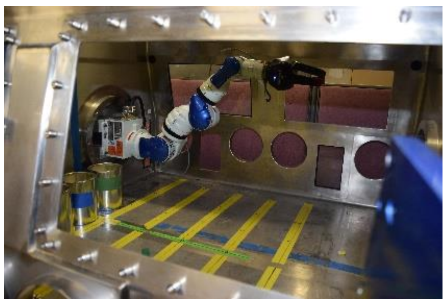
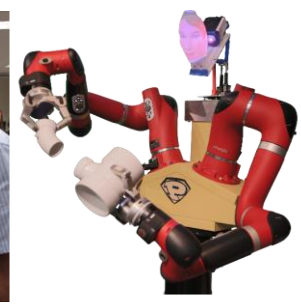
State-of-the-Art of Robotic Handling of High-Consequence Materials – Nuclear Waste

The results of a workshop series funded jointly by the National Science Foundation and the Department of Energy/Environmental Management





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ACRONYMS

AMWTP	Advanced Mixed Waste Treatment Project, Idaho National Lab
CAM	Continuous Air Monitor
CoE	Center of Excellence
COTS	Commercial Off-The-Shelf
CPS	Cyber-Physical Systems
DOE	Department of Energy
DST	Double-Shell Tank
DWT	Double-Wall Tank (same as DST)
HCM	High-Consequence Materials
HEPA	High Efficiency Particulate Arrestance – air filters
HLLW	High Level Liquid Waste
INL/INEL/INEEL	Idaho National Lab
IRID	International Research Institute for nuclear Decommissioning
JAEA	Japan Atomic Energy Agency
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
MARS	Mobile Arm Retrieval System – robotic tank cleaning system
NASA	National Aeronautics and Space Administration
NDA	Nuclear Decommissioning Authority, United Kingdom
NDE	Non-Destructive Evaluation
NNL	National Nuclear Laboratory, United Kingdom
NSF	National Science Foundation
ORP	Office of River Protection, Hanford
OSTP	Office of Science and Technology Policy, White House
PCV	Primary Containment Vessel
PFP	Plutonium Finishing Plant
PNNL	Pacific Northwest National Laboratory
PORTS	Portsmouth Gaseous Diffusion Plant
ROV	Remotely Operated Vehicle (often underwater vehicle)
S/C	Suppression Chamber
SLAM	Simultaneous Localization And Mapping
SRNL	Savannah River National Lab
SRS	Savannah River Site
SWT	Single-Wall Tank
TRL	Technology Readiness Level
TRU	TRans-Uranics – elements with atomic weights beyond uranium
UAV	Unmanned Aerial Vehicle

INTRODUCTION

This report is part of a larger effort to explore the implications robotics can play on the handling of high-consequence materials to meet the needs of the Department of Energy, Office of Environmental Management (DOE-EM). The safe, expedient, and cost-effective handling of nuclear waste, as an example of a "high-consequence material," is of primary interest to the DOE-EM and is the focus of this report. However, this information was gathered as part of a larger effort involving NSF, NASA, OSTP, and the DOE to look not only at specific examples, but to see what commonalities exist between the handling of various types of high-consequence materials, the possible mishaps that can occur, improved testing and estimation of low-likelihood events, and the best steps to take to avoid negative consequences of extremely rare mishandling events.

This report represents the combined opinions of a group of government and academic experts on robotics and automation based on several visits to a variety of government and academic facilities in the United States and abroad that handle nuclear materials, study the handling of nuclear materials, either in the normal course of operations or in response to emergencies. The expert group visited a hand-picked list of important sites in the United States and in foreign countries with close ties to the US nuclear materials complex. The list of sites selected was not intended to be exhaustive, but representative of some of the most difficult environmental problems created by enriched nuclear materials processed and stored in the US along with some of the most innovative solutions to handle such materials explored by developers of robotic systems.

The specific sites visited include Sellafield and its related facilities in the UK; the Waste Isolation Pilot Plant (WIPP), Idaho National Lab (INL), the Hanford Site, the Savannah River Site (SRS), the Portsmouth Gaseous Diffusion Plant (PORTS), NASA Johnson Space Center (JSC), University of Texas at Austin, Texas A&M University, and Southwest Research Institute (SwRI) in the US; Tohoku University, Toshiba Corp, University of Tokyo, International Research Institute for Nuclear Decommissioning (IRID), Mitsubishi Heavy Industries, Kyoto University, Hitachi Ltd, and the Naraha Remote Technology Development Center in Japan; and the ISOFIC Conference, Korea Atomic Energy Research Institute (KAERI), the Ministry of Science and ICT in South Korea. In addition, several members of the team attended or participated in the finals of the DARPA Robotics Challenge.

This study resulted from a pair of proposals created by Purdue University and funded by the National Science Foundation (NSF) and DOE-EM, respectively, to study various aspects of the handling of high-consequence materials and the implications to the science of safety. The lead author of this report and also the principal investigator (PI) for the two studies was responsible for the formation of the various groups of experts that took part in this study, in consultation with the project sponsors. The selection of DOE sites to visit was coordinated with DOE project sponsors. The opinions expressed represent the opinions of the expert study group participants and not the opinions of the NSF or DOE-EM.

What this document is intended to do:

- Survey efforts around the world to use robotics to handle high consequence materials and to compare the state-of-the-art in the U.S. with the state-of-the-art elsewhere
- Support internal DOE dialog concerning the use of robotics to address current and future DOE/EM needs.
- Provide conclusions that give guidance for future roadmapping efforts, but essentially culminating with a set of talking points supported by the observations made at the sites visited.
- Provide a relatively concise summary of the problems identified at the sites visited to ascertain which identified problems may (or may not) be addressed by robotics or automation.
- Propose opportunities to build on the robotics and automation efforts completed or ongoing at the labs, by identifying opportunities to integrate commercial and academic capabilities (as well as other efforts across the DOE complex) to meet future needs.

What this document is not:

- It is not a roadmap document.
- It is not a document that criticizes existing efforts.

To create this document, 45 experts in US and 10 experts from Japan, France, Korea, Sweden, UK, Spain, and Italy were variously assembled to participate in a series of site visits, workshops, and conference calls. International participation was particularly important because the unique nature and infrequent occurrence of exposure events make it desirable to gather the most pertinent experiences from around the world.

This introductory section will briefly define what we mean by High Consequence Materials (HCM) and summarize the priorities related to HCM as we understand them for each interested national agency before outlining the basic structure of this document.

2.1. High Consequence Materials: Definition

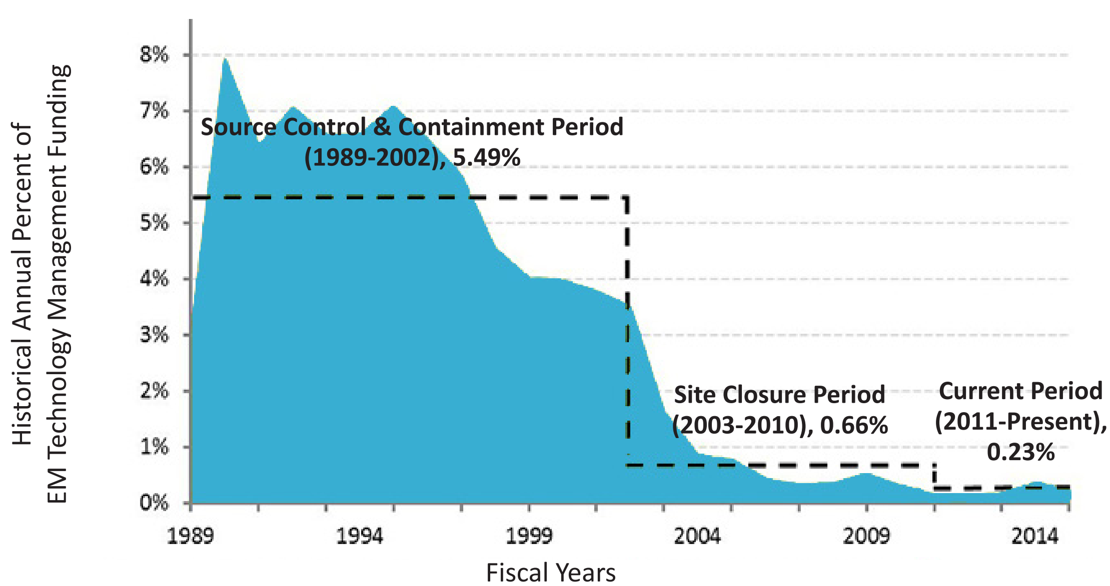
High Consequence Materials (HCM) are materials that if released into the environment in an uncontrolled manner, might cause damage or harm to people, animals, and the Earth itself. Examples of such materials include nuclear and chemical waste, biological contagions for which there is no cure (i.e. the Ebola virus), or even return samples from outer space that may harbor unknown compounds or life forms.

The chance of contamination of the general public by any of these materials is extremely small; however, there are professionals that are exposed to these types of dangers on a regular basis. Since these professionals must handle these materials, it is paramount not only for their safety, but for the safety of the general public, to take extreme measures to ensure that any and all possible mistakes are minimized and contained.

2.2. DOE History of Funding for Technology and Development

The Department of Energy had a long history of funding robotics and high-consequence materials funding in the 1980s and 1990s. Robotics for handling nuclear waste was a priority that supported work in multiple national labs (Sandia, Los Alamos, Oak Ridge, Pacific Northwest, Idaho and Lawrence Livermore) as well as some extramural funding. This work had a strong emphasis on manipulation and control and established a baseline of competence within the national labs and the R&D sector.

Around 2002, a strategic shift in funding occurred as DOE put high emphasis on closing many of the hundreds of facilities around the country that were heavily contaminated, but had long since been mothballed. During this strategic shift, many sites, such as Rocky Flats, were finally cleaned up and returned to civilian uses after languishing for decades on the EPA Superfund list. These facility clean ups were made possible by the decades of research and development on advanced technologies of the 80s and 90s, but an unfortunate result of the mission-shift was a similar funding shift that slashed funding for technology and development (see Figure below).



2.2.1. DOE-EM ROBOTICS CROSS-CUTTING TECHNOLOGY PROGRAM

As an example of the extent of technology development programs that existed prior to 2002, the Robotics Cross-cutting Technology program (RBX) was created by DOE-EM in the 1980's to support the remediation mission. The purpose of the RBX was to support DOE sites with specific projects to reduce the barriers inhibiting the use of robotics and remote systems technologies to reduce costs and hazards in the completion of long-term remediation projects. The program was organized and led by DOE national laboratory technical staff in concert with academia and industry. During its prime years, the RBX was one of the largest robotics programs in the US and produced both practical solutions to EM site projects, as well as spearheaded basic robotics research and development in key areas. To assure relevance and correct prioritization of all activities, the RBX technical agenda was crafted in concert with the EM sites.

The core technical leadership and expertise for the RBX was obtained through technical staff at specific national laboratories and sites with established capabilities in robotics and remote systems. RBX teams addressing specific EM technical focus areas (FA's) from a robotics perspective were expected to become integrated with the broader focus area teams within the Office of Science and Technology (OST). The RBX technology areas paralled the OST FA's and consisted of: buried wastes, underground storage tanks, mixed wastes, remote analytical chemistry, and basic robotics cross-cutting technologies. Each of these areas was led by a national coordinator (selected from the RBX senior team members) who was responsible for assuring that focus area/site needs/priorities were incorporated, establishing project teams across the sites, national labs, universities and industry partners.

2.3. Document Guide

This section summarizes the background and motivations for the DOE and NSF to organize site visits and workshops related to the science of safety for high consequence materials. Section 3 condenses and summarizes the key observations made from each of these sites visits which included:

- Stellafield, UK (April, 2015)
- Waste Isolation Pilot Plant (June, 2015)
- Idaho National Laboratory (August, 2015)
- Hanford Site month, (August, 2015)
- Savannah River Site, (December, 2015)
- Tohoku University, Japan (April, 2016)
- Toshiba Corp, Japan (April, 2016)
- University of Tokyo, Japan (April, 2016)
- International Research Institute for Nuclear Decommissioning, Japan (April, 2016)
- Mitsubishi Heavy Industries, Japan (April, 2016)
- Kyoto University, Japan (April, 2016)
- Hitachi Ltd, Japan (April, 2016)
- Naraha Remote Technology Development Center, Japan (April, 2016)
- NASA Johnson Space Center (July, 2016)
- University of Texas at Austin (July, 2016)
- Texas A&M University (July, 2016)
- Southwest Research Institute (July, 2016)
- Portsmouth Gaseous Diffusion Plant (August, 2016)
- ISOFIC Conference, Gyeongju, Korea (November, 2017)
- Korea Atomic Energy Research Institute (November, 2017)

- Ministry of Science and ICT, Korea (November, 2017)

Some the findings and recommendations of this report were drawn from the additional experiences of the participants from across the DOE complex, similar facilities abroad, and other national institutions who handle high-consequence materials. Participants are listed in the respective subsection for each site visit. Section 4 cannot provide a comprehensive summary of all the possible locations from which we could draw from this report, but does summarize key observations from selected sites, listed above, that are not part of the DOE complex (international sites and U.S. non-governmental facilities). In Section 5, we recognize that many external factors should be accounted for in our final analyses and any such factors are documented here. Finally, Section 6 presents the key findings and recommendations of the participants for consideration by the sponsoring agencies.

