Nuclear reactor maintenance

In late 2003 Ringhals AB asked companies to tender to repair a section of pipe in Ringhals 1. Ringhals 1 is an 830Mw ABB-Atom Boiling Water Reactor located on the west coast of Sweden, south of Gothenburg. Tenders were submitted in mid-January 2004 and the contract was placed just 2 weeks later.

What Ringhals had discovered in the regular summer shutdown of 2003 was a leak in a critical pipe. The inspectors allowed the pipe to be plugged as a short term measure and the reactor continued operating albeit at reduced output. The inspectors also required Ringhals to repair the pipe before the end of 2004 and to demonstrate a generic capability to replace any of the other 156 similar pipes if examination revealed a more widespread problem.

In fact the pipes were never meant to be replaced or repaired. The reactor was nearing the end of its original specified working life, but in the late 1990s a comprehensive audit of all Swedish reactors found that they were in much better condition than expected. Whilst succumbing to pressure from Denmark to close Barseback 1 and 2, the Swedish Government gave the green light for the Swedish nuclear utilities to continue producing electricity on condition that the 10 remaining reactors be operated to the highest possible safety standards and subjected to regular and thorough independent inspections. The commercial future of the reactors is now dependent on having the ability to maintain the reactor in an ‘as new’ condition. With political attitudes around the world shifting back towards nuclear power, maintaining and refurbishing existing reactors is now a key issue for all nuclear utilities.

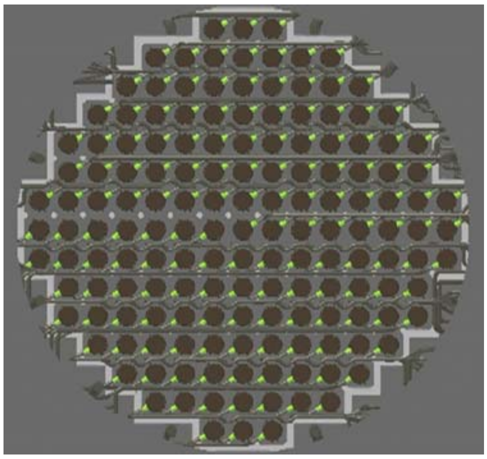
The most challenging area for refurbishment centres on the reactor vessel itself and the complex systems that connect directly to the vessel. Perhaps a useful analogy is to compare the reactor vessel to the human heart - with its own internal valves and muscles and then the complex system of blood vessels that both supply oxygen to the heart itself and allow blood to be pumped around the body. In effect the task faced by Ringhals was to conduct near heart surgery in a minimally invasive manner. Over the coming decades the challenge may progress to equivalent of complex valve replacements and then finally complete heart transplants.

In Ringhals one of the systems of primary importance is the series of 157 control rod drive mechanism (CRDM) pipes that are welded to the bottom of the reactor vessel. These pipes hold the control rods which are driven up and down to maintain a stable nuclear reaction. Each of these

157 CRDM pipes has an associated smaller diameter pipe, called a SCRAM pipe[1]. In a reactor trip, high pressure water is pumped through these smaller pipes forcing the control rods up into the reactor vessels and shutting down the nuclear reaction. The correct operation of these pipes and the control rods is therefore critical to the safe operation of the reactor.

The technical challenge facing Ringhals was two fold. Firstly such a pipe repair had not been done before and required the leaking section of pipe to be removed and replaced with a new piece of pipe using a new 'parent metal' welding technique. The second challenge was perhaps more profound. The leak was located close to the CRDM pipe in a section called the SCRAM nozzle. This meant that the repair had to be made in an extremely confined space with very limited access.

The CRDM pipes and SCRAM pipes are located in a room called the Common Insulation Room (above) which quickly acquired the nick-name 'The Jungle'. The Jungle is directly below the reactor and is almost completed occupied by the 205mm diameter stainless steel CRDM pipes. The CRDM pipes are spaced on a rounded-off square grid with a pitch of 305.5mm. The image on the right shows a plan view of the grid of CRDM pipes with the 157 SCRAM pipes highlighted in green. There are three further pipework systems in the Jungle Room that further complicate the environment. The result is that only alternate East-West corridors are available to provide any access to the SCRAM pipes. Well actually that was not quite true – fortuitously the designers had introduced a series of 62mm diameter holes through the 150mm stainless steel floor. Only half of these holes were populated by additional pipes – leaving the other holes available to gain access from the room below the Jungle.



Options

Three bids were submitted to Ringhals. Two involved cutting down the CRDM pipes to clear a human sized path for a person to make the repair. Uddcomb Engineering AB working with **OC**Robotics and Climax Machine Tools Inc. won the contract by proposing a totally novel approach using snake-arm robots to gain access and repair the pipe. This removed the need to cut down any CRDM pipes. The Uddcomb bid was greeted with 100% support from Ringhals – because the worst outcome would be to re-plug the pipe and contemplate an alternative solution. In

[1] The etymology of SCRAM is 'Safety Control Rod Ax(e) Man'. Norman Hilberry was the first 'SCRAM'. He worked as part of Enrico Fermi's team that built the first reactor. His job was to cut a rope with an axe to drop a control rod into the pile if he saw a blue glow due to Cherenkov radiation.

comparison having cut down the CRDM pipes it might have proved impossible to replace them to the required original tolerances. This could then have resulted in the reactor being shutdown.

