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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

# Remote Systems Design & Deployment

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August 2009

Pacific Northwest
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# Introduction

Deploying remote systems into radioactive and/or chemically hazardous environments presents a very complex challenge.  In the remote environment, tasks are inherently more difficult. Seemingly easy everyday tasks can be quite problematic or impossible to achieve remotely. Operator vision is limited to two dimensions (no depth of field), audio feedback is limited to what microphones and noise canceling technology can provide, and the sense of physically feeling motions or forces is absent without extensive sensor technology.

The Pacific Northwest National Laboratory (PNNL) was funded by the Department of Energy (DOE) Office of Waste Processing Technology (EM-21), to provide information and lessons learned relating to the design, development and deployment of remote systems, particularly remote arm/manipulator systems. This effort directly supports Hanford contractor Washington River Protection Solutions, LLC (WRPS), however, the information in this document applies to the deployment of remote systems in general.

This report reflects PNNL's extensive experience (described in Appendix A) with remote systems and lays out the most important activities that need to be completed to successfully design, build, deploy and operate remote systems in radioactive and chemically contaminated environments.  It also contains lessons learned from PNNL's work experiences at Hanford (including deployment of the pit viper, U-plant crawlers, 324 materials open test assembly arm, and the light duty utility arm), in other contexts (in Iraq, Oak Ridge, and Idaho), and the work of others in the national laboratory complex.

Successfully deployed remote systems are a product of qualified teams that develop and maintain functions and requirements (F&Rs), complete comprehensive design efforts including work envelope assessment, kinematic and dynamic analyses, and design integration.  A tremendous amount of detail is paid to controls, tooling, remote vision, human-machine interface, systems integration, mockup testing, and training of system operators.

# Qualifications

A high performing, multi-disciplinary team will be required to successfully design and integrate a remote system. There is a lot more to successfully deploying remote systems than simply buying equipment and installing it. Each element of a remote system must interact with many others, and these interfaces will include mechanical, electrical/utility, vision, communications, and operators. Each of these interface points must be carefully managed by a systems integration team to ensure that the systems can work together effectively when finally installed. While many of the systems can be found as commercially available “catalog” items, many will be custom manufactured for the payload size, type, and motion required.

A highly qualified integrator will have the ability to understand the project challenges, will be good at matching the needs with technology, and approach the project with a structured systems engineering perspective. Systems integration requires inductive reasoning and knowledge of a large number of topics/technologies gained through research and experience. An equipment vendor is rarely qualified to be a systems integrator.

The system integration team should include a suite of engineers. The key technical leads should have at least a masters’ level education, with emphasis in robotics and remote systems. To succeed with highly complex remote systems, the team must have experience with smaller remote system design and deployment. The team needs a very high level of expertise in taking commercial products and adapting them to radiologically and chemically contaminated environments.

Team expertise should include:

- Mechanical engineers specializing in the design, integration, and deployment of first-of-a-kind field-ready hardware, and design and operation of remote and automated systems.

- Mechanical engineers experienced in the design of remotely operated tooling for use in high radiation environments.

- Mechanical engineers with expertise in fabrication, assembly and electrical/mechanical systems integration, and who are truly hands-on practical workers.

- Electrical engineers.

- Electronics personnel.

- Engineers with experienced in modeling the behavior of both compliant and non-compliant mechanical systems. Kinematic, dynamic and three-dimensional modeling of mechanical systems.

- Computer and robot programming -- experience in programming manufacturing robots and other computer-controlled motion control systems. Experience in developing things like real-time control code for a six degree-of-freedom (DOF) hydraulic manipulator.

- Project manager experienced with large integrated system deployment of highly complex remote systems in radiologically and chemically contaminated environments.

# Functions and Requirements

Defining F&Rs is critical to selecting systems and tools that can successfully achieve the required project mission. The most prevalent reason for deployment failure of remote systems is the application of unsuitable remote systems to the task at hand.

The process of defining F&Rs requires a thorough understanding of the problem to be solved (the mission), and a quality F&R document fully bounds all foreseeable parameters without excessively driving the design.

Development of F&Rs needs to be completed with the full involvement of the user, stakeholders, developers, and operators. All the critical partners need to own the process and ultimate outcome. Assumptions should be clearly documented.

Requirements drive the design of the system and all ancillary equipment. Each requirement needs to be carefully scrutinized to define the basis for it, and then there needs to be an understanding of how that requirement is going to drive design and equipment decisions, and ultimately system operation and cost.

Once the detailed F&Rs are developed and formalized, it is critical that, to the greatest extent possible, they not be changed. Changing F&Rs mid design, fabrication or testing can dramatically increase project cost and schedule. It can render the current design and purchased equipment useless.

F&Rs need to cover all aspects of the scope/mission. The following is a list of potential items to consider during development of F&Rs:

- Facility/work zone-specific requirements
- Waste-based considerations (remote system comes in contact with waste) -- will drive material or sealing requirements
- Disposition requirements – for any waste removed, and for tools, systems, and equipment used to remove waste
- Environmental and regulatory concerns
- Standards or other certifications (NQA-1, ASTM, UL, etc.)
- Material types
- Operational requirements
- Maintenance requirements
- Storage considerations
- Modes of acceptable failure
- Interfaces (power, communications, water, air, ancillary equipment, etc.)

- Documentation package:  drawing packages required, spare parts lists, operational manuals, maintenance manuals, failure mode analyses, etc.

- Degree of redundancy required (e.g., no single-point failures)

- Mean time between system reset, failure recovery times

- Will manual tool change out and repair/replace be allowed? Will remote tool change out be required?

- What manual activities will be allowed?

- Machine travel rates

- Dynamic interactions and frequencies

- Reaction forces

- Reliability and maintainability

- Precision accuracy and repeatability.   Example requirement:  The modified light duty utility arm (MLDUA) system is capable of returning the utility arm and the tool the arm is holding to a known point in space inside the tank to a degree of repeatability, which approaches +/- 0.25 inch. This repeatability was required for reliability of the characterization end effector and wall material sampling operations.

- Controls and integrated control strategy

- Alarm, interlock, and emergency-stop (e-stop) strategies

- Any positioning sensors?  Collision avoidance via sensors and/or by operator training?

- Who will be operating the system?  What involvement will labor have?  What categories of labor will be required to complete the mission?

- Payload size and weight, system capacity requirements.  All of the elements of the system should have capacities in excess of the demands they are expected to support during operation.

- Access limitations – ingress/egress dimensions, loading limitations, etc.

- Operational life, cycles, years of operation – scheduled maintenance, hours per day of operation – in radioactive or hazardous environment (exposure concerns), operator hours/cycles, hours for setup, takedown, etc.

- Decontamination and disposal requirements, ability to reuse in similar environment (package, wrap, transport, etc.).

Preparation lessons learned from the Gunite and Associated Tanks (GAAT) MLDUA Project[1]:

- Prior to beginning the design process, sufficient information on the characteristics of the tanks and the tank waste must be collected. This effort should include the following:

    - Understanding the characteristics of the sludge wastes before selecting classifiers/filters. The classifiers/filters located in the waste conditioning system (WCS) were installed to ensure that the size of the particles entering the waste transfer line was <100 µm. The frequency at which the filters automatically back flushed indicated binding of the filters by particles <100 µm, which resulted in reduced transfer efficiency from frequent back flushes. The classifiers were eventually bypassed when it was determined by sampling and in-line measurements that the particle sizes were predominantly <100 µm.

    - Establishing the characteristics of the waste and process chemicals to ensure the proper selection of materials for all gloves and glove ports. The characteristics of the wastes and process chemicals that come in contact with the equipment must be adequately established to ensure the proper selection of materials.

    - Ensuring that the tank atmosphere is properly characterized and that any impacts on the design and operation of the in-tank equipment are well understood. This is especially important if flammable gases are present.

    - Performing degradation tests using actual waste materials and process chemicals during the selection phase if characterization or resistance data are unavailable.

- Involve inspectors early in the design process to identify necessary modifications to ensure code compliance. The GAAT Remediation Project obtained early involvement of inspectors for the National Electric Code (NEC), American Society of Mechanical Engineers (ASME) code, DOE radiation control, and other applicable codes during the design and construction process.

- When relatively high-pressure gas is used with the Pulseair mixers (PAMs), a considerable shock wave can be produced inside the waste tank. This shock wave may be capable of damaging mechanical and structural elements of the tank. Before Pulsair mixing is used, the structural stability of the tank must be assessed to ensure that it will not be damaged by the anticipated shock waves.

[1] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003

# Design and Design Integration

Three key parts to focus on in the design of arm-based remote systems are work envelope, structural and dynamic analyses, and controls. Design integration is also required. Design integration efforts include considerations for operational flexibility, remote systems engineering perspectives, simulation and modeling, identification of system operators and their functions, equipment interfaces, standardization, operations, balance of plant, contamination control and decontamination capability, equipment services, maintenance, planning for upset recovery and rework, and data collection.

Complex systems require an iterative design process to ensure that the various subsystems can operate together smoothly. If integration issues are not addressed prior to final design and equipment procurement, substantial rework will likely be required to retrofit equipment and components. The more complete and thorough the design integration work is, the fewer decisions will need to be made during final system integration, which is when the actual pieces of hardware are assembled and installed.

## *Work Envelope*

The work envelope of the remote system needs to be adequately assessed in its *intended deployed configuration*. This will determine if the equipment will meet the functional requirements.