DOE SITES VISITED

Enriched nuclear materials are the largest single type of high consequence material that this team is concerned with and these are materials of high national importance. DOE has stewardship of the vast majority of these materials in the US and we chose to examine the sites of greatest importance to the DOE and with the longest term impacts on DOE goals and operations. Those sites include the Waste Isolation Pilot Plant (WIPP), the Hanford Site (Hanford), the Savannah River Site (SRS), and Idaho National Lab (INL). The WIPP was chosen because it is the only designated permanent storage facility for high-level nuclear waste in the United States and because it had a recent critical incident that resulted in an extended shut down. Hanford was chosen because it is the largest site in the DOE portfolio (40% of all the waste Curies of the US are at Hanford) and includes the largest high-level waste re-processing facility in the world. Savannah River was chosen because it is the second largest site in the DOE portfolio and includes the greatest variety of waste types and sources. Finally, INL was chosen because of its proximity to Hanford and the complexity of the calsine waste.

Figure 3.1: Geographic distribution of sites of interest to DOE for enriched nuclear materials.

It was decided that a team of robotics and nuclear experts, primarily from academia and government, but with representation from the private sector, be recruited as a complement to the national expertise that already exists at the national labs. Therefore, national lab employees were initially excluded from the DOE site visits, but team members with former national lab experience were included through a combination of targeted recruitment and open invitation. Subsequent trips to non-DOE sites in the US and abroad included current national lab employees. The primary group focused on the Savannah River Site, due to the variety of needs and opportunities it presents. A smaller subset of the team visited Hanford and INL to report back to the larger group. The WIPP was visited only by the lead PI.

In addition to the important national sites, it was deemed valuable to make occasional assessments of international sites and capabilities. The United Kingdom is an excellent candidate for such visits because they were a strategic partner in the early development of enriched nuclear materials during World War II and face many of the same types of problems that the US does, on a smaller scale. Japan is a strategic candidate because of the Fukushima Daiichi incident and the existing close collaboration the US has with the Japanese government and academic labs in response to that incident.

3.1. Summary of WIPP Visit

The Waste Isolation Pilot Plant (WIPP) is a long-term storage facility deep underground in the salt mining area near Carlsbad, New Mexico, USA. An unfortunate combination of mishaps closed the plant for investigation and clean-up after a release of radioactive material occurred in February of 2014. First, on February 5, 2014, a fire on a salt truck in the underground mine caused an accident investigation that temporarily closed the storage facility. While this was a typical industrial accident that posed no danger to persons outside the facility, less than two weeks later, airborne radiation was detected some 700 meters from the location of the salt truck fire by a continuous air monitor (CAM) in the mine. Multiple CAMs eventually indicated a plume moving through the mine, but nobody was in the mine at the time and the lack of diagnostic infrastructure or robotic tools for investigation limited options: it was known that a radiation cloud was traveling through the mine, making it unsafe for humans to enter, but no further information was available on the cause or precise location of the problem nor the risk to people or other materials in the mine. After more than a month of uncertainty, it was determined that a single canister ruptured in the deep cavern of Panel 7. It was determined that the canister had been packed with improper filler material prior to shipment to the WIPP and other canisters were subject to the same issue.

The salt truck whose brake/wheel caught fire on February 5, 2014.

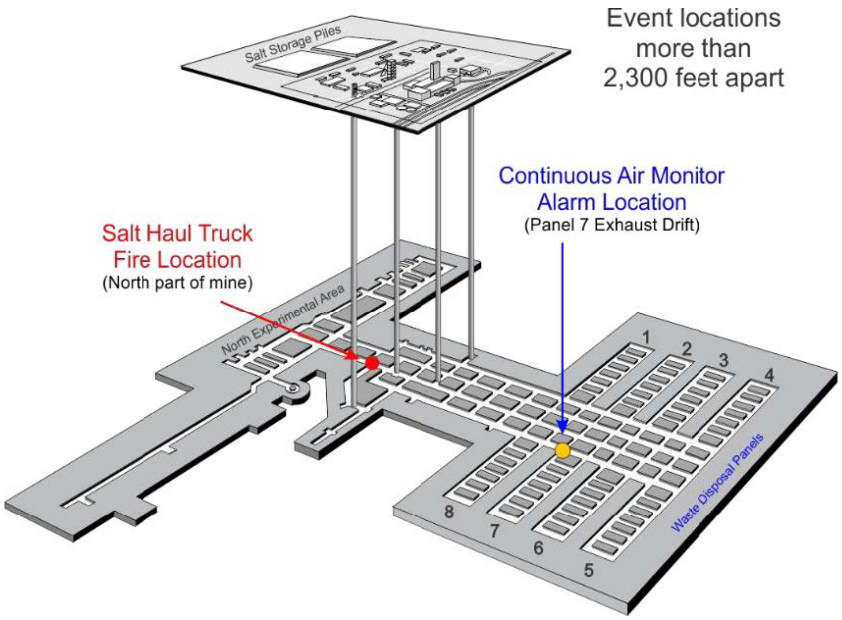
3.1.1. SALT TRUCK FIRE

The salt truck fire of February 5, 2014 is detailed in an Accident Investigation Board report issued March 13, 2014.

An image of the ruptured canister that released radiation on February 14, 2014.

3.1.2. RUPTURED STORAGE DRUM

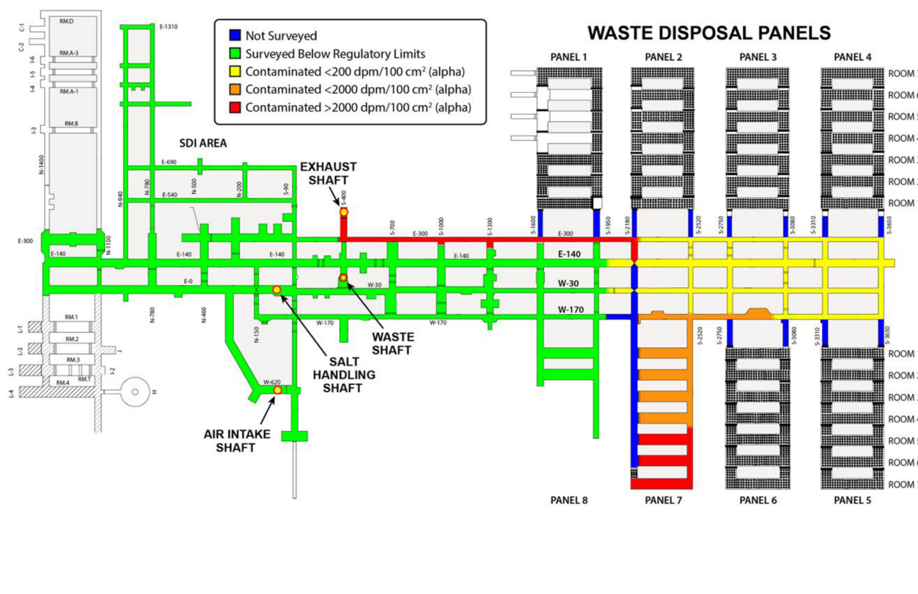
The continuous air monitor in the exhaust draft of panel 7 first detected airborne radiation on February 14, 2014. At this time, the mine was already closed for the salt truck accident investigation, so minimal information was available to interpret the incident. The WIPP's ventilation system automatically switched to filtration mode, and all exhaust air was re-directed to a bank of HEPA filters on the surface of the facility. This prevented the release of radioactive material to the surface (though a small amount was released due to tiny leaks in the exhaust shaft and dampers), but effectively cut the air circulation down to about 65,000 CFM, significantly below normal operating capacity.



Locations of the two incidents in February, 2014.

With airborne radiation floating through the facility, and virtually no information on what had happened nor what might happen in the immediate future, humans were not permitted to re-enter the mine for about a month. Exhaust air was being filtered through the HEPA filters on the surface, but no maintenance was being undertaken in the mine. Re-bolting became a key concern as the mine is constantly deteriorating without regular maintenance. The volume of air flow determines the total amount of work that can be accomplished underground, so with all the air circulating through the HEPA filters continuously, the reduced flow dramatically curtails operations in the mine.

Bolting in uncontaminated areas, a critical periodic maintenance step, resumed in November, 2014.



3.2. Summary of the Idaho National Lab Visit

The Idaho National Lab (INL) was originally a remote testing outpost of Argonne National Lab, and has undergone a number of name changes throughout its history. It was named the Idaho National Engineering Lab (INEL) in 1974, the Idaho National Engineering and Environmental Lab (INEEL) in 2007, and the INL in 2015. It is currently operated by Battelle Energy Alliance, LLC under contract. As a testing facility, it has had a total of 52 nuclear reactors of various types within its borders and now hosts four operational reactors, all of which will face decommissioning and demolition at some point.

The INL tour focused on a few specialized facilities with unique problems. These include the Underground Storage Tanks (UST) and Integrated Waste Treatment Unit (IWTU), the Calcine Solids Storage Facility, and the Advanced Mixed Waste Treatment Project.

3.2.1. UNDERGROUND STORAGE TANKS AND INTEGRATED WASTE TREATMENT UNIT

INL has a total of 11 underground storage tanks that have held waste (one additional tank has never held waste), but these are not a particularly difficult problem for INL. Unlike Hanford or Savannah River, they are constructed of stainless steel and are less susceptible to corrosion and leaking. The largest of the tanks is 300,000 gallons, but eight of the eleven tanks have already been emptied, cleaned, and closed, as of 2016.

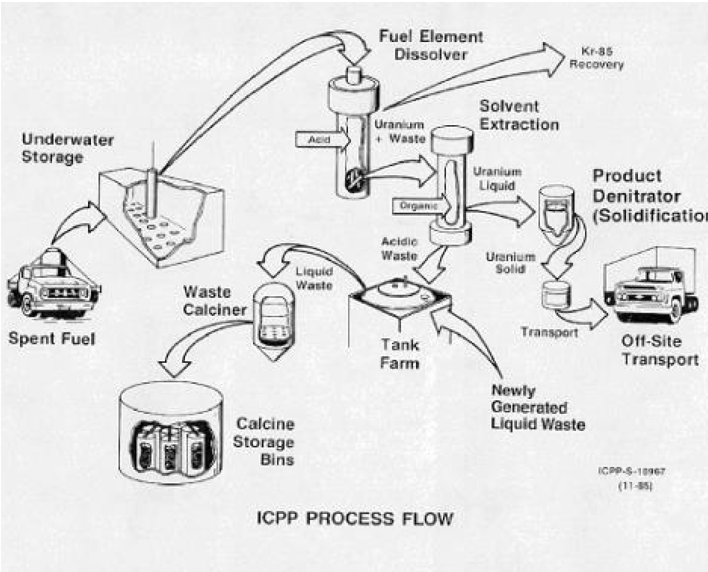
The Integrated Waste Treatment Unit (IWTU) is a relatively new facility designed to treat 900,000 gallons of radioactive liquid waste that is stored in the three remaining full tanks. It is expected to take 2-3 years to process all 900,000 gallons of waste. Only one nuclear waste treatment process in the IWTU uses robotics in the form of a teleoperated arm/gripper for inspection of processed waste. A teleoperated crane is also used for canister plugging, loading, and unloading. Each 2-foot diameter by 10-foot high stainless steel cylindrical canister is placed in a concrete-walled, above-ground vault until it can be transferred to permanent storage. Long-term storage will likely be at WIPP or a facility such as Yucca Mountain.

3.2.2. CALCINE SOLIDS STORAGE FACILITY

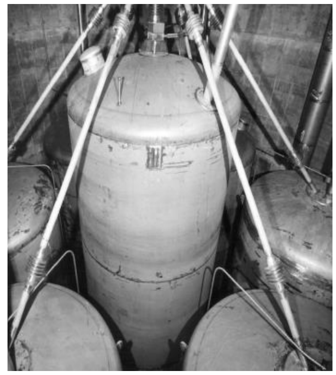
Previously at this site, 9 million gallons of high-level liquid waste were processed, with the liquid being converted into 4,400 cubic meters of calcine grains. This granular material looks like salt, includes fine debris, and is radioactive. The calcine facility is comprised of a total of six large, concrete silos, each of which is partially submerged in the ground and contains four to seven tanks. Each tank is a tall steel cylinder, approximately 20 feet in diameter and up to 60 feet tall, that is anchored to the concrete floor of its silo. Three-inch pipes enter the top decks of the silos and route to the top of each tank. Pneumatic transport was used to deliver the granular calcine material into the tanks. Tanks were filled to capacity, including the fill pipes. Temperatures inside the silos are approximately 400°C, with air convection within the silos as the only means of heat transfer. The tanks and silos "breathe" through HEPA filters on the silo top decks into the local atmosphere. Radiation levels inside the silos are beyond suited protection.