When faced with the Ringhals tender, Uddcomb refused to contemplate cutting down the Jungle and started looking for an alternative solution. Uddcomb recognised the potential of a minimally invasive approach using the two access routes. Not knowing whether a delivery solution existed they started looking on the web for a remote controlled mechanism that could snake into the Jungle.

When Uddcomb found **OC**Robotics the minimally invasive option became feasible. Within a few weeks a new partnership was formed between Uddcomb and **OC**Robotics, and a proposal was written focusing on supplying two types of snake-arm robots one for each access route.

OCRobotics proposed two robots that were unimaginatively called the Manipulation Arm and the Inspection Arm. The Manipulation Arm gained access through the Jungle reaching along the available 90mm wide corridor and then down and around some other pipes to SCRAM nozzle. The Inspection Arm was designed to snake through the 62mm diameter holes in the floor of the Jungle and around a CRDM pipe to the SCRAM nozzle.

Manipulation Arm

The image to the right shows a CAD model of the complete Manipulation Arm. This was the arm that gained access from within the Jungle by passing between adjacent rows of CRDM pipes. The widest part of the design was the 82mm wide Manipulation Arm Box which contained the drive mechanisms for the snake-arm. The arm itself is 60mm in diameter and 800mm long. The arm has 8 degrees of freedom with a further 3 degrees of freedom available within a wire driven wrist which has the same outer diameter. The arm and wrist axes are controlled by 16 motors and actuators located within the Manipulation Arm Box. This box is itself suspended on a rail on the underside of a horizontal beam. The beam was made in modular sections for ease of installation and to cope with the different corridor lengths. The longest beam required would be 6m. The Manipulation Arm Box moves along the beam using a friction drive driven by a motor and actuator within the Manipulation Arm Box. Completing the system, the beam is suspended between two coupled vertical axes that lower the snake towards the work site. These vertical axes were secured to the end CRDM pipes of each row of CRDM pipes. The Manipulation Arm Box is a completely sealed box with a separate sealed channel for services that leads directly into the hollow bore of the arm itself. Keeping all services within the arm avoid potential snagging problems and simplified sealing against contamination.

In all, the Manipulation Arm employs 19 servo controlled motors to produce 13 highly couple degrees of freedom. To avoid the significant problems involved with wiring associated with a centralized controller **OC**Robotics developed its own CAN-enabled integrated intelligent amplifier and servo controller. This PCB allows distributed control which minimises wiring, heat output and enables a multi-layered approach to safety. These controllers are also very small.

The image on the right shows an operator driving the Manipulation Arm. The horizontal scaffolding pipe represented the top of a stack of SCRAM pipes that had to be avoided. The operator is practising moving the fixtures into place around a dummy pipe. The operator has better than 50 micron motion resolution of any tools or fixtures and is able to drive with respect to the pipe coordinate frame in Cartesian space. Computer controlled motion resolution (e.g. point to point) is better than 20 microns.

Once the operators became familiar with the basic operation of the Manipulation Arm it was disassembled and re-assembled in a purpose built mock-up of the real environment. One of the conditions of being able to use equipment within a reactor is to conduct fully representative Factory or/and Site Acceptance Tests. The image on the right shows the partial representation of the CRDM pipes and the Manipulation Arm Box in position with the snake-arm starting to reach down to the worksite. Follow-the-nose motion is achieved by coordinating the motion of the two vertical axes with the snake-arm motion.

After many weeks of training in the mock-up the Manipulation Arm was then taken into the reactor for a trial installation and operation as part of the independently assessed Acceptance Tests. Whereas assembly of the robot took less than 30 minutes in the mock-up the real assembly took nearer three hours. This is not a particular issue since the pipe repair took 48 hours in total but illustrates the effect of working for an extended period in a claustrophobic space in double overalls, hood, mask, helmet, gloves, and double overshoes, with an ambient temperature of 35 degrees C and significant levels of radiation.

The photo above shows the Manipulation Arm in the space around the CRDM pipes. A few SCRAM pipes are visible in the bottom right of the photograph. The photo on the right shows the Manipulation Arm fully assembled prior to moving along the corridor to the work site. The snake-arm had to be introduced in a bent configuration to avoid a variety of ‘other’ pipes that restricted access. The arm was then straightened once it was in the working corridor. Following the trial installation and operation the Manipulation Arm was decontaminated and taken back to the mock-up to complete the Acceptance Tests.

Inspection Arm

The second arm supplied by **OC**Robotics was called the Inspection Arm, Figure 9. The Inspection Arm was designed to stand on the floor of the room below the Jungle. The complete robot when fully extended stands 4m tall. The Inspection Arm was actually designed for a longer arm with a 60mm diameter arm and a payload of 10kg but due to shifting specifications the final arm was 35mm in diameter with a payload of 500g.

