Robotic Removal of High-Activity Debris from a Nuclear Primary Heat Transfer System

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***Abstract*—A unique remote robotic solution, consisting of four single-purpose robots utilized in series, was used to successfully address the extraction of a high-activity source in the drain line of a nuclear generating station heat exchanger. The source activity was such that safety could be compromised in a manual extraction. In addition, the source was located in a confined space, necessitating design of a compact, radiation-hard, remotely-controlled solution. This paper reviews the strategy for extraction, design considerations, testing and execution, with a view to providing operational experience for future.**

***Index Terms*—Nuclear power generation safety, Robots.**

I. Introduction

HIGH-ACTIVITY debris was detected by Ontario Power Generation during a routine survey of the Unit 4 boiler room of its Pickering Nuclear Generating Station. After careful investigation, including several gamma scans, it was concluded that the source was located in the cold leg drain line of Boiler 6, just downstream of the drain elbow located directly underneath the boiler.

The boiler itself is a vertically mounted heat exchanger that is used to transfer heat from the Primary Heat Transport System of the reactor to the secondary system that carries the heat to the steam turbines. It is therefore important that these boilers are maintained on a regular basis to ensure safe operation. Due to the presence of the debris and its radiation fields, approach required special access control, and restrictions were placed on routine maintenance. There was therefore a potential for unit de-rating or shutdown.

This was an unacceptable situation from both a safety and operational standpoint. It was quickly determined that a remote robotic solution would be necessary in order to address the situation with minimal impact to staff in regards to field exposure. Kinectrics was engaged to design a solution that would be workable. With extensive input from OPG engineering and maintenance staff, Kinectrics designed and built four different robots that went through heavy scrutiny throughout the design and test process. The robots were used on Unit 4, Boiler 6 in late April 2010 with a successful completion during a planned outage. The hot particle was safely removed and placed in an appropriate flask, causing the fields to drop down to ambient levels for the first time in almost two years. Boiler maintenance can now proceed as planned.

Employee safety is of paramount importance to OPG so a robotic solution was the best option to ensure a safe execution.

II. Situational Overview

A. Problem

The Boiler 6 situation was unique in that it provided several difficult constraints for the designer of a robotic solution.

The primary difficulty was the target, a high-activity source (Cobalt-60) trapped in the 1” cold leg drain line of Boiler 6 in Pickering Nuclear Generating Station A, Unit 4.

Second, the exact location of the source was not known at the time of the project start date, but it was stated that the source was most likely 4” downstream of the elbow weld joint on the horizontal run. Radiation scans were performed and reported for the area with scans taken directly on top of the existing pipe insulation.

Third, because of the likely location of the source, among a maze of pipe, conduits and heat transport system, there was the nontrivial constraint on the size of the robotic platform.

Fourth, the pipe was filled with heavy water coolant, which posed the potential for spillage – with the concomitant risk of carrying away the debris to a more uncontrolled location. Other attempts to address the radiation source problem had considered a controlled flow, but it had been deemed that the related contingencies posed a higher concern.

Finally, because an upcoming station outage provided a good window for performing the extraction, the team had only 12 weeks to design, build, test, train and deliver the equipment to site.

B. Risks to Success

There was no operational experience (OPEX) in the industry for this type of problem so the team proceeded into unchartered territory. Robots did exist for similar work but were physically too large to enter the worksite and were not suitable to operate in high radiation fields. A solution would have to be designed basically from scratch.

Since the work was scheduled to take place during a planned unit outage, there were 12 weeks to design, build, test, train and deliver the equipment to site. The schedule was therefore one of the biggest risks to success. With the

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technical unknowns and very tight schedule, keeping costs under control was also a challenge.