The silos and tanks were constructed and filled under the assumption that their calcine contents would never be removed. However, a settlement with the state of Idaho has changed that plan. The calcine must now be removed, and the silos must be washed and then grouted in place. DOE/EM is interested in inspecting the tanks to understand if the material is still loose or has sintered or otherwise formed a solid. A variety of potential solutions were discussed: using liquids to flood the silos and float out entire tanks, adding access pipes to the tanks and silos, and using special purpose robot arms (e.g. custom snake-like robots) to extract the calcine. The extraction of an entire tank would be challenging because the tanks were likely never designed for such handling after being filled, and would be difficult to lift and manipulate without causing structural damage. It would also be challenging to maintain acceptable containment during such large-scale operations. Options for extracting the calcine without removing entire tanks include the use of augers and vacuums to remove material through the network of pipes (new or existing).

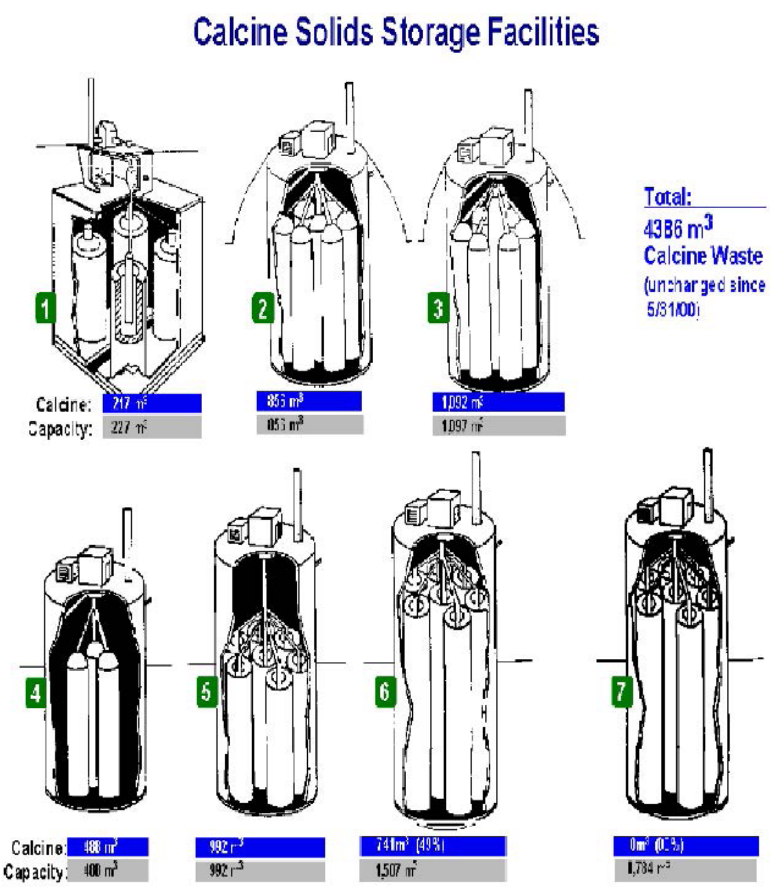
The shipment of the extracted material is not clear, as the final storage depot has not yet been selected. Therefore, the means of transport and form in which the calcine can be safely transported are not clear. Another option discussed was the building of a new onsite factory for converting the extracted calcine into vitrified logs for transport in stainless steel canisters.



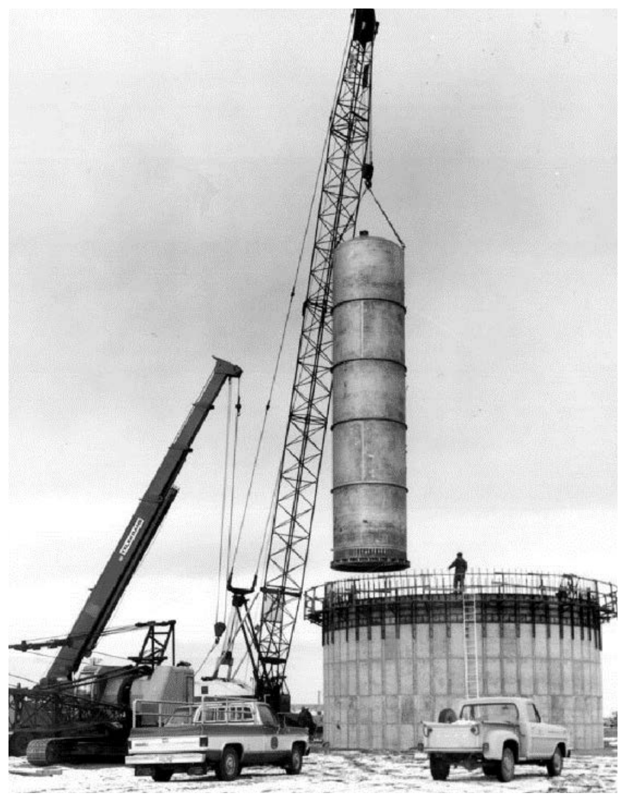
The Idaho Chemical Processing Plant (ICPP) process flow for converting high-level liquid waste into calcine grains.



The interior view of a large concrete silo illustrates the complex system of pipes used to fill each of the four to seven cylindrical tanks within each silo.



Schematics for seven concrete silos show the varied tank configurations, pipe networks, and calcine capacities of each silo.



A tall steel cylindrical tank is being carefully lowered into a concrete silo by a crane during construction of the calcine storage facility.

An unused steel cylindrical tank is shown prior to its insertion into a concrete silo. Fill pipes will be attached to the top of the tank while its base will be anchored to the floor of the concrete silo.

Table A-1. Average calcine compositions, excluding oxides, in weight percent.[1]

Component	Alumina Calcine	Zirconia Calcine	Zirconium-Sodium Blend Calcine	High-Sodium Calcine
Aluminum	87.3	11.8	6.5	53.4
Boron	0.4	1.1	1.0	0.8
Cadmium			5.5	0.2
Calcium		37.7	31.9	4.0
Chloride			0.1	0.4
Chromium		0.4	0.1	0.1
Fluoride		30.1	21.9	1.0
Iron	0.1	0.3	0.2	0.4
Mercury	5.5			0.003
Nitrate	2.6	0.1	8.1	23.0
Phosphate	1.1			0.7
Potassium	0.1	0.1	0.9	2.5
Sodium	1.4		4.1	11.4
Sulfate	1.5		3.7	1.4
Tin		0.3	0.2	
Zirconium		18.2	15.5	0.3

A blank cell indicates an insignificant quantity.

Average calcine compositions, excluding oxides, in weight percent for various chemical components.

3.2.3. ADVANCED MIXED WASTE TREATMENT PROJECT

The purpose of the Advanced Mixed Waste Treatment Project is to repackage legacy waste drums from nuclear weapons plants (primarily the Rocky Flats Plant) such that the TRU wastes are segregated more effectively from other radioactive wastes. In this process, the danger is not radioactive emissions, but rather potential exposure to TRU contaminants (primarily plutonium) and other hazardous chemicals. Consequently, the entire process is remotely operated.

The massive facility receives 55 gallon drums from storage pits onsite at INL and other storage depots around the country. The facility measures and weighs the drums, cuts them open, extracts dangerous items and other materials that are not allowed at the final storage sites (e.g. pressurized aerosol cans), crushes the material, and then stores it in newer and better sealed containers. The newer storage containers are intended to be shipped to WIPP, but are currently being stored onsite since WIPP is temporarily closed as of this visit (February 2014).

A central facility control room having control stations with PC computers and graphical interfaces enables the viewing and remote supervision of all processing cells. Handling of the mixed waste containers is done with conveyors, elevators, and electro-hydraulic manipulators (Brokk, Inc.). An incoming waste barrel is loaded via elevator into a robot cell. There are three robot arms in the cell, each with its own work station. Typically, two robots are in use at any one time, 24 hours a day, 7 days a week. The cell is also used to store many older arms and grippers that are no longer in use. A human operator remotely controls a hydraulic Brokk manipulator to rip open the steel barrel and sort out non-allowable objects. Each 6 degree-of-freedom Brokk robot arm features a spherical wrist and a large gripper/crusher, is approximately 10 feet long, has a payload capacity over 1000 lbs, and has a top speed of approximately 2 ft/sec. No force/torque sensors or cameras were observed on the arms. The arms are controlled by line of sight (approximately 15 ft) through thick windows using simple switches that control each actuator joint individually. The operator must learn to control the robot using a non-intuitive, mirrored joint space since the operator's window onto the cell provides an overhead and reversed view of the workspace (from the front of the manipulator). On average, it takes approximately one year for a new operator to become fully trained and qualified to operate the robot. A maximum of only 2.5 hours of continuous seat time is allowed for the operators.

The waste barrels contain a mix of plastic, paperwork, cardboard, tools, rags, cans, contaminated PPE, and other garbage from the last 70 years. The TRU wastes are contained in polyethylene bags inside of the drums. When a new barrel arrives, the operator must grab and open a tiny latch using a gigantic 1 degree-of-freedom robot gripper. Once the drum lid has been pulled off, the operator must grasp the plastic bag in the drum and use it to swing the drum back and forth until the drum eventually falls away from the bag. This bimanual task is especially challenging for the teleoperator of a single robot arm whose dimensions dwarf the materials to be manipulated. A simple mechanical fixture (or second robot arm) that grabs the base of the drum would make it easier for the teleoperator to pull the plastic bag out and to perform other required bimanual tasks.

Hatches in the cell floor are covered by lids, which the operator opens with the robot arm. The sorted materials are dropped into barrels below the cell. The old barrel is crushed with the robot arm and dropped down one of these hatches. Below the cell, the new barrels receive the sorted material and move on conveyor belts into lid sealer, washer, and crusher operations. The conveyors move within long glovebox tunnels, with glove portals every 2 ft (vertical and horizontal) for cleaning and equipment repair by human hands. New aluminum, 55 gallon barrels containing the sorted waste are crushed down to "pucks" that are 4 to 10 inches in height.

A teleoperated puck picker is used to carefully transfer the pucks to a box for transport and storage using a simple gripper and friction. In one incident, a puck was dropped, which shattered the adjacent glass and resulted in contamination outside of the robot enclosure. Since then, precautionary measures have been implemented, such as the requirement of a 600 lbs "push test" in order to ensure a good grip of the puck by the robot gripper. The inherent challenges of teleoperation, especially with limited sensing and dexterity, make the addition of such safety checks a requirement for any teleoperated system used for the remote handling of high consequence materials.

In discussions with the INL plant operations manager, he indicated that one of the biggest issues is maintenance and repair of the hydraulic Brokk manipulators. The manipulators break regularly, and require 2-3 human entries into the cell per week for repairs, mainly for the repair of hydraulic lines. Due to the TRU present in the cell, maintenance personnel must wear a positive pressure PPE suit with five layers of gloves, which degrades dexterity. Each PPE suit requires extra personnel for donning and doffing, and weighs approximately 31 lbs, which greatly reduces stamina. Each cell entry is limited to 1 hour in a PPE suit due to thermal and radiation exposure limits. Additionally, medical health scans are required prior to and after work in the cells. When repairs are required in the conveyor, crushing, and processing work areas, personnel must perform the repairs via glovebox portals.

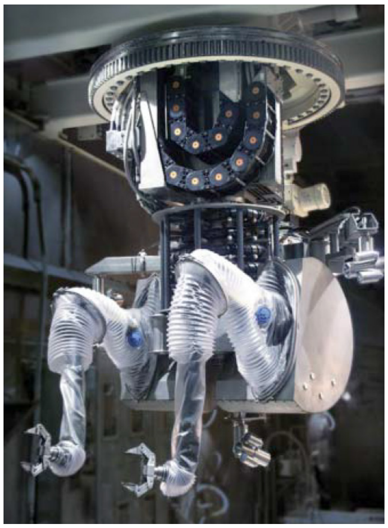
A work cell containing robot arms and conveyors is used to sort mixed waste.

Human workers process waste through glovebox portals.

The donning and doffing of a pressurized PPE suit requires extra personnel and medical health scans prior to and after work in the cells.

Modernization of the teleoperated robot systems is highly recommended. The efficiency of tasks such as the opening of waste barrels and sorting mixed waste could be vastly improved with a more intuitive master controller approach that is typical of modern nuclear and undersea operations (rather than individual joint controls operated from a non-intuitive, mirrored joint space). With technology upgrades, it is estimated that reductions in total task time could be in the range of 3-10x. Several industrial robot manufacturers currently offer electrical robot manipulator packages with the necessary payload and reach specifications. If they can survive the radiation field, electric manipulators of sufficient strength and speed could increase efficiency, reduce downtime due to hydraulic failures and maintenance, and minimize the need for personnel exposure to hazardous work conditions for repairs. The use of modern electric manipulators would not only provide drastically improved reliability, but would also facilitate the automation of many subtasks, thereby increasing throughput.