The Inspection Arm is the more snake-like of the two – with 10 segments and a total of 23 degrees of freedom including a 2 axis wrist. The task of this arm was to introduce cameras around the back of the CRDM pipes to gain a close-up view of the worksite.

The picture on the right shows the Inspection Arm gaining access through one of the 62mm diameter holes in the Jungle floor and then reaching around the back of the CRDM pipe. Figure 11 shows the head of the snake with its two differently fixed focal length cameras pointing towards the SCRAM pipe nozzle. Figure 16 shows the view of the work site from the cameras.

The Inspection Arm was almost entirely controlled in follow-the-nose mode. The operator uses a twin joystick controller with one joystick being used to control progression and retraction along a path. The other joystick is used to pitch up/down and left/right. In effect the path is created by the operator and the computer controls the robot to follow the path as closely as possible. The operator was also able to control individual segments of the arm. This was used to control the wire driven wrist and the final segment of the arm to optimise the viewing direction. By using two cameras with slightly different focal lengths the operator was provided with an excellent view of the Manipulation Arm wrist, gripper, fixtures and tools as they entered the work site. Whilst other cameras were mounted on the Manipulation Arm Beam and at the end of the Manipulation Arm wrist the view from these cameras was often obscured. Having an independent scene view was essential for working in such a congested environment and enabled the fully remote operation to be completed faster than achieved with the operator standing next to the mock-up and trying to peer into the jumble of pipes and fixtures.

In summary the Inspection Arm gave the operators the chance to get cameras where they wanted without compromising the access required by the other systems.

Process

The pipe repair involved replacing a section of the original pipe by making cuts on either side of the fault and then welding a new section of pipe in place. The cutting and final welding were both done from within the pipe gaining access from below through the hollow bore of the CDRM pipe. Uddcomb designed the specialist welding equipment and Climax Machine Tools Inc (based in Portland Oregon) provided the purpose built cutting tool. The main reason for conducting these tasks from within was the ability to use reliable geometric datums and build stiff mechanisms to achieve the precision required. Using both internal and external access made maximum use of the available workspace.

The task of the robots was to do all necessary external supporting tasks.

The first task was to place fixtures to immobilise the SCRAM pipe. FE analysis showed that once cut the free end of the SCRAM pipe might move as much as 15mm. It was therefore decided that the SCRAM pipe should not be allowed to move. In all, three fixtures, that were not much smaller than the space in which they had to be manipulated, were placed around the pipe.

Once the fixtures were in position the Manipulation Arm was withdrawn and the end effector changed to enable the pipe section to be grasped during the cutting process. Each cut took approximately 2 hours. Once the second cut was completed the Manipulation Arm removed the section of pipe.

The next phase involved delivering and locating a weld prep cutting tool which was used to reshape the outer surfaces of the cut pipe in preparation for the new pipe. This was one of the most demanding tasks due to the precise fit between the cutting tool and the cutting machine spindle.

The next task involved introducing the new pipe. The new pipe was then held in place by an internal mandrel which enabled the new pipe and the floating section of the SCRAM pipe to be held in compression against the CRDM end of the SCRAM pipe nozzle.

Once held by the mandrel, the Manipulation Arm was removed and the gripper was replaced with a tack welding tool. This was used to make four tack welds at 90 degrees on both of the welds. This then secured the new pipe in positioned and enabled the mandrel to be removed to allow the parent metal welding process to begin. The Manipulation Arm was then used to place a gas shield around the new pipe to prevent oxidation of the weld.

Having removed the gas shield the Manipulation Arm was then used to deliver an inspection device that took a 360 degree radiographic image of each weld. The final task of the Manipulation Arm was to remove all the fixtures and exit the scene.

Results

By the end of September 2004 Ringhals 1 was back on line and the pipe repair was heralded as a complete success. More than that – the snake-arm robots had proved themselves able to 'reach the unreachable'.

The actual pipe repair was completed in less than 3 days, well within the allocated time slot. Due to the incredibly tight timescales it was decided that the repair should be conducted manually – since the leaking SCRAM pipe was just within reach of an operator lying outside the Jungle and reaching in through the CRDM pipes.

A few weeks later, under slightly less pressure, the robots successfully replicated the manual process using the tools used for the manual repair and completed the full process of replacing a pipe in less than 24 hours on the mock-up. Completing the Factory Acceptance Tests also required CE marking of the robots. Both of these tasks were non-trivial for two completely new robots especially taking into account the lack of time to make any substantial changes to either design.

This, however, is not the end of the story. Whilst there are no indications that any of the other 156 SCRAM pipes is leaking, Ringhals have now installed a monitoring system that looks for potential leaks and will over the next few years conduct a thorough assessment of the state of all 157 nozzles. This work will be part of the annual shutdown. If a leak or potential leak is found then the robots will be have to be instantly available to make the repair during the same shutdown. This means that whilst the robots are now safely decontaminated and packed away, they will be brought out of their winter hibernation so that the operators and robots can be revalidated and made ready for action.