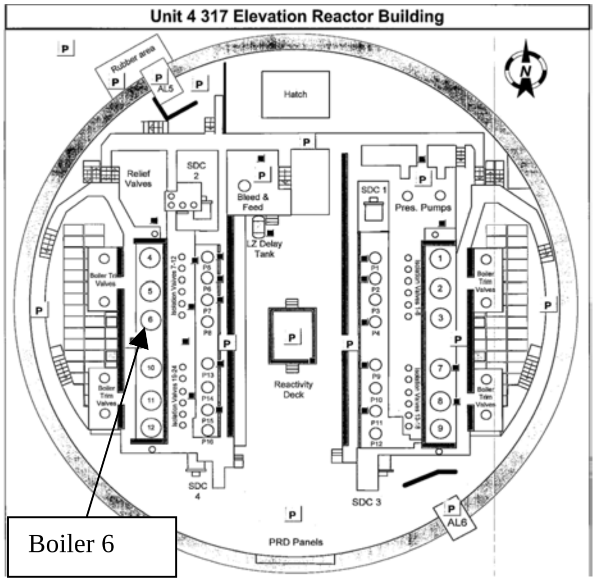

Fig. 1. Plan view of Pickering Unit 4, Boiler Room

C. Project Team

Both OPG and Kinectrics chose to assign dedicated team members during the early project stages to ensure the success of the project. This facilitated the formation of a core group of individuals which would play a very strong part in the project's success. Other support teams – senior management, supply chain, quality assurance (QA) – contributed along the way and were all an integral part of the project development.

During the early stages of the project, it became clear that it was extremely important that the team succeed. It was clear that this outage opportunity provided the best window for extraction; failure was not an option. The presence of the hot particle was challenging the ability of station personnel to work safely and effectively, and all other alternatives to robotic extraction were considered to be prohibitive.

III. Design Strategy

A. Design Philosophy

The initial criteria set down by the design team were simple and direct and were as follows:

- Tooling design and operations to be as simple and reliable as possible;
- The design of the tooling and removal procedure should aim to eliminate the need for workers to take any radiation dose during the removal of the source;
- Tooling should be based on proven designs and technologies;
- Tooling should be flexible enough to allow for as-found conditions;
- Tooling should isolate the particle and positively retain the particle during transportation from the worksite to the in-station storage flask;
- The design should eliminate all single points of failure;
- Real-time tracking of the particle should be maintained in order to verify location of the source at all times; and
- Manual intervention tools should be provided for contingency planning but should only be used as a last resort.

B. Initial Concept

After numerous design discussions, the team settled on a basic extraction concept, which turned out to be key. This concept was based on transporting the tools to the source location, freezing the coolant and radiation source in place, cutting the ice bar, and transporting the pipe section containing the frozen coolant and source to a shielded flask.

The initial design concept was simple as required but would require elaboration to meet the final goal. Fig. 2, below, depicts this initial concept.

Fig. 2, shows the freeze jacket, scissor lift to retract jacket into enclosure, two separate cutting mechanisms that would allow the robot to move anywhere along the horizontal run of the drain line. At this stage there was no major effort put into all the other operations that would have to be done – gamma scanning, insulation removal, water draining, transfer of particle, and so on.

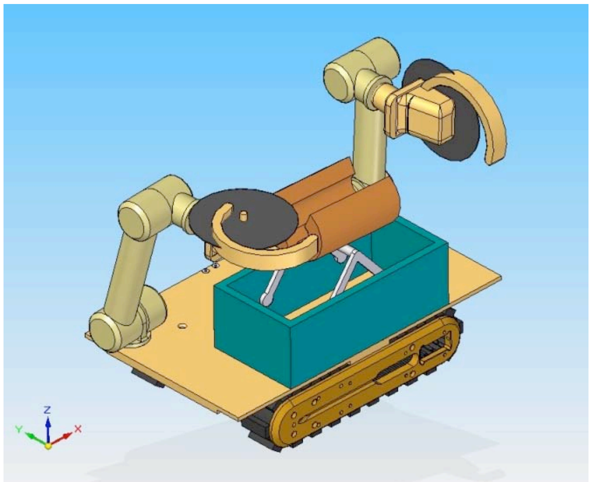

Fig. 2. Original basic concept for pipe removal robot

C. Design Requirements and Supplier Chain

Adherence to the relevant QA requirements outlined by the station, including documentation, was key to meeting the tight deadlines.