A robot's work envelope is typically defined as its range of motion. The work envelope is usually represented as a series of graphics from different two-dimensional views. The shape of the work envelope is modeled by considering all possible joint angle combinations to yield the maximum reach and access to the base. In the case of a manipulator arm, this includes reaching forward, backward, up, down, left, and right. Depending on degrees of freedom, the robot may or may not be able to reach over or around itself. For example, a rotary base actuator may have a 270 degree range of motion because of internal hardware. This would leave a 90 degree dead area directly behind it. Figure 1 is an example of a work envelope sketch. The blue shaded area is the available work envelope.

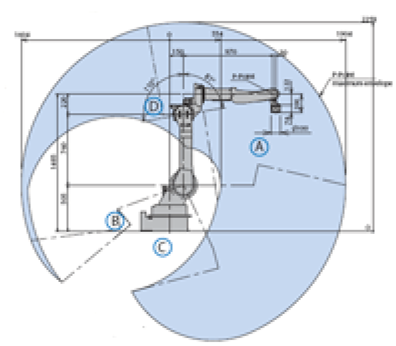


**Figure 1. Work Envelope Sketch**

However, these work envelope models do not give an accurate impression of the *true* work envelope of a robot. The true work envelope depends on a number of other factors such as total degrees of freedom, redundant degrees of freedom, control strategy, environmental obstacles, task/tooling, and operator vision. Some of these constraints cannot be known unless accurate computer simulation or mockup testing is performed. Additionally, tele-operation of robots (human in the loop) in unstructured environments can reduce real-time work envelopes simply through operator fatigue with diminished capacity for avoiding obstacles to position the end effector appropriately.

The number of total and redundant degrees of freedom greatly affects the work envelope of a system. In unstructured environments, it is important to have redundant degrees of freedom located near the end effector to do fine positioning. Not all degrees of freedom are available at different orientations because of joint limits and physical obstacles.

Unstructured environments pose additional difficulties because of navigation around existing structures. A work envelope may appear to support activities in a certain position, but because of other physical constraints may not be accessible in a useful orientation. The end effector may not be able to rotate about the correct axis to position the tool for use. Also, other parts of the robot that are vital to performing a desired tool path may be obstructed by physical obstacles or joint limits. Perhaps a sweeping motion is necessary, but an instrument tree is in the way. The operator may reach around the tree, but the required joint orientation leaves no range of motion along a particular axis because of joint limitations.

Example: The MLDUA deployed at Oak Ridge, TN for the waste cleanout under the GAAT Remediation Project (see Figures 2 and 3).

- A crawler was used (deployed from another riser) in conjunction with the MLDUA to assist the arm in cleanout of the underground radioactive waste tanks. In general, when remote arms are deployed via risers into waste tanks, there will be a circular dead space directly under the riser that has a radius that is equal to or larger than the first fixed length of the arm. Unless there are multiple and redundant degrees of freedom in the arm (that allow the arm to curl up under the fixed length), the arm will not be able to access that dead space. To completely cleanout the tank, an additional piece of equipment will need to be used (like the crawler for the MLDUA) or the arm will need to be deployed through multiple risers.


**Figure 2. Main Components of the GAAT In-tank Equipment**


**Figure 3. GAAT In-tank Equipment Deployed via Three Risers in Cold Test Facility**

## *Analysis*

It is very important to conduct the appropriate structural and dynamic analyses of the system (and all components) including the affects of tooling/end effectors and movement of water, air, and/or waste hoses associated with the deployment mission. This is to ensure that the machine can meet performance requirements when operational (and potential upset condition) loads are applied to it. One issue that can be overlooked in this area is the elastic compliance of the machine. Even if an arm has sufficient static load-bearing capacity, it may deflect unacceptably under static load, dynamic load (from working end effectors) and/or motion. This is particularly likely to be an issue if the machine is deployed in an orientation other than the one for which it was designed or if a machine designed for non-robotic use is adapted to robotic control.

In addition, if the equipment is to be deployed into a waste tank for example, an analysis will be required regarding the imposed loads and forces on any in-tank hardware/equipment and the tank itself.

Lessons learned from the GAAT MLDUA Project[2]:

- The dynamic effects of the decontamination spray ring impinging on the MLDUA mast resulted in having to use the spray ring below the maximum available pressure to avoid inducing position errors in the arm controller.

- Design accessories (end effectors) to ensure that their weight does not exceed the payload limitation for the remotely operated systems. This restriction requires consideration of the weight of the hose, gripper device, and the accessory.

- Design accessories to ensure that their lateral forces do not exceed the design limitations of the remotely operated system.

[2] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003

- Design accessories to operate outside the fundamental frequency of the remotely operated system. The first fundamental frequency of the MLDUA is ~1 Hz. Any frequency generated near 1 Hz is likely to result in severe vibration problems for the MLDUA.

### Modeling

Development of robust three-dimensional simulations of the equipment and its environment can be very valuable. These models will allow the designer to deal with mechanical interference, reach, and fit issues prior to specifying purchases (Can the machine reach the target? In the appropriate orientation? Without colliding with obstacles? etc.). It is important to deal with these issues during the design phase; otherwise substantial rework will likely be necessary to enable the equipment to perform within the overall system environment.

The models will also expose a wide variety of other issues that can be challenging to uncover using other methods. Some of the more important kinds of issues include:

- Deployability – can the machine be deployed into the work zone?
- Visibility – will the proposed camera locations and types provide sufficient feedback to the operator?
- Speed and timing – how long are tasks likely to require?

Lesson learned[3]:

- A three-dimensional robot simulation tool was used to create a simulation of a robotic work cell design for handling components at a nuclear arms facility. This initial simulation identified problems with the customer's proposed work cell layout, and allowed a correction to be proposed before hardware was purchased. In addition, refinement of the simulation allowed the design and construction of a work cell mockup and accurate off-line programming of the system. The simulation package's off-line programming capabilities were used to develop the motion control code for the work cell.

Lessons learned from the GAAT MLDUA Project[4]

- Risers, in-tank equipment, and debris in the tank can hinder the deployment of retrieval system components. Ensure that all in-tank materials and equipment are mapped and their interference with the retrieval system components is well understood prior to operation.

## *Controls*

It is critical to define the controls approach for the remote system, and to do this very early in the design process. If the system consists of multiple products designed/procured to be used together (arm, camera, lights, gripper, and tooling for example), there will be significant control issues to deal with. Unless specified and purchased as one integrated system, each component

[3] Baker, C.P. Off-line Programming and Simulation in Handling Nuclear Components. Unpublished white paper. Pacific Northwest National Laboratory, Richland, WA.
[4] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003

will have a separate controller. Decisions will need to be made early regarding how to integrate those controllers and operate the equipment in a safe and efficient manner. Alarms and interlocks for personnel safety should also be considered for equipment interacting with process or waste operations.

In addition, if a system or component is a commercial product being used in an application it was not designed for (which is usually the case when using commercial off-the-shelf (COTS) equipment), the control system will need to be modified. An example of this is remotely deploying a system that comes with line-of-sight controls. There is an enormous leap in going from line-of-sight control to control via remote vision. Many times, vendor-supplied controls will not suffice, even with modifications, for truly remote applications.

Typically left out of vendor supplied equipment is emergency stops (e-stops) for safety, which are absolutely critical for all remote systems operations. A system-wide e-stop philosophy will need to be developed and implemented. These are not trivial to develop for large, integrated systems.

Next, decisions will need to be made about the type of control strategy to be used. Industrial robots generally have one of two control strategies: joint control mode or Cartesian control mode. In joint control mode, each joint only can move in two directions and is controlled by manually positioning each joint in succession. Coordinated joint motion is very difficult, but can be obtained with enough training and practice. An off-the-shelf backhoe is a good example of a machine that uses joint control mode.

Cartesian control is based on an XYZ coordinate system on some part of the robot (generally the end effector or base actuator). The control interface gives the operator the ability to “move along Z” or “rotate about the X-axis”. A gantry crane is a good example of a Cartesian control mode. A robot in Cartesian mode with six degrees of freedom or more can perform much more complex coordinated movements because the task of arranging the joints is left to a computer system. This type of control system should also have the ability for system programming so that automated functions can be utilized.

It is possible (desirable) to be able to control an articulated machine (such as a backhoe) in Cartesian mode. Given enough time, effort, and budget, a system with only joint control or only Cartesian control can be converted to use both control schemes. This would require writing software and retrofitting the necessary hardware with position indicators.

Ideally, a robot for use in unstructured environments should be able to easily alternate between the two modes (a pushbutton on the human machine interface), allowing joint mode for operator-guided gross positioning and Cartesian mode for fine control of end effector positioning. The task performed may also dictate whether the operator would prefer to use joint control or Cartesian control. Additionally, speed control is highly desirable for tele-operated control modes. Speed control mode works well for tele-operated control, but position control is necessary for automated work (pre-programmed paths). Gross movements can be done somewhat rapidly, but low speed is necessary for most fine tasks.

Lesson learned from the GAAT MLDUA Project[5]:

- The tank wall was scarified using the confined sluicing end effector (CSEE) water cutting jets operating at 6500 psi. The CSEE was held in a horizontal orientation, cutting jets toward the wall, about 6 to 12 inches from the wall. Using the arm auto joint sequence, a scarifying path was programmed for the arm to follow. Because the arm was deployed in the center tank riser, a path for the CSEE to follow was easily programmed using only the vertical positioning

[5] Glassell, R.L., et al. ORNL/CP-I 01283. 1999. Use of the Modified Light Duty Utility Arm to Perform Nuclear Waste Cleanup of Underground Waste Storage Tanks at Oak Ridge National Laboratory. Oak Ridge National Laboratory PO BOX 2008, Oak Ridge, Tennessee

mast (VPM) and shoulder yaw joint. The other arm joints were kept fixed to keep the CSEE a fixed distance from the wall. The auto joint sequence program consisted of repeating vertical paths that covered 10 to 20 degrees around the tank wall. Within minutes after starting the scarifying operation, the tank would become so foggy from the CSEE cutting jets that none of the cameras could be used to view the inside of the tank or arm, making the auto joint sequence the only safe way to operate the arm.