While the teleoperators of the Brokk manipulators are highly trained and experienced, the existing operations are crude and inefficient as compared to other remote manipulations routinely performed with mechanical master/slave manipulators and newer servo-manipulators. For instance, the Spallation Neutron Source at a modern DOE facility at Oak Ridge National laboratory employs a teleoperated dual-arm servomanipulator in its hot cell work areas. The manipulation system enables dexterous remote handling and features scaleable force reflection, joint indexing, tool weight cancellation, and other advanced control features to minimize operator fatigue and give the teleoperated arms capabilities beyond those of standard mechanical master-slave manipulators.



Left: A teleoperated dual-arm servomanipulator is used for dexterous remote handling operations in hot cell work areas at the Spallation Neutron Source at a modern DOE facility at Oak Ridge National laboratory. Right: A remote operator controls the dual-arm servomanipulator from a control room equipped with a multi-camera viewing system.

3.3. Summary of Hanford Visit

The Hanford Nuclear Reservation hosted an international team of robotics experts from August 11-12, 2015. The objective of the visit was to have a small subset of the larger team understand current practices related to the use of robotics for the continued decommissioning of the site and report back to the larger workshop at Savannah River. The hosted team included 9 individuals from the United States and Japan. Participants were selected from academic, industry, or other governmental departments that had expertise in either relevant areas of robotics or had experience in other high-consequence domains (space, military, infectious disease, etc.)

Dr. Roy Gephart kicked off the mini-workshop with an overview of the history of the Hanford Site from its establishment in 1943 as part of the Manhattan Project until today where the mostly decommissioned nuclear production complex serves multiple purposes. It holds approximately 66% of the nuclear waste (by volume) in the United States, facilities to process this waste, a commercial nuclear power plant, a nuclear research facility (PNNL), and one of the two observatories completed in 2002 to detect gravitational waves. At the height of the cold war, a total of nine reactors and five processing facilities were built. They produced 67 metric tons of plutonium from 1945 to 1987 which was about 70% of the plutonium for the US weapons program. The by-product high-level liquid waste (HLLW) from reprocessing, with a volume of 200,000 cubic meters, was stored in a total of 177 underground storage tanks (USTs). The original tanks were single-shell and the later ones were safer double-shell designs. There are a total of 149 single shell tanks and 28 double shell tanks holding a total of 56 million gallons[1] of radioactive and chemical wastes. Dr. Gephart noted that multiple reprocessing canyons for the various wastes were designed and built in parallel. The processes were designed for complete remote operation, maintenance, and change out of major process components, made possible by the development of the Hanford Remote Pipe Disconnect.

The waste streams are extremely complex and varied. Some liquid wastes were treated and precipitated into salt cake. Today it is estimated that the total UST inventory is made up of 23M gallons of salt cake, 21M gallons of supernate, and 12M gallons of sludge. Multiple tank farm areas are interconnected to other facilities through underground piping systems. Internal radiation levels can be as high as 2,000 rad/hr. The design basis for hardware being introduced into a tank is 1,000 rad/hr.

[1] One way to visualize or estimate 1 million gallons of waste is to picture a pool that is about 50 feet deep as well as 50 feet long and wide. It is worth also noting that the amount of liquid processed will be closer to 250 million gallons once the water required for transport and processing is included.

3.3.1. GLOVE BOX OPERATIONS

Glovebox D&D is a challenging problem throughout the DOE complex. The removal of two 12-foot high gloveboxes from the Hanford Plutonium Finishing Plant (PFP) in February, 2016 was reported as some of the most hazardous operations at Hanford. The size of the boxes, the level of contamination, and the type of contamination combine to make this a particularly dangerous project. The gloveboxes were too big to be removed from the plant in one piece, so they had to be cut up and sealed for movement and disposal.

Sealing of one of the large 12′ gloveboxes at the Hanford Plutonium Finishing Plant (PFP) in February, 2016.

While these two gloveboxes posed unusual hazards, they are just two of the 238 gloveboxes in the PFP and an even smaller portion of all the gloveboxes at Hanford. The number of gloveboxes to be removed is daunting. Some are still actively used. In many cases, gloveboxes were abandoned during plant shutdowns with hazardous materials left inside because of the risks of cleaning them to workers. In some cases, this has led to degradation of the glass and materials of the boxes. Automation can address both the repetitive, hazardous tasks in active gloveboxes and the non-repetitive task of removing contamination from dormant gloveboxes prior to their removal and disposal.

Glovebox operations at the Hanford site.

3.3.2. UNDERGROUND STORAGE TANK FARMS

Plutonium production yielded millions of gallons of liquid waste which was pumped into storage tanks. The site has numerous underground tanks of varying age (as much as 75 years old), size, construction type, and current condition. The Hanford Site includes 149 single-shell tanks and 28 double-shell tanks. All Hanford tanks are carbon steel, as opposed to the largely stainless-steel storage tanks of INL. These tanks have piping that runs in/out, riser pipes that provide access from the above ground, and vary from single wall carbon steel to more complex double walled tanks with concrete liners. The contents vary from sludge, to salt cake, to a liquid mixture called “supernate.” As some tanks have begun to fail (i.e. leak), material has been processed or moved to newer tanks. Some of the newer tanks are linked, but older ones are either not linked or linked by piping that is too old to use. The goal is to clean out all the tanks and pipe the waste to the new Waste Treatment Plant[2] for processing once it is operational.

There are many challenges to decommissioning and decontaminating waste storage tanks:

- Characterize the waste;
- Access the waste;
- Dislodge and/or mobilize the waste as necessary based on its current form(s);
- Convey the waste from the tank;

[2] https://www.hanfordvitplant.com/about-project

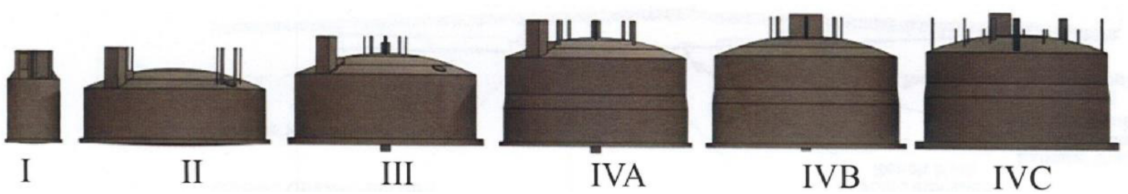
- Transport the waste;
- Inspect and ensure the viability of tanks that contain waste; and
- Decommission the tanks and grout-in-place once as much waste as possible has been removed.

Emptying a tank is a problem because the tanks are below ground, access is limited to small pipes (3-12 inch), the tanks and waste are large (1 million gallons), acidic, thermally hot, radioactive, humid, and filled with a mixture of sludge, cake and liquid. They may contain explosive vapors. Another problem is the inspection of the interstitial volume in between the inner and outer walls of double walled tanks.

Existing methods to transfer material from a tank use spray hoses to push material to a central pump and dissolve it. Pusher robots are lowered into the tanks and then used to push material with a bulldozer blade. Some have articulating pan/tilt units with spray nozzles on their ends, or articulating arms that have spray and vacuum tools on their end-effectors. All these tools must enter the tanks from above, through 3-12″ diameter risers (some newer tanks have larger risers) or with the excavation of larger access tunnels.

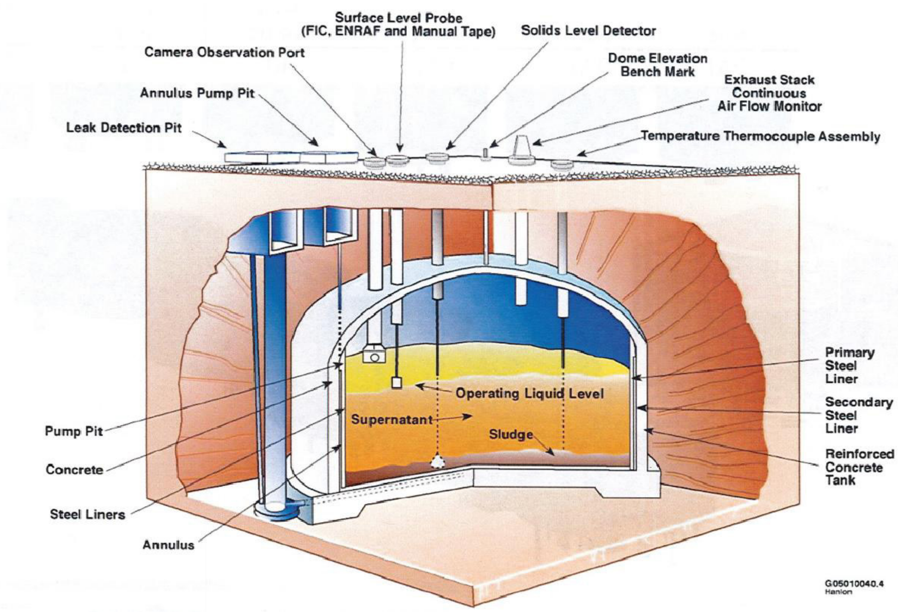
Hanford waste storage tanks during and after construction including one example of the waste stored inside a tank.

The single-shell tanks come in a variety of sizes and are illustrated below.



The six variations of single-shell tanks at Hanford.

A cut-away of a typical double-shell tank is illustrated below.

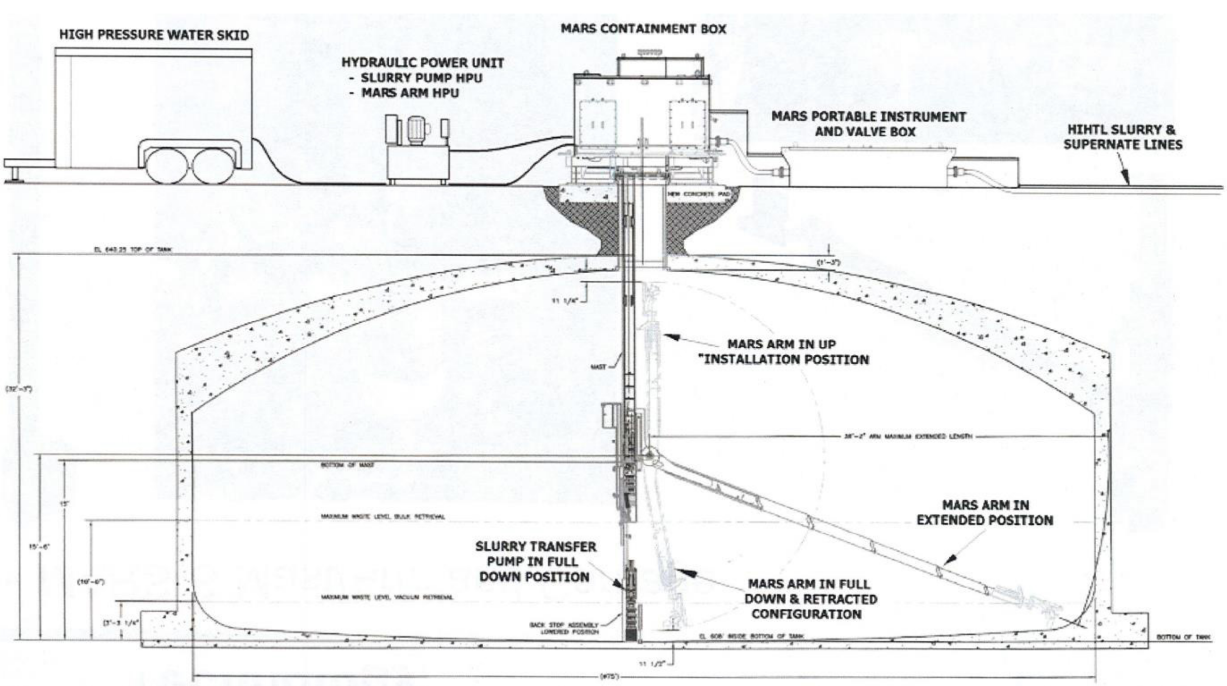


Cut-away of a typical double-shell tank.

Robotic tools are needed that can enter through the 12 pipes, breakup material and push it to the center of the tank floor. Robots are also needed to inspect wall integrity, take samples, map/measure contents, and monitor conditions. Thus, some robotics systems have been used and/or evaluated for cleaning and inspecting waste tanks. During inspection or waste removal tasks, the tanks environment must be continually monitored to ensure safety including temperature, humidity, gas content, dose, and – ideally – isotopic identification. Such monitoring is necessary even if human operators are completing the work.

The Mobile Arm Retrieval System (MARS) is a commercial robotic device for cleaning of the tanks. It inserts through a 55" riser and can reach 35 feet horizontally and 40 feet down into a tank. It can be fitted with a sluicer or vacuum. The system is controlled with a standard game controller. For many remote systems (such as remote hot cell manipulators), kinesthetic correspondence has the potential to help reduce training times and decrease the cognitive burden on the operator, but – as the QWERTY keyboard demonstrates – the human operator is capable of learning to effectively use counterintuitive user interfaces.

MARS in the double-shell tank mock-up facility.