It was found that a critical piece was the Design Requirements document. This document basically built on the basic station requirements, but elaborated such that it could be used to base the detailed designs on, and also as a document to set acceptance criteria.

Another key document in our design was the failure modes and effects analysis (FMEA) document, which helped with contingency planning.

Documentation and communication was important to ensure that all suppliers in the chain to provide subsystems for the platform were capable of meeting all requirements, including meeting the aggressive schedule.

D. *Contingency Planning*

The normal design process of prototyping before production could not be followed in this project because of the aggressive schedule. This meant that the design had to be as close to final as possible with minimum changes required after testing.

It was important that the design was capable of handling the many unknowns regarding Boiler 6 space constraints and be prepared to handle the "what can go wrong" scenarios.

The FMEA was one document that facilitated the "what if" scenarios to be documented and helped steer the design evolution. OPG and Kinectrics also instituted numerous site walk-downs and challenge meetings, at all points during design and manufacture, which were excellent forum to voice opinions which also steered the design evolution.

E. *Design and Scope Control*

It was understood that once the design process was done and accepted by both OPG and Kinectrics, it was necessary to apply a design freeze that would allow the manufacturing process to start. However, it was also understood that some changes may have to be introduced, depending on as-found conditions. These were handled by careful consideration of the effects on a triple constraint (time, cost and quality) before proceeding. All changes were documented.

IV. Design, Manufacturing and Testing

A. *Issues During the Design Process*

Originally three robots were designed – gamma probe/camera, insulation removal, and pipe removal (freeze and cut) – but as the contingency planning process unfolded, coupled with the unknowns regarding the specific location of the source, it was clear the project needed a contingency robot. This robot was designed with simplicity and ease of use in mind. The robot was very flexible, however, its controls were very basic which was all we could do to meet schedule constraints. The contingency robot utilized radiation hardened pneumatic actuators to reduce the likelihood of failure due to exposure.

Figs. 3-7 show the four robots and the debris transfer station.