Sensors can be integrated into systems to assist with things like collision avoidance, positioning, and force feedback. Integrating and coordinating this type of sensor input will require both high and low level control. This would necessitate, for example teleoperation (man in the loop) from an operator station, provisions for interfacing to the incoming sensor data, and ability of the low level machine control to accept position commands from the high level control system.

However, few, if any, systems are available with any level of integrated sensors for use in unstructured environments. Sensor technology is regularly used in fixed industry applications, however there has not been enough market share in the unstructured world (not enough similar applications) to warrant vendor investment in this area. Adding sensors to systems that did not have them designed into the machine poses challenges. The integration of these types of sensors increases the controls complexity significantly, and it becomes cost and schedule prohibitive to implement. Each deployed system requires custom design and development. In addition, cables and sensors are inherently fragile and those added post-manufacture are potentially exposed to damage from collision, snagging and joint motions.

Mapping sensors and systems can also be used to try and understand details of unstructured environments. However, real time updates of changing environments becomes challenging, and likely expensive to implement.

Known obstructions in environments can be programmed into control schemes, however decisions about how a remote system completes a “work around” because of these is probably better left to the system operator.

During operations in unstructured environments, remote systems are teleoperated, except for very specific activities/functions where robotic control is necessary or clearly advantageous (reduce cost or safely increase productivity). Operationally, human control is desired (equipment safety). One example of advantageous robotic control is automated tool acquisition. However that translates to requiring that storage locations be fixed, ubilicals be completely under control, and tool alignment always correct for robotic acquisition.

Lesson learned from the MLUDA project[6]:

- Preprogramming the robotic arm worked well and helped to simplify operations. However, it is recommended that the number of robotic/computer-controlled actions be limited to only those actions that require such a degree of precision or control that programming will increase flexibility and reduce cost. Some of the MLDUA operations that should have been manually controlled rather than remotely controlled include the following:
    - Mobile deployment system (MDS) X, Y, and roll adjustment
    - VPM housing gate valve operations
    - Raising and lowering the VPM housing
    - MDS outrigger operations.

[6] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003

## *Design Considerations*

System designers need to plan for the unexpected and must incorporate system and tool flexibility to allow multiple approaches to different problems. This is to compensate for lack of information, and the vast array of uncertainties associated with remote operation. Yet, this flexibility must not translate to overly complex systems. It is virtually impossible to design a remote system that is "too simple" for use in a radiologically and chemically contaminated work environment. The designers also need to be cognizant of the human-machine interface complexities associated with the full system and all components (tools, cameras, lights, etc.).

### Equipment Modifications

Many times COTS components will be utilized in developing remote systems because they are proven, robust products. However, these components will need to be physically modified for use – to be operated "remotely" and for operational safety (speed control, etc.).

Pit viper project example. The following is a list of the modifications that were made to a standard COTS backhoe for the pit viper (these modifications were considered simple):

- The hydraulic system was filled with a mineral-oil-based non-hazardous fluid.
- Bellows were installed on all of the cylinder rods on the backhoe boom to reduce the potential for hydraulic fluid contamination.
- The machine was fitted with remote grease zerks for application of grease to the backhoe boom pivot points (while booted up in the containment tent).
- Electrically operated locking valves were installed (retrofitted) for the dipperstick and bucket curl cylinders.
- Electrically controlled locking solenoid valves were added to limit boom shifting and drooping from hydraulic leakage.
- Throttling valves were installed to slow the movements of the swing, boom, stick and bucket curl joints.
- The cab was wired for remote video display.
- Weight was added to the loader bucket and the front tires to help balance the load of the manipulator arm during setup operations when the outriggers could not be deployed.
- The machine was ordered with the optional hydraulic remote on the backhoe, and that was plumbed so that it could only operate in one direction.
- The machine was fitted with quick connectors at the base of the backhoe so that hydraulic oil to the arm could be supplied by either the backhoe or an external hydraulic power unit (HPU) using the lines supplied on the backhoe.
- The hydraulic remote line was fitted with a 3 micron filter to protect the manipulator.
- The hydraulic remote circuit was fitted with a "normally closed" valve wired into the e-stop circuit.

- The hydraulic remote was fitted with a pressure switch that was used to inform the arm control computer that sufficient pressure was available to operate the arm.

## Other Considerations

If a system is being designed for long-term use, standardization can be an important part of reducing spares, maintenance complexity, and system integration. However, desires to standardize should not constrain the true functional need for equipment (for example, more than one camera type will be needed for remote operation -- pan/tilt/zoom cameras for fine motion work and area view cameras for avoiding unplanned physical contact between equipment).

On a more micro scale, for maintenance it would be ideal for most fasteners (bolts, nuts, screws, etc.) to be the same size so that a single tool could be taken into the radiation zone for repair. However, this type of commonality of parts is highly unlikely to occur across vendors.

Standard balance of plant considerations should be made for items such as ventilation and conduit space/routing, utilities and utility redundancy, space claims (bulkheads, shielding, pumps, breakers, etc.), e-stops, hose/cable life and remote replacement, servicing equipment (filter change outs, etc), and off gassing. Evaluate the needs and space requirements for any type of sampling, and the disposition of the samples and sample holders/transporters.

Consider all ancillary equipment. Designers need to look at all the required ancillary equipment – HPUs, generators, power distribution centers, skids, pumps, containment structures, decontamination devices, water lines, sluice lines, waste lines, air lines, electrical lines, fuel and fueling devices, etc., and the affect these all impose on space, structural integrity, and safety. Often utility and other lines cross contamination boundaries. Assess heat loads on motor control centers, and assess the need for things like HPU cooling and noise abatement.

Develop an overall contamination control and decontamination philosophy. Remote decontamination will be required to keep the activity as clean as possible. What equipment can be decontaminated, and what methods should be used? High contamination levels will affect the ability to survey, maintain, and operate equipment. Design or specify equipment that is free of crud traps (nooks and other small spaces that can collect debris and contamination) and sharp edges.

Repairing the cables, hoses and connectors in a contaminated environment is a very tedious and difficult operation (i.e., in a glove box or other hot maintenance area). Design in the ability to disconnect and replace the entire hose or cable – that will significantly reduce repair/down-time of equipment. Provide waterproof potting on the back shell of all connectors to improve the resistance to moisture.

Will tools, end effectors, cameras, lights, etc. need to be wrapped or bagged in plastic? If so, this will affect aspects of remote vision, lighting, tool selection, approaches to tasks, and limit tool access (need larger access opening if arm is wrapped).

What components will be considered “disposable”?

Detailed and concise work, such as equipment assembly, is difficult to accomplish remotely. When necessary (because of space constraints for example), some amount of remote assembly of ancillary components can be accomplished. In general however, this is difficult and time consuming, and fatiguing to system operators.

## Hydraulic vs. Electric vs. Pneumatic

Manipulators are generally classified by the input energy used to produce motion. The three most common types are hydraulic, electric, and pneumatic.

Electric manipulators use electricity to drive motors and solenoids to create mechanical motion. Electric systems are typically high precision devices with excellent repeatability, but have limited load capabilities and ruggedness. Additionally, electric systems are not suitable for flammable environments, where motor arc could ignite the environment.

Hydraulic manipulators utilize a non-compressible fluid (typically oils such as Shell Tellus 32) run through a series of hoses and servo valves to exert forces on the actuators thereby producing motion. Hydraulic systems are rugged and typically have a very good payload to weight density because of the ability to transfer large amounts of force through high pressure fluid. Additionally, while pressurized, the hydraulic system is very stiff because of the incompressible fluid and therefore, is very difficult to back-drive. High precision servo valves allow for relatively precise motion and repeatability, though less than electric manipulators. Hydraulic systems require a significant amount of maintenance including fluid cleaning, leak repair, and filter replacement of the fluid transport system. Non-flammable and non-hazardous fluids are available for operation.

Pneumatic manipulators use compressed air to operate system actuators. Because the compressibility of air, most of these systems are imprecise with poor repeatability except in orientations where joint hard stops can be used for control (such as grippers that are either fully open or fully closed). Pneumatic systems lack of stiffness makes them ideal for lighter loads that can also tolerate relatively slow system response times. Pneumatic manipulators are relatively rugged like hydraulic systems, but also suffer from some maintenance issues and the requirement for fluid transport systems.

Integrated systems may use multiple types of actuators such as a hydraulic manipulator and a pneumatic or electric gripper. There are risks of mixing systems. First, additional utilities must be routed through the manipulator to supply power or air to the end effector. Second, the payload of the manipulator system may exceed the ability of the gripper to hold on to the payload. Additionally, each type of power system integrated will increase maintenance and chances of failure. If designed well, these risks can be minimized and common tool plates can be used allowing multiple types of tools to be utilized.