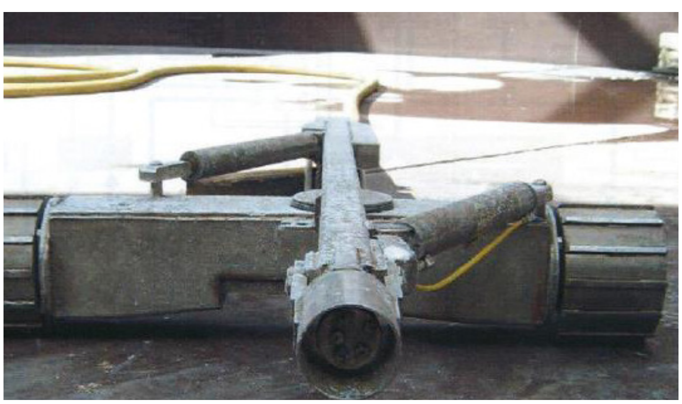
The FoldTrack, developed by Non-Entry Systems Limited, was used inside tank C-110 for 230 hours.

The MARS was used in tank A-105. It was provided by a local equipment supplier that positions a multi-jet high pressure sluicing head for salt cake mobilization. The fluidized materials are then pumped out of the tank. A vacuum end-effector was used for the removal of "tails". A 24-inch riser was used for access and approximately 300 hours of jet time over several months was required for each tank. The MARS-S system was abandoned in place after project completion. The MARS cannot be used in some tanks that have internal equipment. For example, the Savannah River tanks are more likely to have internal cooling pipes and other obstacles inside the storage tanks. The Waste Retrieval System is a sluicer that can be used in tighter situations.

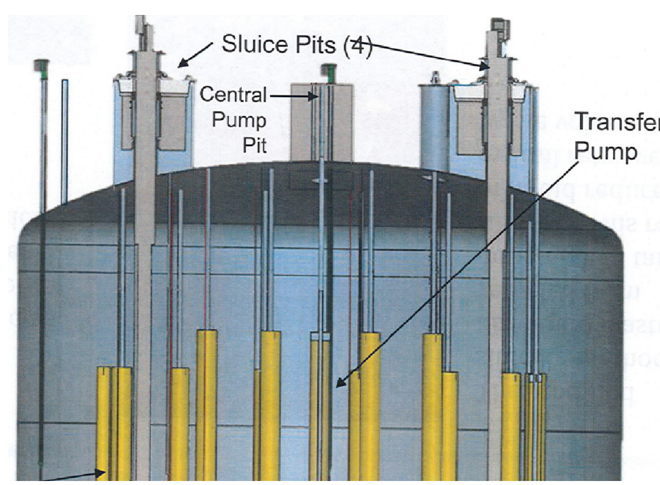
The objective of the FoldTrack vehicle from NESL (used in tank C-110) was to push sand-like residual waste towards the center of the tank's floor. The system could be introduced through a 12" riser, but there were issues with the tracks coming off the system and the need to leave room for placing the centrifugal pump. Despite some of the issues with these approaches, DOE expressed a strong interest in improving and building on the successes of existing solutions like MARS instead of considering proposals for new, but untested MARS-like systems.

The FoldTrack robotic vehicle for cleaning inside of tanks with limited access risers.

Another in-tank vehicle, made by TMR, was used to clean up the last 4% of the heel inside a tank. (The other 96% was cleaned by the MARS or other means.)



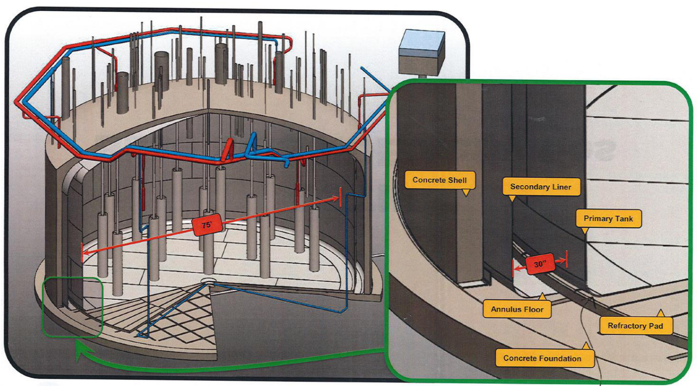
In-tank device made by TMR.



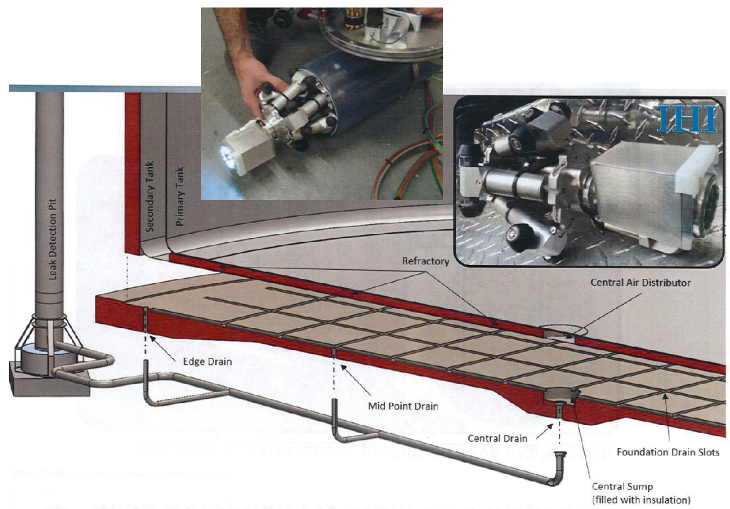
Example of a tank with additional internal obstacles such as piping for cooling, etc.

Inspection tasks on the outside of the tank have also been addressed with robotics. The air shaft below a tank or the area between the two hulls in a double hulled tank can be remotely inspected to detect leaks, undesired material build-up or areas where the tank walls are deteriorating. The cooling slots are typically 1" x 3" and would require sufficiently small and maneuverable (possibly sacrificial?) robotic devices. Such areas can be extremely confined and vary greatly from one tank to the next.

Magnetic wall climbers with NDE capabilities are used to inspect welding seems on the DSTs with good results. Building on these successes, additional inspection tasks should be automated and include many upper tank operations to avoid operator exposure to tank vapors. Illustrative examples are shown in the following figures.

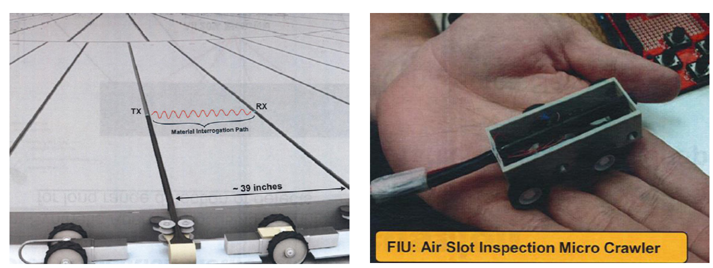


The areas between the hulls, channels in the refractory pads, and ancillary piping should all be remotely inspected and/or decontaminated.



Pipes – including tank drainage systems can be accessed by snake robots.

Compact systems deployed for inspection and decommissioning



Examples of miniaturized systems under development for inspecting air slots and other extremely small spaces.

Given the combined number of tanks at Hanford and Savanah River that must be addressed, a long-term investment in robotic systems that can be redeployed makes sense if their use can be viewed across a multi-year, multi-tank basis to properly amortize the development and operational costs.

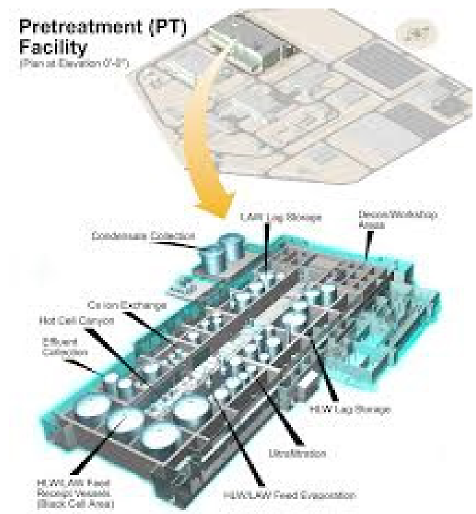
3.3.3. HANFORD WASTE TREATMENT PLANT

When completed, the Waste Treatment Plant (WTP) will process the liquid wastes stored in the multiple tank farms. Liquid waste will be pumped from the Hanford tanks to the new facility over distances of up to seven miles. The material is pumped through a pre-treatment facility then routed to either high- or low-level facilities. Both outputs are vitrified into glass, then poured into stainless steel canisters for final transport and storage. These facilities are huge, concrete structures filled with pumps, piping, storage and mixing tanks, heaters, canister-handling gantries, rail cars and massive vault doors. The operational concept involves few human workers once treatment begins.

Black cells are regions of the facility where no people (or ideally their surrogate robotic systems) will ever go once treatment begins. A concern involves the use of jet pulse mixers to continuously stir the waste and prevent sediment fallout. There will be limited sensing in place to monitor this process and detect issues before they become a problem. The facilities will include HEPA filters, but access to the inner side of the filter channel requires people in suits for monitoring and then replacement if a spray/spill occurs. When inevitably necessary, working in the black cells will be difficult because there are few openings. The cells have no power and limited sensing. If a spray leak occurs, the entire cell could be contaminated before a radiation sensor in the sump detects a problem. If this happens, HEPA filters will also be contaminated, and they will need to be inspected and replaced.

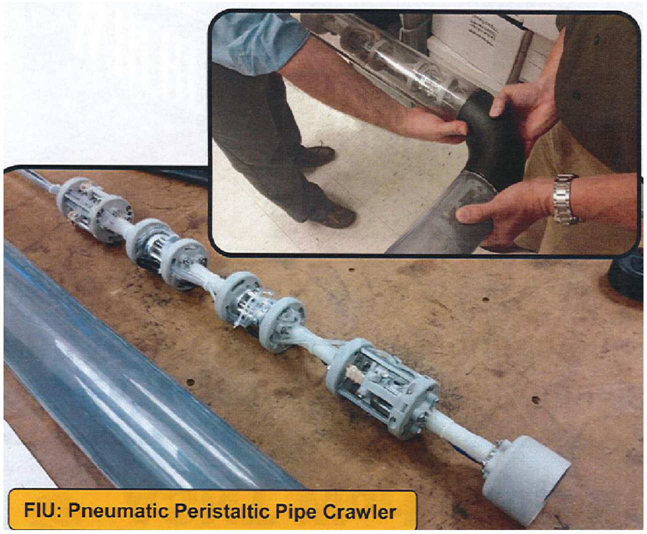
Even though they are designed for zero maintenance, we must assume that such maintenance will be necessary as their task is estimated to take 50-75 years to complete. As a comparison, the Mars Rover's mission was completed in just 10 years in – arguably – a less hazardous environment.

The Waste Treatment Plant (circa 2015) under construction at the Hanford Site.



Examples of waste after the vitrification process is completed by the WTP.

Before construction is completed, it is recommended that the design be changed to accommodate robots if they are ever needed to enter the black cells for sensing, monitoring and future repairs. It may also be beneficial for robots to enter areas built for people if contamination is detected in order to reduce exposure to human operators.



One example of many pipe crawling robots under developed at various academic institutions.

3.3.4. PIPE INSPECTION

In addition to tank piping, pipe and duct inspection is a major issue that was highlighted in many facilities at Hanford and throughout the DOE complex. Given number and range of pipes and ducts at the site (from the tiny air pathways under the DSTs, to the multitude small pipes that run through the WTP's black cells, to large distribution pipes that move waste across the entire site) inspection and – inevitably – repair will be necessary. Inspection of the water lines on-site is also necessary. Security is also an issue in the cross-site transfer lines – which can be up to 7 miles long – since they carry highly contaminated waste.

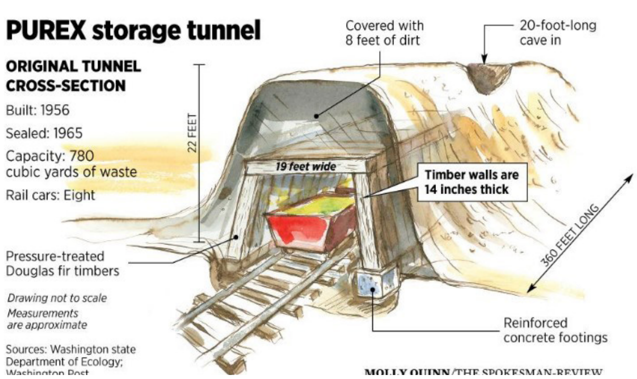
Some lessons and solutions can be collected from industries with similar issues (i.e. Oil & Gas transmission, sewage system inspection, etc.), but Hanford's challenges are unique given the variety of pipes, lack of standardization, and unique hazards (i.e. radiation, etc.).

3.3.5. PUREX TUNNELS FOR STORAGE OF ODD-FORM WASTE

The plutonium/uranium extraction (PUREX) process was a chemical process to remove the cladding from spent fuels. The PUREX facility is one of the major D&D sites at Hanford because of the high levels of radiation that remain. Yet, a curious feature of the PUREX facility is the creation of two "PUREX tunnels" for the underground storage of large contaminated equipment, adjacent to the canyon buildings. These tunnels were primarily used for the storage of "odd-form" pieces of equipment, which include the ambulance used to transport the "atomic man" to a local quarantine facility after a 1976 chemical explosion exposed him to the largest dose of radiation from americium ever recorded.[3]

Aerial picture of the PUREX tunnels.