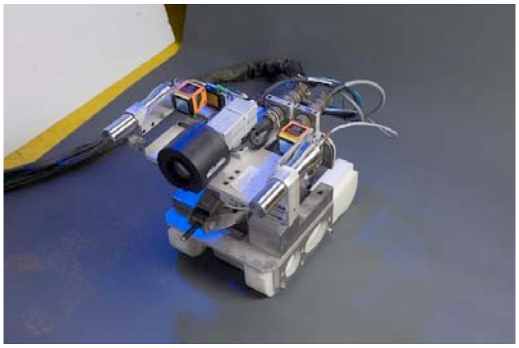

Fig. 3. Gamma Probe and Camera Robot

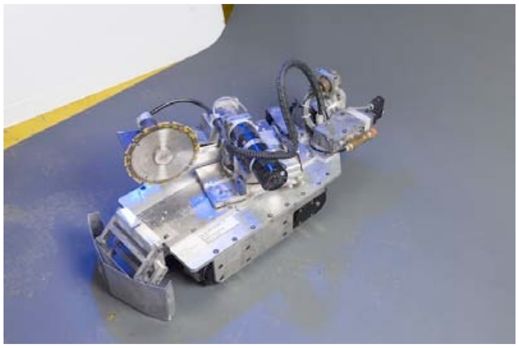

Fig. 4. Insulation Removal Robot

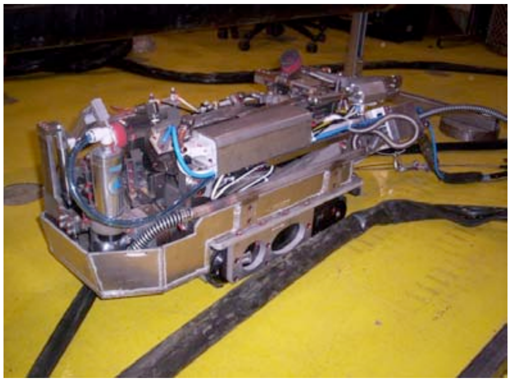

Fig. 5. Pipe Removal (Freeze and Cut) Robot

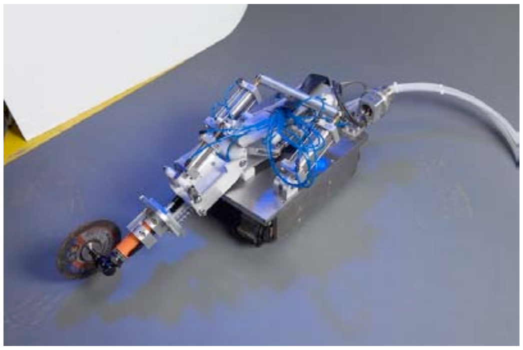

Fig. 6. Contingency Robot

Fig. 7. Transfer Station

Four small robots were required instead of one large one to cope with the space constraints, and to optimize the tooling payload for each robot.

B. Failure Modes and Effects Analysis

To capture all failure modes it was necessary to follow a structured approach that would allow the design process to benefit and reduce the risk of design alterations once manufacturing had started. This document was completed early in the project, and was updated as required following any of the challenge meetings. A standard format was used for the FMEA with recommendations given to the design team.

V. Mock-Up Testing and Training

A. First-Round Testing

The first round of testing was at a Kinectrics subsystem supplier site.

The mock-up that was built was very simple, but important in that it provided a bare-bone means of determining if basic requirements were met before shipment of the subsystems to Kinectrics.

Fig. 8. Supplier Test Mock-Up

B. Second-Round Testing and Training

Following initial testing at the supplier facility, the next phase of testing followed at Kinectrics. Here the mock-up was more representative of site conditions. All robots were tested while at the same time team members had a chance to familiarize and train in the operation of the robots. A test plan was agreed to for acceptance and carried out before shipment to the OPG site.

Fig. 9. Views of boiler bowl mock-up at Kinectrics Facility

As testing and training progressed it was necessary to assign roles for team execution. Not everyone on the team had an affinity for remotely operating the robots. It was necessary to ensure those who did operate the robots had the patience and understanding to execute well. Others were given roles of cable management, site support, gamma scan operation and team backups.

VI. SITE TRAINING

A. Testing in Unit 2

After the equipment was shipped to site the plan was that the robots would be tested, with personnel in full plastic suits on safe-storage Unit 2. This unit provided a similar configuration to the actual base of operations in Unit 4.

However there were issues. The configuration on Unit 2, Boiler 6 was somewhat different that what the robots were designed for (Unit 4, Boiler 6) and so delays were incurred in correcting for the differences.

The robots are primarily pneumatic and used station service air. Using service air turned out to be a real challenge. Moisture build-up in the service air line accumulated and was pulled into the robot system as a water "slug", rendering the robots unfit for use.

Following station procedure for safe back-out, the team reassembled to determine path forward. After switching to instrument air and flushing/testing the robot and control systems we were back on track. The exercise proved to be an excellent test of teamwork and the reliability of the robots also despite potential water damage – important to the actual execution scenario.

B. High Hazard Review

After Unit 2 testing was complete, OPG hosted what is known as a high hazard review meeting. This meeting was held to ensure all team members knew their roles when any high hazard work was being done. All events up to that point were also discussed to ensure all parties were satisfied in moving forward with executing the hot particle removal on Unit 4. The meeting was a success and the go-ahead decision was given.

VII. EXECUTION

A. Overview

Execution on Unit 4 started on April 26, 2010 and ended late April 30, 2010. All work was completed on day shift only to ensure team members did not grow weary. Any major work evolutions were not started late in the day in order to leave room for contingency.

Since this project was high profile there were many eyes on the execution work. Senior OPG staff, plus representatives of the Canadian Nuclear Safety Commission (CNSC) regulatory body were present throughout the operation. There was constant scrutiny from all areas at the "teledose room" (where dose records were constantly monitored to ensure they stayed at safe levels for staff that were in the reactor building).