## Data Collection

If the system being deployed has a long-term mission, a data collection strategy should be developed. Beyond standard data collection activities, consideration should be given to maintaining historical process/operational information. There will be a significant amount of operator turnover during the life of the system, and capturing and communicating past knowledge and information will be extremely valuable. This might be thought of as an experience or process knowledge data base, and it could contain information such as what tools are effective for what tasks, and what operational approaches have been tested (successful and not) for specific challenges.

In addition, real time collection of operator functions could be considered. This might be a system for automatic tracking of system and operator information at log-in. It could include recording of information such as what tool/task was used to do what by what operator. Information like this could then be sorted to evaluate system, process and operator performance, or to focus on the root cause of upset conditions.

## *Ancillary Equipment*

In deployment of remote systems, there will typically be a tremendous amount of deployment support/ancillary equipment. This can be upwards of ten times the size/volume of the basic remote system. Figure 4 shows the ancillary equipment and footprint required to support the MLDUA during waste cleanout operations at Oak Ridge, TN.

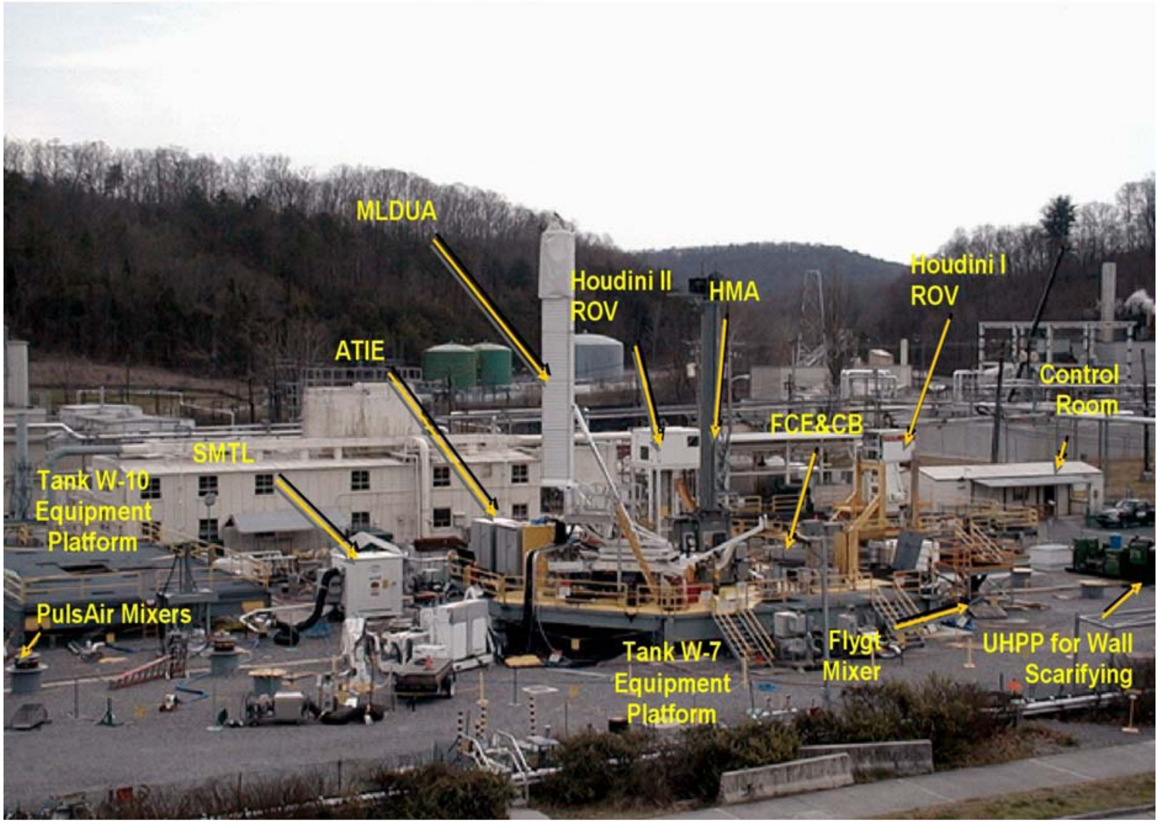


**Figure 4. GAAT MLDUA Operations during Waste Retrieval Operations in Tank W-7**

Lesson learned[7]:

- Even when commercial components are used as the core tools, there is significant time and funding that must be devoted to the systems integration part of the task. There is a tendency to think that buying a remote tool solves the deployment task. The parts do not make a whole.
    - For the GAAT project, the MLDUA and Houdini crawler were procured from commercial companies to do the tank clean out. The auxiliary systems to manage the deployment of both MLDUA and Houdini were actually more substantial than the tools themselves. Moving equipment in and out of the tank, providing containment for all systems, managing utilities to support all the equipment, and tying into the sight required a substantial investment in time and funding to properly execute.
    - For CP-5 (Argonne, Chicago Pile 5) dismantlement, manipulators and tooling were procured, but what was commercially provided did not include the deployment

[7] Mark Noakes, Oak Ridge National Laboratory, 2009.

system. A major portion of the development time went to the deployment concept, fabrication, and systems integration for the dual arm work platform (DAWP).

Lessons learned[8]:

- During tank waste retrieval operations, the addition of heavy equipment loading on the tank dome must be considered. A load-bearing platform that bridges the tank may be needed if the tank dome is not capable of supporting the load. Load-bearing platforms were successfully used by the GAAT Remediation Project to transfer the weight of required equipment to the soil around the outside diameter of the tanks.

[8] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003.

# System Integration

Beyond individual component integration tasks, there will be substantial effort required to complete system-wide integration. This includes mastering how individual components interact with each other as well as with things like process fluids and waste. It will involve things like software interlocks (timing of valve openings, etc.), and decisions regarding e-stops (how components will be included and where).

Interfaces that will need to be integrated will be mechanical as well as electrical/other utilities, and they will involve ancillary equipment, vision and lighting systems, and operators. Inadvertent interfacing must be considered, including such issues as electrical noise, electromagnetic interference, mechanical vibration, etc. Each of these interface points must be carefully managed to ensure that the systems can work together effectively when finally installed.

The system integration should also consider different failure modes. It may be desirable for a system to fail in a particular way to facilitate system removal for repair. Or, it may be desirable for the system to fail in the last known good configuration. In the case of an emergency stop, does the manipulator hold its position, or should it go limp? Should it hold onto whatever tool/object in the gripper, or let it go? Each piece of equipment should be specified with the desired behavior so that recovery conditions are predictable to the greatest extent possible.

## *Equipment Operators*

Integration efforts will address the number of operators, what their jobs are, where their work area is, if they share control over any pieces of equipment, and which other operators they work with closely, etc. Generally remote systems require multiple operators. The MLDUA, when in operation with the crawler vehicle, used up to six operators at one time. The pit viper at Hanford required three operators.

Additionally, operators should be considered early in the design phase to make the user interface as operator friendly as possible. Successful operation of the equipment is much more likely if the operators are presented with a familiar interface. If most of the operators typically run joystick controlled devices (such as a backhoe), a joystick interface may be friendlier than utilizing a space ball, touch screen, or mini master interface.

## *Tooling*

One of the most difficult integration tasks required for remote systems is tool selection, testing, and modification. Although most tools utilized are COTS devices, they generally are not useable without modification for manipulator/remote use. In fact, each tool will require unique modification to allow the manipulator to coordinate orientation and motion of the tool effectively, to avoid applying excessive force to the tool, and to accommodate reactions of the tool to varying task characteristics during the course of an operation. Even after modification, testing will show that some tools are nearly impossible to deploy remotely.

The first modification for tooling is to change the grip from a human or other machine grip to a grip suitable for a manipulator, or to add an interface plate. Several types of fixtures can be added to tools to orient them properly when the arm grips them. The most popular type of grip requires a physical handle to be applied to the tool such as a square block or a T-handle that will be easy for the arm to grip and have some orientation control. This method requires the tool to be rugged enough to bolt on this grip fixture without breaking the tool when force is applied to it. One negative aspect of this type of grip is that utilities must be managed separately as umbilical cables/hoses. These can become tangled or snagged on various other objects in the environment and also limit the tool use to a confined area. When storing the tools, similar handling challenges exist.

The most effective type of grip fixture is a robotic tool change interface plate. A tool change plate consists of two mating parts (a master plate and a tool plate) that have been designed to lock together automatically. These plates generally pass utilities (e.g., electrical signals, pneumatic supply, water, etc.) from the arm directly to the tool so that no external umbilical is required. The master side of the tool changer mounts to the arm/manipulator/robot. The tool side mounts to tooling. Tool change plates require significant engineering design and integration foresight to allow flexibility in tool selection later on. For example, if the tool change plate only included electrical power, a pneumatic tool could not be used in the future without handling an umbilical hose separately. Tool change plates allow the tool to be used anywhere within the robot work envelope and are easily transportable. Because there are no external utilities to connect, tools are easier to replace remotely. Each tool change plate is also somewhat unique for each tool because not every tool will mount exactly the same way to each tool plate. They are often custom-designed and fabricated.

Another significant issue with modifying COTS tools for manipulator use is that the arm may not be able to recreate the motion required for using a particular tool. Even non-contact tools can have their effectiveness limited by arm motion.

Several things can be integrated into the gripping fixture to improve tool performance. Compliance can be built into the fixture such that when pushing too hard in one direction, the tool still is able to align itself properly.

Replacing consumable parts of remote tools will also present various challenges. It may be very easy to change a part by hand, but doing it remotely may be nearly impossible. Tools that have nozzles and supply hoses for example, will require change out or cleaning throughout the life of the deployment. A cost benefit analysis would be needed to determine if, for example, the entire tool should be treated as consumable.

