and missing the middle sections to make them shorter. Additionally, the tube sheets were much thinner and removable so that the stainless steel blocks for weld approval could be fitted as required.

Operator Training and Trials

Operator training included both sessions in the classroom and in the workshop. Presentations, talks and demonstrations of the equipment were provided along with a typical operational sequence. Operators were given the opportunity to thoroughly familiarise themselves with operator interfaces and the equipment. Tasks also included the setting-up procedure and deploying the equipment. Operators were able to carry out further trials including inserting and welding a plug.

SUMMARY

The reheater systems used to re-energise exhaust steam in the UK's AGRs need to be inspected and repaired if necessary. Some of these employ pod type boilers for steam generation with feed water, superheated steam and reheated steam systems entering/leaving the boiler through headers that penetrate the concrete closure at the top of the pod. The reheater consists of tube bundles located below the pod headers that penetrate the concrete closure. Servicing of these reheater systems requires the headers to be opened and a remotely operated machine deployed to access the reheater inlet and outlet tube sheets.

James Fisher Nuclear (JFN) designed and manufactured a remote manipulator system known as the Reheater Tube Plugging System (RTS) to support the inspection and repair tasks, notably to identify a leak, clean the leaking tube and then insert and weld a plug to isolate the tube from the steam circuit.

JFN worked closely with the client to incorporate the system requirements into the design including fail safe and recovery functions, and an intuitive operator interface. The system consists of an Operating Station, Control Cubicle, Welding Set, Deployment Unit, Umbilical, Tool Body, and Tool Heads. The operations of the RTS are achieved through the use of interchangeable tool heads including a gas-detection tool, pneumatic cleaning tool, and weld head, supported by visual checking using camera displays. The system allows automatic functions, whilst the operator maintains ultimate control through a bespoke operator interface.

The RTS successfully satisfies all functional requirements; the system has passed acceptance testing and has been delivered to site.

REFERENCES

Ruffell, A.E. (2011), "Coiled Tube Boilers" [ONLINE] *A-to-Z Guide to Thermodynamics, Heat & Mass Transfer, and Fluids Engineering,* [Accessed: 20 July 2015], http://dx.doi.org/10.1615/AtoZ.c.coiled_tube_boilers