B. Process

The execution of the extraction operation with the remote robots continued with the following process:

1. Survey area to reconfirm the location of the high radiation source;
2. Remove cold leg drain line insulation;
3. Re-survey the area to confirm the exact location of the high activity debris;
4. Nick vertical section of drain line to drain residual heavy water from boiler bowl (Fig. 10);
5. Secure the radiation source within the pipe by applying a freeze jacket encompassing the source;
6. Cut out the section of drain line containing the source; lower the section of pipe into a shielded box;
7. Transport pipe and source to an intermediate vessel; heavy water solidifier will be present in intermediate vessel;
8. Detach shielded section of crawler; base crawler to be used in future applications;
9. Transfer intermediate vessel into Bleed Filter Can which has been pre-installed in the In-Station Flask (ISF).

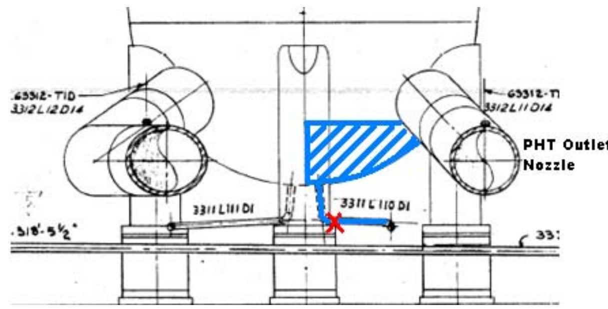

Fig. 10. Shaded area showing expected volume of D2O remaining in bowl. "X" marks expected location of high-activity debris.

Several issues were encountered on site during the actual extraction that affected the operation.

First, as-found insulation turned out to be different than what was expected (two layers of fiberglass opposed to one); this required a longer time to remove than anticipated (two and a half days instead of one).

Second, the crawler tracks failed to separate. While this made things difficult, the work plan took this into account and the recovery steps were pre-planned and pre-approved. Thus there was no delay to the extraction schedule, and no additional dose to workers.

Finally, video cameras proved difficult to use throughout the entire removal exercise (across Unit 2 and Unit 4). This made control difficult and would be the first thing to improve upon in a similar situation.

Overall, the extraction operation was a success. Figs. 11-13 display some representative photographs of the robots during the operation. While the removal required two extra days, the operation resulted in very low overall dose rates to the team. Success of the operation means that boiler maintenance can be carried out during the next planned outage, so that the unit will be able to power Ontario for several years to come.

Fig. 11. Insulation Removal Robot making circumferential cut.

Fig. 12. Gamma Probe and Camera Robot locating debris.

Fig. 13. Pipe Removal (Freeze and Cut) Robot in position.

VIII. Conclusion

The rigor put into the early phases of the design, three months earlier, paid off in terms of station confidence in the team and the robots. Both the team and the robots were tried and tested many times before the actual operation, and this resulted in a smooth operation, and a confidence that unseen circumstances that might arise could be dealt with – which is what, in fact, transpired.

Even though the robots performed extremely well it should be noted that the excellent teamwork among the robotic team and station personnel was a strong contributing factor to the project's success.

IX. Acknowledgments

In an operation this complex, numerous individuals, acting as a team, contribute to success, and it is impossible to name every one. The authors gratefully acknowledge K. Maynard, D. Cuthbert, Y. Verzilov, G. Corbin, C. Suessman, M. Hooper, D. Sim, I. Cord, D. Cuthbert, A. Heics, D. Zvanovec, J. Thrasher, R. Bishop, M. Hoggart, T. Watt, D. McAlpine, N. Taylor, J. Zic, C. Glover, J. Page, L. Mann, J. Szulc, R. Boss and all who contributed to the work described in this document.

X. References

[1] S. Burany and A. Hamilton, "Hot source extraction from Unit 4 Boiler 6 of PNGS-A," Kinectrics Technical Report, to be published, 2010.

XI. Biographies

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