Development will be required to adapt the end effectors for remote change out. Most tooling currently relies on manual intervention (someone pulling a pin to release the tool and manually making utility connections) for tool change out.

Operator control of the tools should be kept as simple as possible. A single on/off switch for a tool is better than having several knobs and buttons that need adjustment during tool use. Although there may be instances when this is required for a particular tool, a simple operator control is generally better. It may be helpful to provide an operator control that is closely analogous to the normal controls for common hand power tools, where used.

An issue with remote tools is the logic of powering them on and off. Tools powered by draped cables are connected to their power source continuously, and it is possible to (potentially inadvertently) turn them on when they are in a storage area. Other tools powered by end-of-arm services may turn on and off in different ways, because they may use different services. A relatively simple system would use a series of toggle switches to turn different tools on and off. However, this allows the operator to turn on tools that are not currently in the gripper. It also makes it difficult to distinguish between two tools that use the same end-of-arm service. Significant design work needs to be done in this area to ensure that appropriate safety interlocks are in place and that the operator can easily and accurately activate the desired tool.

Services are often best dealt with by draping the required service lines to the tool from a wall- or platform-mounted fixture. While this requires the operator to manage the lines without having them damaged or interfere with the task, this is not too onerous compared to permanently routing these lines along an arm. Routing heavy, bulky lines along a manipulator reduces the range of motion and payload and can add unacceptably to the bulk of the arm.

If running cables down the inside of a hollow arm/shaft, that space fills up very quickly, and any flex or telescoping action will present rubbing, pinching, and other cable management issues.

In any deployment, a cable payout and retrieve system may be required, and significant effort should be focused on methods to keep cords from pinching, fraying, and knotting up; and how to deploy, coil, and replace umbilicals that are contaminated.

To improve tool effectiveness, some amount of operator feedback may be desired. This may include electrical load monitoring, force feedback, or audio. Power feedback may indicate that a tool motor is overstressed or drawing high current. Force feedback can sometimes be utilized to give the operator an idea of how much force the manipulator is applying to a tool, and help prevent the operator from damaging the equipment. Audio allows the operator to hear if too much force is applied to a tool. Adding system feedback generally translates to more complex system integration.

Tool storage and acquisition is another complex integration task. Each tool will require a storage location within the work envelope. Each tool must be oriented precisely when in the storage location to facilitate remote tool acquisition. Tools with umbilicals must avoid tangling with other tools or objects in the storage location. Tool acquisition is a difficult task to complete remotely. Most vision systems inadequately show depth, which makes acquiring tools a time consuming exercise when attempted manually. However, a combination of precisely-located tools, well-engineered interfaces to the arm, and routine controls programming can make tool exchanges a matter of a few keystrokes and a few seconds of automated arm activity.

Lesson Learned[9]:

- A band-saw-type pipe-cutting tool was successfully used to remove piping obstructions from the inside of the tank; however, improvements to allow the release of the band-saw blade when the saw is trapped are needed to improve the utility of the tool.

## *Remote Vision*

Vision systems are key aspects of remote operations. Correctly located and selected cameras are essential for successful remote operations. Conventional camera views do not provide the depth of field information required for efficient remote operations. While stereoscopic vision systems can provide this information (and allow the use of fewer cameras), all of the display methods available have shortcomings, such as operator fatigue and motion-sickness issues.

A remote system will require a number of cameras, some in fixed locations and others mounted to moving elements of the system. Managing the information from all of these cameras becomes a task-loading issue for the operator.

When the robot must bring a tool to a surface, a camera view parallel to the surface (perpendicular to the approach direction) is extremely beneficial. Simulation can be tremendously helpful with camera placement.

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[9] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003.

Camera systems are generally COTS, but options/adaptations will be required for remote use. System design integration efforts should address:

- Automatic/manual focusing and the control parameters and technology for automatic focusing. Some systems may not work well under the lighting conditions or will tend to auto focus on whatever provides the best contrast in the field of view – not necessarily what the operator wants to focus on.

- Degree of radiation hardening required, to be weighed against predicted useful life, image quality and fully burdened replacement cost of "disposable" cameras (acquisition, installation, and disposal). Cameras will fail regardless of whether they are radiation hardened or not over a long service life.

- Mounting – cameras should be accessible for replacement using some planned methods, and the mountings specified, designed, and tested to support this. Designing for quick remote change out will be important.

- Positioning – location of cameras to provide appropriate perspectives on all operations. Determine pan-tilt mount requirement for each location.

- Zoom/telephoto/macro lens focal length.

- Cable management – power, communications, with no interference with any other equipment

- Monitors and display stations

- Controllers, switches – decide which camera views go to which monitors

- Recording capability (digital video recording).

Lesson learned from the GAAT MLDUA Project[10]:

- At least two camera views are needed for in-tank operations. A single camera view does not provide the operator with an adequate depth perception to reliably operate the in-tank systems. Cameras used for monitoring interior tank operations should be equipped with adequate zoom capability to provide detailed close-up views and light sensitivity to provide views with adequate depth of field. The camera systems should be easy to install and replace. Cameras should be relatively inexpensive unless they are proven to be radiation hardened. The cameras used inside the gunite tanks suffered cumulative damage caused by overheating from the lights and radiation exposure. Rather than having a camera fail during waste retrieval operations, problematic cameras were replaced before they were deployed in the next tank undergoing remediation.

- Ensure that the camera systems can be easily positioned inside the tanks. Each camera system at the GAATs was mounted on a pole that could be vertically extended by attaching additional 6-ft. sections. A separate camera cable was factory installed inside the camera pole for convenience and contamination control.

- Ensure that the cameras are waterproof. A waterproof box with a connector was attached at the top of the camera pole so that the main camera cable could be connected from

[10] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003

outside the tank. Although this worked well, a plastic bag covering the top of the extension pole and riser was still required to prevent water from entering the connector box and the vinyl boot inside the tank.

- Use cameras that are easy to replace and inexpensive. The in-tank overview camera systems used in the GAATs were not radiation hardened but were high-quality cameras that cost ~$1K each. The total cost of each overview camera system used in the GAATs was ~$30K, which included the waterproof sealed camera module, lights, pan and tilt, extension poles, cables, and controllers. The cameras used inside the GAAT tanks suffered cumulative damage from overheating and radiation exposure, resulting in frequent repairs and replacements. On average, the camera modules were replaced about once every 6 to 12 months.

- The camera included a zoom feature with both automatic and manual focusing capabilities. This feature turned out to be important when performing tank inspections, because manual adjustments of the focus were sometimes needed to provide a clear picture of interesting tank or waste features, especially when the auto focus focused on water droplets on the lens.

Pit viper lessons learned:[11]

- The pan and tilt cameras and controllers procured for direct support of the viper system were chosen because they were compatible with existing systems used in tank farm operations and therefore thought to be good choices when planning for this application. The field performance of this equipment, however, was poor. Specific problems with the existing video system included large cabinet controllers that take up too much space at the control console. This layout made camera switching and controls cumbersome and difficult. There was also insufficient field of view for wide range viewing capability on the pan and tilt cameras, and this limited the in-tent viewing for any camera placement. Additionally, the relatively slow pan and tilt mechanisms did not perform well due, in part, because of control cables that were overly large and external to the pan and tilt. This made the cables difficult to route and made covering the mechanism for contamination control problematic.

## *Lighting*

Strategically placed lighting will be required; the ability to move, dim, aim, and turn individual lights on and off is important. This will allow the lighting to be customized to accommodate the work. It is important that the operator be able to easily manage the lighting without distraction from the main task.

Lighting is generally COTS, but most will likely require special fixturing to promote remote change out. Different types of lighting (i.e., light-emitting diode (LED), fiber, fluorescent, metal halide, etc.) may be advantageous for different positions (i.e., general area lighting versus specific task lighting versus visual inspection lighting). Remote change out may be more difficult depending on what type of lighting fixture is designed and where the light is located. Cases may exist where lighting needs to be on a pan/tilt mount to allow more precise positioning. Task lighting may need intensity control so vision systems are not blinded or to increase visual contrast. Cabling for all the lights will need to be routed out to the operator control station.

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[11] CHG-0201279, Pit Viper 241-C-104 Heel Pit Hot Deployment Demonstration Report. DP Niebuhr, CH2MHill Hanford Group, Inc., BS Mewes, Babcock Services, March 2002

Lessons learned from the GAAT MLDUA Project[12]:

- In-tank lighting systems must be compatible with the environment and the selected camera system. The two factory-standard 35-W lamps integrated into the video camera housing were not sufficient to illuminate the 25- to 50-ft-diameter tanks. Camera housings were modified to include a single 250-W lamp with a polished stainless steel reflector shield, instead of the two factory-standard 35-W lamps. Heat from the 250-W lamp, plus the position of the housing relative to the camera, caused the camera to frequently overheat. In future applications consider positioning the lights to the side of the camera and maintain enough distance so that heat generated from the lights does not overheat the camera.

- Adequate heat dissipation for the lamp housings is needed to extend the life of the cameras. As a result of the overheating problems with the in-tank camera, a heat shield was required between the 250-W lamp and camera. A heat shield was initially constructed of aluminum with fiberglass taped around it; however, because of continuing camera problems, this shield was replaced with a high-temperature plastic shield.

- Cameras can be cooled using a variety of means, including internal purges, internal fans, heat shields, or other means to dissipate the heat from high-wattage lamps. When cameras are not in use, they should be turned off or operated with reduced lighting.