Inspection and cleanup of the underground tunnels presents many unique challenges above and beyond the challenges of the underground tanks and the remaining decommissioned facilities and are a clear opportunity for robotics and remote technology. In fact, the urgency of these challenges was made apparent by the recent collapse of a section of the smaller PUREX tunnel in 2017.



A diagram of a cross-section of the smaller PUREX tunnel (left), showing its construction. An overhead picture (right)

[3] http://www.oregonlive.com/today/index.ssf/2014/07/feds_to_clean_site_of_1976_ato.html

Grouting operation in November, 2017 to stabilize the smaller PUREX tunnel after a section collapsed.

3.3.6 MAJOR PROCESSING FACILITIES AND CANYON AREAS

Other Hanford challenges presented included the handling of nuclear materials in telemanipulation cells, and the processing of ^{137}Cs and ^{90}Sr waste. The major processing facilities (B-Canyon, T-Canyon, U-Canyon, Redox, and PUREX) all need near-term monitoring prior to their eventual decommissioning, demolition, or grouting-in-place. Some of these facilities have no HVAC and are losing the ability for manual entry for inspection and characterization. Mobile robotics will be necessary to complete many of the required D&D tasks.

One area of interest is the sump in Building 324 under B-Cell[4] where a spill occurred in 1986. This sump has a high build-up of 137Cs and 90Sr with a dose rate of up to 8,900 rad/hr. Contamination may be up to 11m below the building foundation. Some sort of digging robot was suggested as a possibility. There is a significant need to characterize the spill.

3.4. Summary of Savannah River Site Visit

The Savannah River National Laboratory hosted an international team of robotics experts December 7-10, 2015. The visit was jointly sponsored by DOE-EM, the National Science Foundation and Purdue University. The objective of the visit was to understand current practices related to the use of robotics and automation for handling "High Consequence" or Special Nuclear Materials (SNM) to develop an accurate picture of the current state-of-the-art. The visiting team is interested in surveying and identifying opportunities to develop and deploy new (or existing) technologies which would improve the safety of its workforce, reduce the cost of decommissioning and decontamination (D&D) activities, and ensure that DOE meets its obligations to close and remediate the remaining legacy sites related to the past research and production of SNM.

The visiting team included 26 individuals from four countries. Participants were selected from academic, industry, or other governmental departments that had expertise in either relevant areas of robotics or material handling in other hazardous domains (space, military, etc.).

3.4.1. GLOVE BOX OPERATIONS

A lot of testing is done on waste materials at different points in the treatment process. A sample is taken from within the environment (using a crane), put into a lead box, transported to a nearby facility, and into a glove box where human workers perform measurements on the sample (using chemical processes). Workers either put their hands into this environment through plastic gloves, or use a master-slave manipulator to do the experiments. Both approaches are tedious; the glove boxes are dangerous due to the risk of puncturing a glove. One of the glove boxes at SRS has substantial airborne plutonium leftover from a grinding operation, which is difficult to clean. SRS has built a mock-up of the glove box and are trying to determine how they can safely start decontamination of this facility based on the hazards (workers need to wear suits in addition to the gloves).

[4] http://www.pnnl.gov/main/publications/external/technical_reports/pnnl-21214.pdf

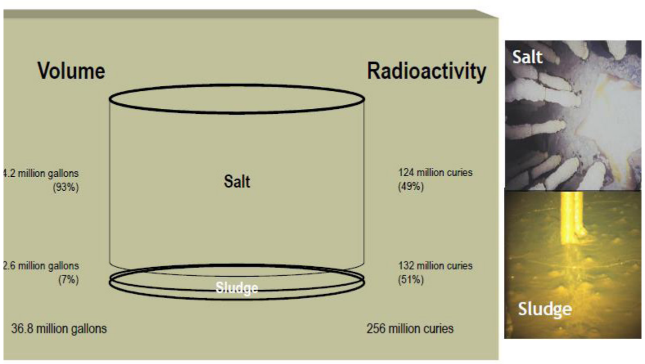
3.4.2. WIPP CAMERA

When the radioactive incident occurred at the WIPP in February of 2014, it was initially uncertain what had happened. There was little information other than the Continuous Air Monitors tripped alarms detecting radioactivity. Nobody was in the mine at the time, nor was anyone allowed to enter, so the staff was it the dark for several weeks. Eventually, as evidence was pieced together, it became necessary to develop a remote camera system to try to inspect the extent of the incident.

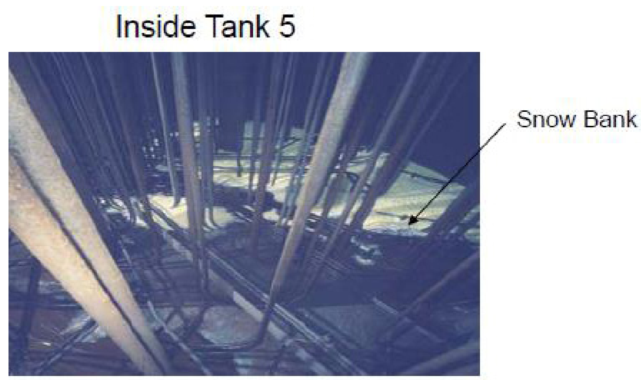
It was suspected that a drum in panel 7 had ruptured, but the drum was inaccessible, near the interior of the cache of materials. An extended-boom camera system was developed by SRNL to inspect the drum and verify that the problem.

3.4.3. UNDERGROUND STORAGE TANK FARMS

The underground storage tanks at Savannah River have both important differences and similarities with the tank farms at Hanford. In both cases, the amount of radioactive material is enormous. The Savannah River tank forms contain about 256 million curies of radiation, while the Hanford farms contain about 195 million curies. The Savannah River tank material has been evaporated to remove much of the water, leaving the 43 single- and double-wall tanks with a volume of about 37 million gallons, with the largest tanks holding up to 1.3 million gallons. A key practical difference is that most of the Savannah River tanks are laced with internal cooling coils, making internal cleaning much more difficult. A centralized manipulator, like the MARS system is not practical in most of the tanks.



Inventory values as of 2015-03-31



Disposal is done at Savannah River by separating out the sludge (high-radiation) from the dissolved salts, then distilling the salts several times to remove the highest-radiation components. These two streams of high-radiation materials are sent to a "vitrification" process where they are mixed with sand, melted and turned into glass, and poured into steel vessels for indefinite storage (initially planned for Yucca Mountain). The lower-radiation stream is mixed with concrete (grout) to a consistency of latex paint and poured into a large concrete vat for on-site storage above ground. Once a tank (or a whole canyon) is clean "enough", it is typically filled with concrete (grouted in place) and decommissioned on site. Clean "enough" is defined as removing all "transferrable" contamination, leaving only the "fixed" (e.g., can't migrate).

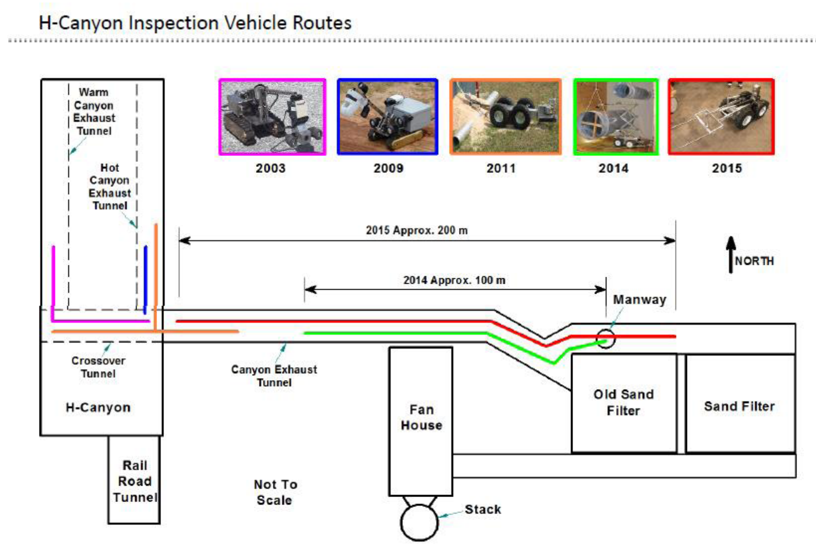
Some custom manipulators were developed for tank inspections. The robot below was used in tank 18F to sample sludge not directly under the riser entry point.

3.4.4. CANYON OPERATIONS

Canyon cranes present an interesting history of automation and remote operation. SRS initially had a worker in the crane pod that used a periscope system to remotely handle high gamma, and high neutron dose materials. Now these are teleoperated. Wireless cranes and cameras are controlled by workers in remote areas.

A unique problem within the canyons at Savannah River is the H-Canyon Exhaust Air Tunnel. The H-Canyon is the only hardened nuclear chemical separations plant still in operation in the United States. The exhaust air tunnel carries acid-laden, radioactive air to a bank of sand filters at a velocity of up to 30 miles per hour. Because of the caustic composition of the gases, the tunnel has eroded on the inside over the many decades of operation and needs periodic inspections. The tunnel represents a particularly challenging environment for both man or machine due to the acidic gases, large amounts of erosion and debris, and puddles, but over the past twelve years, six inspections have been attempted with five different robotic vehicles. In fact, these inspections have been successful with their limited objectives, although most robots have been abandoned in the tunnel. While each vehicle has cost less than $75,000 (the sacrificial part), the total costs of development have been much higher. From the images of two of the vehicles in the figure below, it is apparent that much is changing from iteration to iteration and it is not clear a strong body of generalizable expertise is building up across trials.

Two of five different robots developed for the H-Canyon Exhaust Tunnel at Savannah River. (reprinted from Reid 2015)



3.4.5. PIPE INSPECTIONS

As at the other sites, there is a large need for pipe inspections. A unique application at SRNL was the development of the "Large Diameter Pipe Crawler" to redirect a 36-inch diameter air flow pipe in the F-Canyon. The pipe crawler employed a custom-designed tether system to navigate roughly 300 feet to the point at which it was used to successfully remove a section of pipe inside the canyon. The plasma arc cutting torch was teleoperated via onboard cameras. The tether system required heavily-protected workers to manage tethers.

3.4.6. ADDITIONAL OBSERVATIONS

The existing manual intervention points represent opportunities for robotics. Manual operation in the tanks and canyons is done using a large overhead gantry. Pinch-type end-effectors are generally used. For example, in the vitrification facility, the canisters are put in place, reoriented, and taken out using a master-slave manipulator. Another remote manipulator is used to clean up the pour spout when it gets clogged. Due to radiation, most electronics are remote (outside of the environment), with pulleys inside.

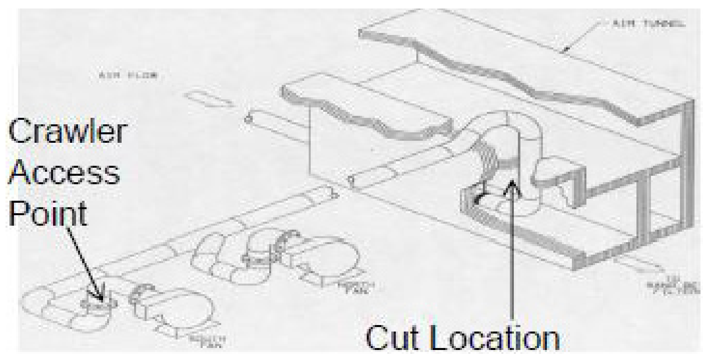
There is an interest in inspecting the tanks (and other facilities such as air handling) for structural stability (e.g., finding cracks) and radiation levels. Most of these structures were built in the 1950's-70's. Sewer inspection robots have been used extensively, all teleoperated, sent in with a tether and video for inspection (sometimes 2 robots, one to watch the other). Often the robots are left inside the environment afterwards (due to difficulty of decontamination), creating more obstacles. It may take 5-7 weeks to inspect a tank. If samples are needed, they are taken by the robot, put in a basket, pulled out with the crane (then the basket is dropped down again). The inside of the tank may be full of piping making access for robots difficult.

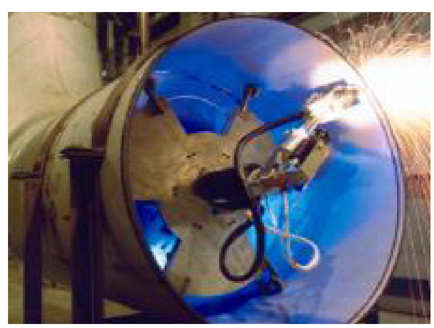
Aerial robots could be interesting for inspection, but the airflow inside a canyon or ventilation duct could be up to 30mph. Also, a rotary-wing platform could disrupt the contaminated material within in the environment, increasing the measurement and characterization challenge.