## *Maintenance*

All remote systems will require maintenance, repair and possibly replacement. If the remote system is intended to be used for long campaigns over periods of years, the project will need to plan for outages for the repair/replacement of critical components. It is not uncommon for large projects to plan for regularly-scheduled outages, and planning for these can prevent critical schedule issues if a system breaks down unexpectedly. The West Valley Remote-Handled Waste Facility endured a 2-month outage in 2005 to repair a remote gantry system.

Categorizing risk and consequences, and whether to repair or replace items will greatly depend on the challenges encountered, radiation and contamination levels, how long equipment has been in use, the ability to pull the unit into a maintenance bay, glove box or containment system; and commonality of parts. In some instances, remote repair will be less expensive and faster than a complete remote replacement effort, especially if it involves a large piece of complex and integrated equipment. Cost and schedule penalties should always be considered.

Lesson learned[13]:

- Ensure that adequate tools and a maintenance area are available for camera maintenance. A glove box with the necessary tools was provided for camera repairs in a designated maintenance area. These proved essential for efficient maintenance operations.

[12] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003
[13] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003

# Testing and Training

A comprehensive system mockup will be required for testing the functionality of any large, integrated system. Selection and testing of individual tools, operator training, and task/operational planning should be done within this mockup. It is absolutely critical that all system functionality be fully tested prior to any hot deployments.

## *Cold Mockups*

There are two approaches that can be taken with regards to mockups. The first uses one set of equipment and runs it through cold testing and then deploys it. This option saves money up front. The second approach uses two sets of equipment – one dedicated to cold testing, training, upset recovery practices, and technology evolution, etc. It remains in the mockup and a duplicate system is deployed in the field. This option results in a much more comprehensive testing and training methodology, but it is expensive. However, it is advantageous, and sometimes critical for long-term, highly complex system deployments. During the operations, the mockup facility will become indispensable for things like recovery of upset conditions (potential paths forward can be tested prior to hot work), and scrubbing potential procedures for work. In addition, a system that operates for numerous years, there are going to be equipment operators that come and go, tools and equipment that will change, new technology will be discovered, and approaches to challenges will change with processing experience. All of these things will necessitate a working cold mockup while the system is in operation.

Any cold mockup design will require flexibility with regard to the ability to control equipment during tests. The cold mockup will physically need to be able to accommodate the different stages of controls-related activities within the mockup, and to be able to freely move from one mode to another in the mockup. Testing modes will include:

- Operator having line of sight visual and audio available for system testing. In general this type of testing will be used until the team is satisfied with equipment setup and operation.

- Operator having line of sight visual, and audio available, with the addition of surrogate waste movement through the system using all tools and equipment.

- Full remote operation. Isolated equipment controls location where there is nothing but remote vision and audio feedback. Full movement of surrogate waste through the system using all tools equipment.

A cold mockup facility will have additional emergency stop requirements. Normally, emergency stops are located to protect human health and safety. Because operators may have more “hands-on” involvement with operation of the test facility, there may be greater need for a system-wide (or subsystem) e-stop. It is important to keep the e-stop system simple – it is not reasonable to expect the operator to rapidly choose which of a half-dozen e-stop buttons is the correct one in an emergency situation. A thorough understanding of both the operational and cold test facilities and their operating procedures will be required to develop an appropriate emergency stop system. It may be that only a few e-stop systems would be required for a few specific subsystems or that some type of system-wide e-stop would be required. Some tools and subsystems may require substantial engineering to accommodate an e-stop circuit.

It would be advantageous to incorporate the ability for incident reconstruction in the mockup – time stamped digital video recordings of all operations to allow for reconstruction of events/accidents during testing/training in the mockup (and live operations).

## *Testing*

In addition to testing all system functionality, operational approaches will need to be developed to support remote deployments. These might include:

- Operational fine tuning – working out details such as:
  - When the end effector is used, all the cameras shake
  - Too much reflective glare for the cameras from lights shining on stainless steel components
  - Optimal configuration and operation methods
- Determine appropriate actions to facilitate recovery from upset or abnormal conditions
- Equipment replacement strategies and approaches
- Dry runs for process flow, physical interference, cross-talk, electronics cooling, network bandwidth, camera controllers, and recording capabilities
- Multiple operator communication and coordination
- Camera views for all potential activities
- Lighting for all potential activities
- Tool/end effector selection, adaptation, and testing
- Tool/end effector acquisition and storage
- Contamination control of equipment – bagging, boots, and decontamination methods, etc.
- Operational readiness review (ORR) type of activities
- Maintenance activities
- Installation and removal activities.

Lessons learned from GAAT MLDUA Project[14]:

- Thorough cold testing of all equipment and checkout of operating procedures must be done before deploying the equipment in a radioactive environment. Cold testing allows the systems to be successfully integrated and provides training opportunities for personnel in a low-risk environment.

[14] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003

- Cold testing should be performed under simulated conditions similar to the tank being remediated and with the actual systems that will be deployed in a radioactive environment. Use the same deployment and maintenance requirements, including representative lighting, communications equipment, identical platform access, and identical procedures.

- Workers should wear full personal protective equipment (PPE) during portions of the cold testing to ensure that activities can be performed within the confines of the PPE. This process also allows personnel a chance to develop specialized tools and techniques that can decrease their exposure during field operations. It is much easier to develop a solution to an equipment or process problem during cold testing than during field deployment where access is significantly limited.

Lesson learned[15]:

- Cold mockup and testing are critical parts of the overall project that take significant development time. Often techniques and hardware change significantly during cold testing. The cold test phase should not and cannot be short changed. For the MLDUA and Houdini systems used for the GAAT cleanout, cold testing showed that the management and deployment system (primarily for Houdini) was too unwieldy for operators to manage. As a result of testing, design changes were made to the deployment systems and maintenance glove boxes that greatly enhanced usability and led to a successful deployment.

Lesson learned[16]:

- Training on Rosie (a telescoping boom mounted to a large skid-based vehicle) and the DAWP yielded some interesting statistics. The overall failure rate for Rosie trainees was 40%. The overall failure rate for the DAWP was 30%. In other words over 33% of the average personnel at a decontamination and dismantlement (D&D) project will not be able to be basically trained on a given robotics/remote system. Next, out of the eventually qualified personnel, less than 30% became proficient operators in normal daily operations. Of the successful trainees, the average training time needed to basically learn the system and prove that they meet a minimal standard to continue with more advanced training was significant. For Rosie, the average qualification completion time was approximately 6 hours of reading and classroom instruction and 16 hours of run-time on the machine. For the DAWP, the average qualification completion time was approximately 2 hours of reading and classroom instruction and 6 hours of run-time on the machine. Note that this training only provided an indicator to project management that the trainee has the aptitude and motor skills to allow basic responsibilities as an operator and that they may be suitable for more training and tasks. This does not indicate that the operator will be proficient in operating all of the various end effectors; can safely, efficiently and reliably operate the system in the long-run; or has the stamina, responsibility or motivation to operate the systems on a daily basis. In our experience, this determination took an average of 2 more months to accomplish after the initial training phase, and only 10-15% of the originally available candidates became truly proficient and reliable operators for most of the tasks assigned for their performance. In addition, it took an average of 3 days per operator per tool to become proficient and reliable in the use of the end effecters designed and used at CP-5. There were eight primary end effecters utilized by the DAWP during the remote dismantlement of the reactor assembly, and they ranged in sophistication from modified crowbars to oil cooled and lubricated worm-drive circular saws. The time needed to qualify the minimum, requisite number of operators was approximately 4 months for Rosie and for the DAWP, it was approximately 8 weeks.

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[15] Mark Noakes, Oak Ridge National Laboratory, 2009.

[16] Seifert, L.S. ANL/TD/CP-96600. Robotic Dismantlement Systems at the CP-5 Reactor D&D Project, Argonne National Laboratory, Technology Development Division, 9700 South Cass Avenue Argonne, IL 60439-4841

Lessons Learned from W-320[17]:

- The fast tracking did account for a portion of the project W-320 delay. A common feature of fast track projects is the elimination of a sound engineering scale up sequence for pioneer systems. Consequences are predictable, and Project W-320 tank C-106 retrieval was not an exception. During FY 1999, about 3-1/2 months were expended troubleshooting, and a significant part of it was associated with eliminating the recurring submersible slurry pump airlock, and pump hose kinks. These pump problems occurred in a location that could be viewed with the in-tank imaging system but that was accessible only at great expense. A full-scale mockup operation simulating the full range of planned sluicing operations would have identified the issues before the system was placed in tank C-106. Mockup testing was conducted by the W-320 project, but it failed to include the full range of planned sluicing operations.

Lessons learned -- adequate cold testing of equipment and systems[18]:

- Additional cold testing and qualification of the Discflo pump should have been conducted to improve the initial success of the system in the GAAT. The Discflo pump was tested by the vendor in the presence of Oak Ridge National Laboratory (ORNL) personnel and shipped to ORNL, where it was subsequently stored for several months prior to deployment. No additional qualification or cold testing at ORNL was performed because of the modifications required at the test facilities to accommodate the pump and because of schedule considerations. On-site qualification consisted of the attachment of power leads to briefly “bump” the motor. Following this brief test, the Discflo pump was installed in tank W-9. During the initial testing and installation of the Discflo pump in tank W-9, an electrical breaker on the 480-V power supply to the pump tripped open after a few hours of operation and could not be reset. Troubleshooting revealed a problem with the variable frequency drive, which was sent to a local authorized service contractor for diagnosis. The drive had been damaged by extremely low line impedance and a current imbalance across the phases on the ORNL power system. Installation of an isolation transformer and load reactor corrected the situation.