Aging workforce is another issue. Workers are very well-trained (they've been working on these problems for 20+ years) but not always ready for change. The replacement workforce may be more open and accustomed to working with robots and automation.

Safety is paramount. There are at least four primary risks: (1) common industrial hazards, (2) chemical hazards, (3) radiological hazards, and (4) criticality (nuclear explosion, to be avoided at all costs). During the recent economic stimulus, the complex received additional funding and hired many new workers, but there were some accidents. There are risks to doing this type of work, and risks of not doing it (some level of clean-up must be done).

Several of the issues that have already been identified in previous sections about INL and Hanford also apply at SRS but are not included in this section to avoid redundancy.





A recurring set of questions arose around the criteria used to justify and fund projects at SRS. What are the key decision factors that ultimately drive solutions? For example, the cost of worker radiation exposure is clearly a factor. What does a man-rem cost at SRS? The value of providing jobs is clearly valued at SRS. What are the tradeoffs between human labor and capital equipment? What is the relation between TRL and fundability for new technology insertion?

Another item of note is that full-scale mockups appear to have been a critical factor in successful safe operations from Day 1 but transition to varying grades of virtual/augmented reality remains low (e.g. for F canyon D&D). The VR implementation appears to not have kept pace with the increased levels of immersivity feasible (including haptic/visual and other multimodal interactions).

NON-DOE SITES AND ROBOTIC CAPABILITIES

The direct observations by the committee at the four sites discussed in previous sections (Hanford, INL, WIPP, and SRNL) can and should be augmented by independent observations by the committee of other efforts and/or solutions in place across the DOE complex and in other nations with related needs. Based on discussions within the committee, several additional efforts are documented here including:

- Automation at the Sellafield, UK
- Automation efforts resulting from the Fukushima incident in Japan
- Automation efforts in South Korea
- Robotics efforts in non-government organizations in Texas

4.1. Summary of Sellafield Visit, UK

A United States delegation of government representatives took a week-long tour of various facilities on and around the Sellafield nuclear waste processing site in the United Kingdom. The tour was organized on the U.S. side by Dr. Rod Rimando of the Department of Energy Environmental Management group (DOE/EM), and included Dr. Monica Regalbuto, presidential appointee for the position of Assistant Secretary for Environmental Management, DOE, Dr. Richard Voyles, Assistant Director for Robotics and Cyber-Physical Systems, White House Office of Science and Technology Policy, Dr. Albert Kruger, Bill Hamel, and Brad Eccelston, all of DOE/EM. Sellafield is the only site in the United Kingdom for handling non-military high-level nuclear waste.

The team met with individuals from three distinct entities: Sellafield LLC, National Nuclear Laboratory (NNL), and the Nuclear Decommissioning Authority (NDA). Sellafield LLC is responsible for the operation of the plants, NNL performs nuclear research and development, and NDA provides oversight and strategic direction.

4.1.1. ROBOTICS AT SELLAFIELD

The UK appears to have a substantial lead over the United States in development and application of robotic technologies for the problem of nuclear waste remediation. Nuclear processing sites all over the world use “manipulators” to allow humans to work remotely during nuclear processing operations. These manipulators are basically unpowered master/slave mechanical grippers that couple human motions at the “master,” through the wall of a hot cell, to the “slave” inside the hot zone. These manipulators may provide active or passive gravity compensation, but possess no intelligence and offer no autonomous capability.

The difficulties of these manipulators are manifold. Fatigue and repetitive strain injuries are common, due to the loads and friction of the mechanical system. The hot cells, which may have walls of concrete up to 2m thick, require costly windows to be installed with leaded glass from 1.2 – 2 m thick, as well. These windows are costly to produce and must be installed, sealed, and inspected.

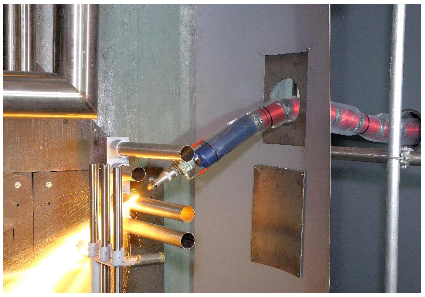
In contrast, the NNL has explored several robotic technologies for operations, inspection, and maintenance that are in use or in development at sites such as Sellafield. Base-mounted robot arms are being developed for opening containers and sorting waste. ROVs (remotely operated vehicles) have been used in spent fuel pools to inspect and sort waste for processing. Manually operated “sensor snakes” are used to measure the wall thickness of pipes and inspect welds. UAVs have even been tested to map the distribution of material inside rooms with overlays of information such as material temperature.

4.1.2. ROBOTIC SORTING

The cell pictured below at NNL uses large Kuka robots to re-process waste composed of a variety of largely unknown materials. While primarily teleoperated at this time to use various end effectors to open cans, pour and sort contents, and crush things, NNL envisions semi-autonomous and autonomous capabilities to improve the slow pace of human-driven operations through thick glass windows. They provide numerous video cameras around the work cell, eliminating the need for expensive and restrictive lead windows for operator viewing. They also tie the robot to a real-time CAD model of the work cell to provide a form of virtualized reality that enhances situational awareness.

Example fixed-base robot arm similar to those under development at Sellafield, left (image courtesy Kuka), CAD model from Sellafield, right.

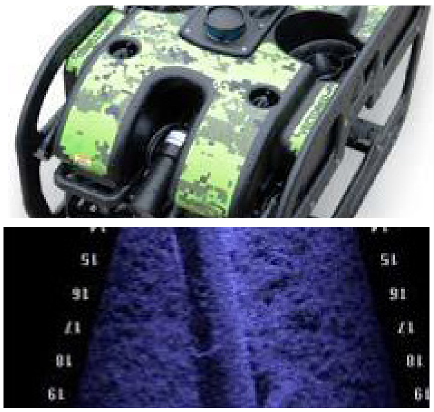
Workers at NNL set up a lab test with a mock pick-and-place operation.



The LaserSnake cutting a pipe in a mock cell.

4.1.3. LASERSNAKE

Another application of robotics the Sellafield team is pursuing is the “LaserSnake.” This is a highly articulated continuum manipulator (elephant-trunk-like) with a laser head for cutting. As shown in the picture, the continuum manipulator can reach into difficult and cluttered spaces, avoiding multiple complex obstacles in its path, and use its high-power solid state laser to cut metal and other potentially contaminated waste into manageable pieces.



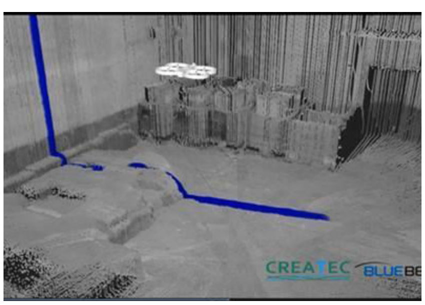
Example ROV and high-resolution SONAR images of an underwater pipe.

4.1.4. UNMANNED UNDERWATER VEHICLES

UK researchers are advanced with the use of ROVs in spent fuel pools relative to US counterparts. Operators at Sellafield use pairs of ROVs with manipulators to sort waste using both vision and sonar feedback. The ROV pairs permit better situational awareness while the matching of high-resolution, 3-D sonar data to CAD models of the environment and known objects in the pools. This provides photo-realistic visualizations of the scene, even in the presence of sediment plumes stirred up by the ROV thrusters.

4.1.5. PIPE INSPECTION

Pipe inspection inside active evaporators is achieved with long, unpowered snakes carrying arrays of displacement sensors. The snake is first pushed down the inside of the pipe and then pulled back out while the inductive sensors (typically eight arranged radially around the “spine” of the snake) provide high-precision measurements of pipe diameter. Each array of sensors, while only roughly centered in the pipe, provides an accurate measure of cross-section to an accuracy of about 60 microns. While some “shine” affects the sensor snake, it is on the “clean” side of the pipe and not prone to contamination.



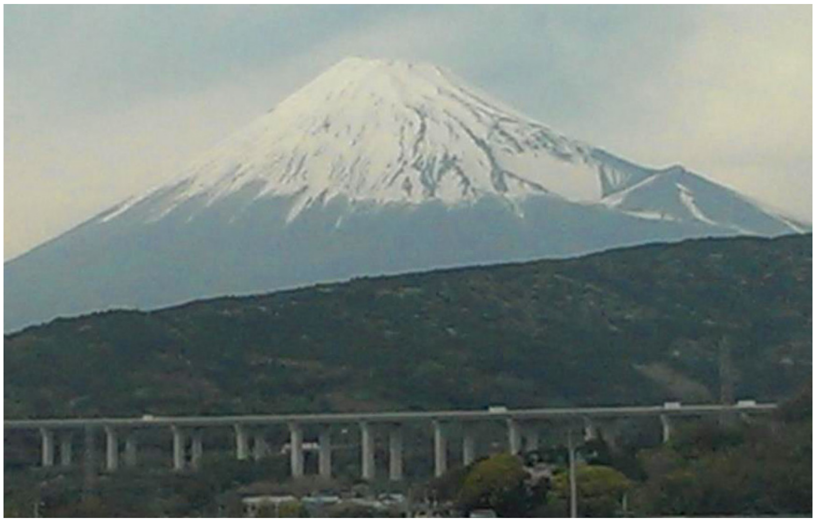
The point cloud resulting from a UAV scan of a room in the lab.

4.1.6. UAV-BASED SLAM

NNL researchers have used UAVs equipped with LIDAR to map complex areas with overlays of temperature imagery which can help them localize “hot spots” and areas of concern. The 3-D models of the piles can also provide initial plans for sorting and unpacking the waste. An example point cloud is shown in the adjacent picture.

4.2. Summary of the “DOE Satoshi Tour”, Japan

A United States delegation of DOE personnel, national labs administrators and researchers, Electric Power Research Institute (EPRI), and university researchers took a week-long tour of various Japanese facilities engaged in robotics research and development related to the clean-up of Fukushima Daiichi. The tour was organized on the U.S. side by Dr. Rod Rimando of DOE-EM, and included Dr. Richard Voyles, Professor and Associate Dean for Research, Purdue University, Dr. Robin Murphy, Professor, Texas A&M University, Dr. Bill Hamel, Professor, University of Tennessee, Dr. Steven Tibrea, Savannah River National Lab (SRNL), Dr. Tom Nance, SRNL, Dr. Phil Heermann, Sandia National Lab (SNL), Mr. Jon Salton, SNL, Dr. John Jansen, Electric Power Research Institute (EPRI), Dr. Rob Ambrose, NASA, and Dr. Josh Mehling, NASA. The tour was organized on the Japanese side by Dr. Satoshi Tadokoro, Professor, Tohoku University and President of the International Rescue Systems Institute.

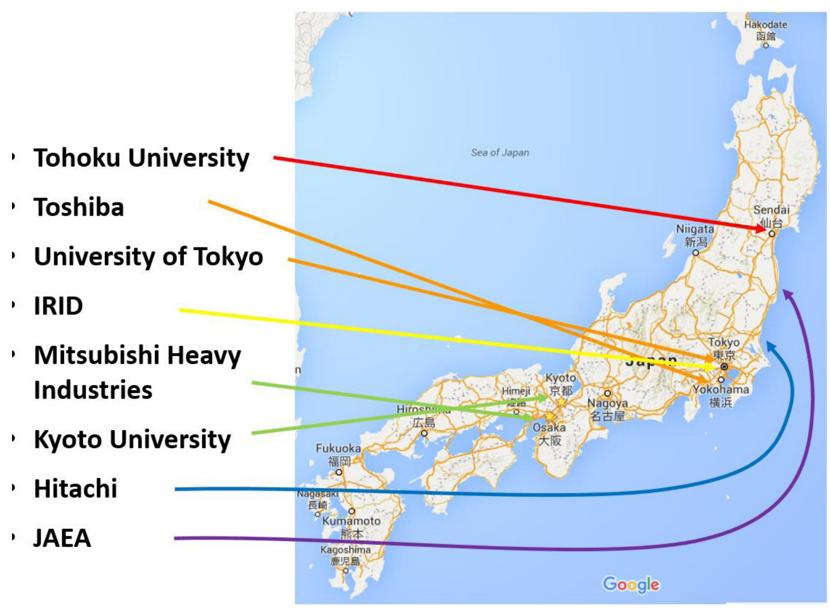


The team met with individuals from three universities, three companies and two quasi-government entities: Tohoku University, University of Tokyo, and Kyoto University; Toshiba, Mitsubishi Heavy Industries, and Hitachi; Japan Atomic Energy Agency (JAEA), including the Naraha test facility, and International Research Institute for nuclear Decommissioning (IRID).

4.2.1. TOHOKU UNIVERSITY

Tohoku University, in Sendai, was directly impacted by the earthquake and tsunami. Several buildings were damaged at the university and in the surrounding city of Sendai and loss of life in the local community occurred. Tohoku also has significant investment in emergency response robotics, which includes response to nuclear disasters. They have played a key role in the investigation and clean-up of Fukushima Daiichi, including being the driving force behind the insertion of the Quince research robot into early investigations of the inside of the reactor buildings (along with the iRobot PackBots).