  These problems manifested themselves during the DOE readiness assessment for the initiation of waste transfer operations and may have been identified earlier if a complete qualification and cold testing of the equipment had been performed. It is not certain, however, that the problem would have been identified simply through testing. Operation at the different locations of the GAAT and test facility implies that different electrical supply circuits were used. Thus, complete qualification must include analysis or testing of equipment for susceptibility to power supply irregularities. The timing brought the most intense scrutiny experienced during any phase of the GAAT project. At stake was the ability to transfer waste slurry from the south tank farm, which was the fundamental interest of regulators and DOE. The challenge to correct the problems was compounded by the fact the problems surfaced after the Discflo pump had been installed in tank W-9, a highly contaminated environment. The lesson learned from this situation cannot be overstated — all equipment, especially mission-critical, expensive, or long lead-time equipment, should be thoroughly cold tested and qualified prior to deployment in a hostile environment where maintenance and repair become difficult and costly.

[17] Waste Retrieval Sluicing System And Project W-320, Tank C-106 Sluicing, Lessons Learned, RPP-5687

[18] ORNL/TM-2001/149, Gunite and Associated Tanks Description and Operational Summary, February 2002, J. A. Emison, Informatics, Inc., B. B. Spencer B. E Lewis Oak Ridge National Laboratory

Lessons learned from the U-plant drain line inspection deployment:

- Design and test beyond what the information provided suggests. Conductivity probes were expected to be present in the drain line that would obstruct a straight line deployment of the crawler system. The drawing packages indicated the probes would be 1-inch pipe suspended from the top of the drain pipe. In cold testing, PNNL used 2-inch pipes to simulate the obstructions. During the field deployment, the team found that the obstructions really consisted of multiple pieces of pipe with large nuts attached at the base, making them even larger and more difficult to get around than what was conservatively tested for. A photograph of one of the obstructions is shown in Figure 5.

**Figure 5. Drain Line Robot Inspection Pipe Obstruction**

# Deployment

Physical access to the area that needs characterization/remediation/cleanup is one of the largest constraints placed on remote systems. Flexible and simple designs, redundancy, ease of setup, ease of operation (operator interface), cable management, and ability to perform failure analysis (diagnosing system or tooling problems) in the field (remotely—via cameras and audio alone), are critical design elements.

It is important to verify access dimensions and physical characteristics. Drawings are often out of date or not “as-built”. The Remote Tank Inspection Project failed upon installation because the installation riser was smaller than the system designers realized.

A lot of remote systems work is actually preparation work to get the system installed so that it can perform the mission. Here are some examples of highly constrained access issues encountered in recent deployments:

- The U-plant rail tunnel characterization deployment was constrained by a 22-inch hallway with one 90 degree corner right before the contamination boundary. Every component, including the robot and lifting and deployment platform had to be designed for transport through the hallway.

- The U-plant drain line inspection deployment was constrained by the same 22-inch hallway, and the actual drain entrance was 27 feet under deck level in a water-filled pit. This entrance was severely constrained by objects protruding from walls of the cell.

- The Materials Open Test Assembly (MOTA) Project required that the remote arm be installed into a standard 10-inch mechanical manipulator port in the hot cell wall.

Lessons Learned[19] :

- In-tank radioactive waste retrieval operations are highly specialized and unique. The design process should specify the use of proven high-quality equipment whenever possible, rather than one of a kind or cheaply made systems. Design and manufacture the equipment to be as rugged as possible to avoid mechanical problems and to withstand the harsh environment inside the waste tanks and the sometime rough handling during installation, removal, and operation. It was not uncommon for the equipment being inserted or withdrawn from the tanks to be dragged against the tank risers or to have protrusions hang on entrance or exit from the tanks.

- Design the equipment to withstand a harsh environment. Some equipment will be more vulnerable to radiological and chemical damage than others. If a piece of equipment must be deployed and retracted frequently to minimize exposures, incorporate a trade-off evaluation to determine whether it will be more cost-effective to design the equipment for prolonged exposure than to spend the time required for frequent deployments and retractions.

- Seals on all equipment contacting the waste should be designed to withstand the harsh chemical and physical characteristics of the wastes. The abrasive nature of the waste caused excessive wear on the seals on the CSEE. As the seal wore, the vacuum at the CSEE inlet was reduced and pumping efficiency decreased.

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[19] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003

- All systems should be designed for reliability to ensure sufficient availability to meet the project schedule and to avoid costly downtime for repair. Designs should be modular and permit subassembly replacement to reduce the repair time and avoid personnel exposure to contamination or harsh environments. Use redundant systems, when possible, to minimize downtime for repairs. For example, the CSEE and the jet pump could be operated with identical high-pressure pumps. This provided flexibility in operations in the event that one pump failed and also reduced the spare parts inventory.

- Consider freeze protection when designing systems that handle water. For long-term projects or short-term projects conducted during the winter months, all piping and equipment systems should be self draining and have clearly defined procedures for freeze protection. Use hard rubber seals whenever watertight seals are needed. This type of seal necessitates using rigid panel frame designs. Hard rubber seals retain their flexibility and resist absorbing liquid contaminants better than foam sealing or expanded rubber materials.

- The containment system should be designed to minimize overspray from decontamination systems. Water spray and splash from the decontamination spray ring (DSR) made sealing the 20-inch in diameter bag-out port (located in the tether management and deployment system (TMADS) containment bezel) very difficult. Because of a poor seal design, the port had to be cleaned and decontaminated before a polycarbonate window could be installed to provide additional light for workers. Ensure that tank access is sufficient to allow deployment of the selected retrieval system components with relative ease. In waste tank applications, access risers must be large enough to allow easy deployment and maneuverability of equipment. Separate risers are needed for each piece of equipment to be installed inside the tank.

- To increase the visibility of equipment during waste retrieval operations, paint in-tank equipment with bright colors that provide high visibility and contrast in the tanks. Visibility is limited during operations that generate a fog/mist. Reflective tape can also be used to make equipment more visible in high-fog conditions. This was used very successfully with the linear scarifying end effector (LSEE) so that operators could verify that the nozzles were moving appropriately. In-tank visibility can also be improved by using indirect lighting during high-mist- or fog-generating operations. Additional light sources, installed perpendicular to the camera view, may also be used to provide indirect lighting and cast shadows to aid in depth perception.

- Provide lights and cameras inside the equipment containment structures to monitor equipment deployments or retractions and to provide additional views for equipment operators. For example, an additional camera installed in the hose management arm's containment structure could have provided visual feedback if a leak was to occur in the waste transfer line.

## Equipment Failures

Deployed remote systems will have equipment and component failures. All hoses, connectors and cables will be prone to damage, and it is common to have hydraulic leaks, electrical/electronics problems, and cable handling issues. Remote systems are highly susceptible to operator abuse. It is recommended that critical spares be identified and kept on hand at all times during a deployment.

If using hydraulic manipulators:

- Do not use water glycol hydraulic fluid. It is environmentally acceptable, but it causes damage to internal hardware (the fluid is conductive and corrosive to the electrical cabling and connectors used for servovalves and sensors). Any hydraulic leak of this fluid causes serious problems.

- Use mineral oil hydraulic fluids. Do not use conventional petroleum-based hydraulic fluid.

- Keep fluids pristinely clean

- Filter, flush and test fluids often

General Field Problems and Equipment Failures from the MLDUA[20]:

- The inlet screen on the CSEE was easily plugged by waste and debris. Back-flushing was not as effective as originally anticipated. In addition, the back-flush operations added a significant volume of water to the system.

- Rotation of the nozzles on the CSEE was occasionally interrupted by loose debris such as rags, tape, and rope. The design should be improved to either better protect the rotating nozzles or allow for easier debris removal.

- The primary and secondary contamination-prevention boots both required replacement. The primary boot was replaced because of tears in the boot. The secondary boot was replaced several times because of tears, significant contamination, and when oil leaks had sufficiently dirtied the boot. An O-ring seal in the wrist pitch joint failed twice causing significant downtime. The VPM encoder cable was separated from the guide pulley because of interference with a camera cable.

- Worker exposure during maintenance and operations that require access to contaminated in-tank equipment can be an issue for worker safety. To mitigate this, decontamination spray rings are used to remove waste during equipment removal, and all “hands on” work is done through glove ports in containment devices.

- Use vinyl boots to protect the camera equipment. A 2- to 3-inch rubber polyvinyl chloride (PVC) pipe coupler was attached to the vertical extension pole above the camera head using hose clamps. This technique was used to secure a vinyl boot, which was taped at the coupler and at the top edge of the aluminum camera adapter to keep the vertical extension pole from becoming contaminated. When a camera was removed from the tank, the boot was peeled inside out to contain any contamination, and the excess was cut off and properly disposed of. A new boot and coupler were installed on the vertical extension before the camera was returned to the tank.

- The MLUDA was deployed in numerous tanks. The following problems were noted by logbook entries during waste retrieval operations in tank W-6[21]:

    - A software problem with hose management arm control system caused erratic movement of the arm.

    - Hydraulic fluid leaks on the track drive motor for Houdini I remotely operated vehicle (ROV) occurred. The leaks were repaired and the Houdini I returned to service after 3 days of downtime.

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[20] ORNL/TM-2001/142/V1. The Gunite and Associated Tanks Remediation Project, Tank Waste Retrieval Performance and Lessons Learned, September 2003
[21] The MLDUA was deployed into 9 waste tanks, with multiple riser deployments per tank, over a period of more than 3 years. Tank W-6 was the third tank the system was deployed in.

- A jet nozzle on the CSEE became clogged. The jet was unclogged and operations continued after 1 day of downtime.

- Problems with the hose management arm cable bundle delayed completion of sluicing operations.

- Sludge caked onto the CSEE and wedged between the rotating and stationary components. Removal of the caked-on sludge did not completely alleviate the rotational problems for the CSEE but did allow continued operation and the completion of sludge removal operations.

- The manipulator arm on the Houdini II failed as a result of a water leakage into the tether termination on the Houdini II. The tether could not be repaired and had to be replaced. An improved sealing and termination system is needed.

- During the initial deployment of the Houdini II, several minor hydraulic system leaks developed.

- Frame bolts and manifold plugs on the Houdini II periodically had to be inspected and tightened.

- At a ultra high pressure pump (UHPP) operating pressure of 25,000 psig, the MLDUA shoulder yaw joint faulted, necessitating operations of the gunite-scarifying end effector (GSEE) at pressures <20,000 psig. Lateral force limitations must be considered when designing and operating high-pressure scarification equipment. Operating limits for the MLDUA design were calculated and verified during use of the gunite-scarifying end effector with the UHPP.

- The MLDUA began experiencing signal problems in its main cable bundles, which eventually led to the partial loss of movement in one DOF. The system lead worked around the signal problems to the greatest extent possible to keep the system operational.

- To reduce unnecessary wear and tear on the MLDUA and to avoid likely downtime, high pressure wall-scarifying operations were discontinued.

- Operations were temporarily halted when a hydraulic fluid leak developed at the base of the VPM for the MLDUA.

- When attempts were made to retract the LSEE from the tank, loops in the supply hoses for the LSEE jammed the MLDUA. The limited size of the riser would not permit both the MLDUA and LSEE hose loops to pass. No quick repair for the LSEE could be identified, so it was abandoned in place to avoid adversely affecting the remediation schedule.

- The CSEE nozzles were inadvertently plugged with sludge during deployment when the water feed to the nozzles was turned off. Manipulating or pulsing the water pressure and cleaning with the DSR were used to clear the obstruction. Such trial-and-error methods were often used to clear plugs or free the rotation. Direct hands-on repair of problems in which the precise cause could be identified, was the method of last resort because of the cost, time, and potential radiation exposure to personnel.

- In the future, it would be better to mount the MLDUA umbilical tethers in cable carriers that could take the strain of the tether motion and tension, rather than placing the signal-carrying cables under tension.

Lessons learned[22]:

- Two problems developed in the MLDUA system during operations in tank W-3. The first problem was a hydraulic oil leak within the utility arm. The second was a failed position sensor for the inner VPM tube.

  The wrist pitch hydraulic servo control manifold developed an oil leak in one of the fittings to the hydraulic piston. The first indication of a hydraulic oil leak was that the wrist pitch joint drifted when the joint was locked. The second indication was the presence of hydraulic oil inside the clear second boot. The utility arm was immediately removed from tank operations. The utility arm was deployed inside a contamination control bag on the W-3 platform outside the tank riser interface containment (TRIC). The utility arm was decontaminated, and repairs proceeded outside the contamination bag. The cause of the leak was a bad “O” ring, which was replaced. After a hydraulic pressure test, the utility arm was returned to service. Within a few days of operation, the same hydraulic oil leak returned. Utility arm operations continued for about 1 week before the utility arm was again removed from tank operations for repairs. The cause of the oil leak was found to be in the same hydraulic fitting in which the “O’ ring failed. Further investigation determined that the hydraulic fitting components were incompatible with each other. The hose end fitting was modified to accept the “O’ ring and form a seal. Since the second repair, this hydraulic fitting has not leaked. Approximately five gallons of hydraulic oil leaked from the fitting during the week of utility arm operations. All of the hydraulic oil except approximately 1-quart was captured inside the secondary boot. The lost oil leaked into the tank. The gripper end effector (GEE) camera was found to be damaged during the first leak, and the camera was replaced during the second leak repair. The MLDUA system was out of service for a total of 2 weeks to perform all repairs.

  Also during tank W-3 operations, the inner VPM tube reel position sensor tracking cable jumped out of its guide pulleys. The reel position sensor works like a retractable tape measure. When the tracking cable jumped out of its pulleys, the tracking cable became jammed in the pulleys. The inner VPM tube position information needed by the computer was lost. Repairs consisted of returning the tracking cable to the guide pulleys. The camera cable for the VPM mast cameras was attached to the outside of the umbilical cable. This cable formed a loop outside the boundary of the umbilical cable because of umbilical cable motion. This loop had knocked the sensor tracking cable off the pulleys. The loose cable was fastened back to the umbilical cable, and no further problems with the pulleys have been observed.

Equipment failures encountered with the pit viper system:

- Gripper failure
- Hydraulic actuator electronics failure
- Hydraulic actuator catastrophic mechanical failure (manufacturing defect)
- Linear velocity displacement transducer (LVDT)/cam feedback failure (rotary potentiometer read by an LVDT board)
- Unstable software
- Electronic board overheating.

[22] Glassell, R.L., et al. ORNL/CP-l 01283. 1999. Use of the Modified Light Duty Utility Arm to Perform Nuclear Waste Cleanup of Underground Waste Storage Tanks at Oak Ridge National Laboratory. Oak Ridge National Laboratory PO BOX 2008, Oak Ridge, Tennessee

Pit viper lessons learned/experience[23]:

- Have common connector types
- Force reflection could be advantageous
- Specify that the arm be able to be flushed without opening it up
- Touch screen camera selection would be nice at the human machine interface
- It is not fruitful to boot the gripper – just assume it will get contaminated
- Gripper extend/retract axial DOF or Cartesian mode needed
- Stereo vision would have been useful
- A positive means of gripper control, available on some systems used in other remote industry applications (e.g., blocking valves), is necessary for the tank farm environment to prevent the loss of the gripped object during all possible upsets.
- Some electric power for operating the equipment was provided from the control trailer, but much of the support equipment needed in the farm was powered from available power sources within the tank farm. This cannot be relied on consistently for future deployments because each tank farm has a widely different layout and available power. For this reason, providing power from the control trailer to the farm for all activities and equipment associated with the deployment is both desirable and necessary.
- For grippers – specify the ability to grip items with the jaws nearly completely open as well as fully closed.
- Specify gripper position/velocity/closing force
- Specify that gripper has a design factor > 1.0 at operating pressure.  At operating pressure, stresses should not exceed 75% of yield strength of the material.

[23] CHG-0201279 Pit Viper 241-C-104 Heel Pit Hot Deployment Demonstration Report, DP Niebuhr, CH2MHill Hanford Group, Inc., BS Mewes, Babcock Services, March 2002

# Appendix A

# PNNL Background

# Appendix A.  PNNL Background

The PNNL Mechanical & Robotic Systems Team has a long history of remote systems work that spans from cutting edge robotics research through deployments of large integrated remote systems in radioactive and chemically hazardous environments performing mission-critical tasks. The team is experienced in designing, adapting, integrating, deploying and operating robotic/remote systems and possesses a critical understanding of radiation, contamination, and other hazardous environments.  The following is a brief listing of remote systems work completed recently by the team.

Hanford deployments:

- Robotic crawler deployment in the Z-9 crib for structural inspection.
- Remote arm deployment into the 324 building Shielded Materials Facility (SMF) for MOTA sample retrieval.
- Robotic deployments in the 325 building High-Level Radiochemistry Facility (HRLF) A, B and C tank vaults for inspection and characterization.
- Pit viper manipulator system deployed for cleanout and refurbishment of tank pits.
- Robotic crawler deployment for visual inspection of structural integrity, characterization, and collection of samples from the interior of the 250-foot U-plant railroad tunnel.
- Robotic crawler deployment for visual inspection of structural integrity, characterization, and collection of samples from the interior of the 800-foot U-plant ventilation tunnel.
- Robotic crawler deployment for visual inspection, characterization, and collection of samples from the 800-foot U-plant subterranean drain line.
- Remotely operated annulus inspection vehicle for nondestructive examination of the knuckle region of double shell tanks.
- Light duty utility arm (LDUA), design, integration, testing, controls, end effectors development.

Other deployments/bodies of work:

- Waste retrieval system developed for the International Atomic Energy Association (IAEA), Baghdad, Iraq, for use by nuclear weapons inspectors to remove uranium from an underground storage tank.
- Hanford M-91 remote-handled transuranic (RH-TRU) waste processing facility.  Provided remote systems expertise for development of the M-91 facility, including development of process layout and flow, remote equipment selection, identification of technology development needs, and testing and mockup requirements.
- Long reach arm technology development program.  Integration and testing of system dynamics, flexure control, tooling and operability.
- Waste retrieval and characterization end effectors developed:
    - Hanford, C-106 heel removal, waste retrieval end effector

- Oak Ridge, gunite tank sludge retrieval, confined sluicing end effector
- Idaho, high level waste tank cooling coil cleaning end effector
- Hanford, high pressure waterjet scarifier
- Fernald Silo Retrieval Project:
    - Gripping end effector and sluicer
    - Video and lighting system
    - Waste conveyance jet pump
    - Waste retrieval end effector

- MLDUA support, GAAT Project, Oak Ridge, TN
    - Annular manifold jet pump
    - Hose management.