Researchers at Tohoku University have been actively involved in robotics for hazardous environments for many years. Prof. Satoshi Tadokoro organized the visit of our delegation as he was involved in the roadmapping effort of which this report is a product and was also directly involved it the robotic response to Fukushima Daiichi. In addition, Prof. Tadokoro was one of the founders of the IEEE TC on Search and Rescue Robots and is the current President of the IEEE Robotics and Automation Society.



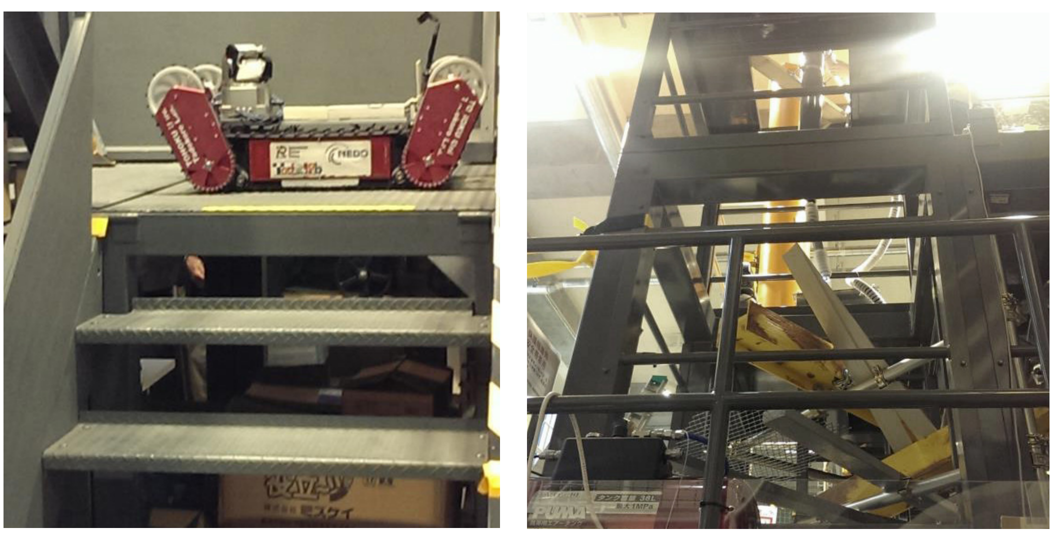
Map of Japan with visited sites chronologically color-coded in ROY-G-BIV order.

The team met with several professors and other researchers in an impressive test facility purpose-built for emergency response robotics. Some of the faculty involved in the tour included Profs Tadokoro, Tadakuma, Ohno, and Okada. The high bay contained a customizable tower for mock-ups of pipes, walls, and various forms of debris along with steps for climbing and descent. The steps included landings and variable tread materials.

Quince robot on a rubble pile (left) and in-use at Fukushima Daiichi (right).

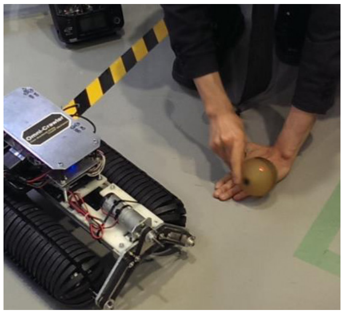
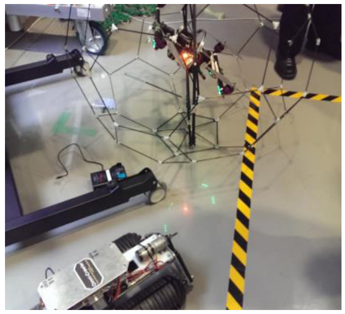
The high bay is a spacious area with Vicon cameras for ground-truth positioning that allows for numerous types of ground robots as well as flying space for UAV inspection robots. Demos included the Quince robot mapping its environment and climbing stairs and the Omni-Crawler, with its unique cylindrical tread mechanism. The ball-enclosed quadrotor UAV for inspection was demonstrated with its ability to come in contact with structures for stable viewing and up-close inspection. The Active Scope Camera, which is a serpentine-like device with a steerable, active tether that delivers a camera to remote inspection sites, was demonstrated inspecting the tower through pipes and debris. The tether has vibratory motion and directional scilia to propel itself while a twisting motion allows for highly agile locomotion through complex terrain. Finally, research with canines in search and rescue is enabled with dogs carrying camera/sensor packs into difficult environments.

Quince was tethered with an onboard reel with 400m of tether. They needed the entire length to reach the second floor of the reactor building. The robot was exposed to up to 75 mSv/hr (7.5 rem/hr).

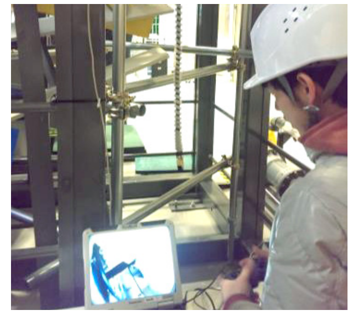


Mock-up tower at Tohoku University rescue robotics facility with Quince robot (left).

Overall, there was much activity around emergency response robotics with numerous innovative devices and approaches for inspection and remote navigation through complex environments. The labs the team visited had a clear emphasis on disaster sites and de-engineered inspection and situational awareness, which is directly relevant to the disaster climate caused by the Fukushima incident. This work is highly relevant to DOE for preparation and response to emergency scenarios and has applicability to decommissioning activities as well. The team saw nothing relevant to the routine processing and handling of waste.

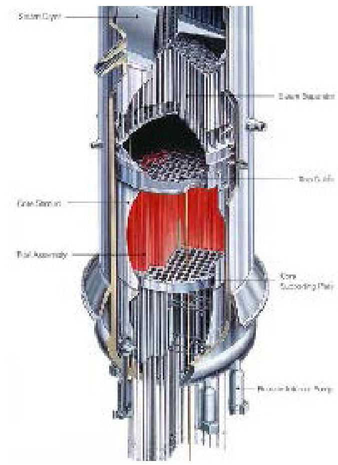
The Tohoku Omni-Crawler (left) and the UAV contact-inspection ball with Omni-Crawler (right).

Tohoku's Active Scope Camera (ASC) on a pile of rocks in the lab (left) and the operator console with PlayStation controller (right).

4.2.2. TOSHIBA

Toshiba has long been involved in the construction and maintenance of nuclear reactors and have been involved in robots for the remote handling of materials. A strength of Toshiba in Yokohama is the design and construction of reactor pressure vessels and turbines. They spent considerable time explaining to us their 6D CAD system for project management and immersive 3D projection room.

Toshiba has strong expertise in the nuclear industry for producing reactor vessels (left) and power turbines (right).

Toshiba has been engaged in the development of robots for the Fukushima clean-up and we were shown a few robots in a lab environment. They have developed a quadruped robot that can climb stairs and carry a wheeled tethered robot for inspection, but we didn't see it in action. It is designed to handle radiation at a rate of 100 mSv/hr (10 rem/hr) and be ready by 2020 for actual clean-up operations. They also have developed a small, scorpion-like, shape-shifting robot for crawling through pipes to access the primary containment vessel (PCV), but it is not clear if it has been deployed. A large amphibious robot for retrieving spent fuel rods was developed and tested in Fukushima. It was described to us as a manual operation, but published reports suggest autonomy. We were not shown this work, however, nor provided significant details, but they expect it to be operational by 2017.

They noted that there is a collaboration ongoing with United States entities on the water treatment system for tritium and technicium. Fukushima Daiichi has about 1000 tanks of about 1000 m3 (264,000 gal) each.

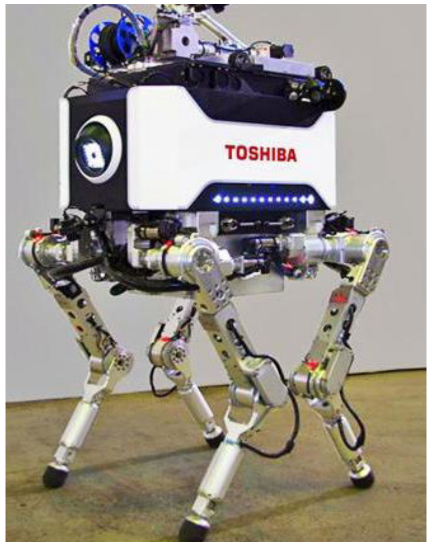
Toshiba used a custom robot with laser scanners to scan units 2 and 3, then used the scans to simulate the removal of a large structure that fell into the pool during the explosion. Unit 2 has internal radiation levels of about 20 mSv/hr (2 rem/hr). Toshiba built some pipe crawling robots, which rely on fairly simple actuation. They don't have any onboard sensing, but can deploy an inflatable bladder to seal off flow.

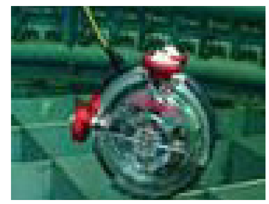
Rod Rimando, DOE, at Toshiba with a copy of the shape-changing "scorpion" robot that plans to enter the containment vessel (left). Posed image of the robot on a grate (right).

4.2.3. UNIVERSITY OF TOKYO

The University of Tokyo has a rich tradition of research in engineering and related fields, including robots for emergency response and search and rescue. The University of Tokyo also works with the Quince robot and the team saw computer vision work for greater situational awareness by providing synthesized third-person views of the robot and its immediate surroundings. (This was a common theme across several of the robotics labs that were visited.) In addition, the team saw acoustic analysis of materials by tapping. (This has an analogy to the WIPP, where they tap the ceiling to determine where to bolt.)

Researchers reported the Fukushima PCV could contain as much as 100 metric tons of melted mass at the bottom (64 tons of fuel melted together with other structures). TEPCO apparently built and 3D printed their own tracked robots with smartphones.





Toshiba quadruped robot that can climb stairs and carries a remote, tethered robot for inspection. An underwater inspection robot, far right, inspects inside the reactor vessel.

4.2.4. IRID

IRID is a government-mandated and government-funded consortium of stakeholders in the Fukushima Daiichi accident response that was formed in 2013. The members include TEPCO, JAEA, AIST, Toshiba, Hitachi, Mitsubishi, ATOX, and eleven additional power companies. Projects are funded 65% by the government and 35% by the member companies. It is not clear what level of funding the Japanese government provides, nor the method by which projects are proposed and selected. Projects seem to vary considerably in quality. According to published IRID reports, projects range from 300M yen ($2.8M) to 4B yen ($37M). Listed government subsidies are either 50% or 100% on a per-project basis. It is not clear how it is determined what level of subsidy is applied to each project.

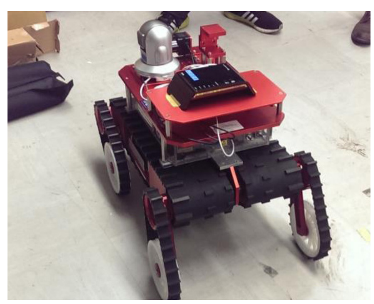
Through muon tomography, they had confirmed there is no heavy metal in the core area of unit 1. The fuel in the cores of the units prior to the tsunami included:

Unit 1: 69 tons

Unit 2: 94 tons

Unit 3: 94 tons

Unit 4: 0 tons

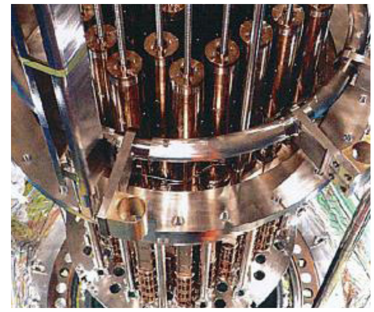


The Quince robot, left, is also being used at the University of Tokyo for research on autonomy and computer vision. Acoustic analysis of materials is represented on right.

4.2.5. MITSUBISHI HEAVY INDUSTRIES

Mitsubishi Heavy Industries is also a major builder of nuclear reactors and reactor components. The Kobe site also builds and services the new submarines built for the Japanese navy.





The US team (left), a reactor vessel produced at the Kobe site (center), and reactor internals (right).

Mitsubishi MEISTER two-armed robot with heavy duty versions of the PA-10 commercial manipulator (left). The MHI power suit allows heavy loads to be borne by the exoskeleton (right).

4.2.6. KYOTO UNIVERSITY

Kyoto University is another university with a rich history in emergency response and search and rescue robotics. Some of the faculty involved in the tour included Profs Matsuno, Nakanishi, Kamegawa, and Tanaka.

The US team with a Yamaha Rmax autonomous helicopter at Kyoto University.

Pipe inspection snake robots.

4.2.7. HITACHI

The shape-changing robot that was part of the demonstration was designed to fit through a 100 mm diameter, 7 m long pipe. The robot was designed to withstand 1000 Gy cumulative dose. It operated for three days inside the vessel until the camera died at about 10 Sv/hr. The robot took radiation measurements and pictures and the human operator used a map of the vessel to manually localize the robot. IRID sponsored the development and did the investigation. Hitachi also built a swimming robot to investigate the suppression chamber for leaks. To detect leakage, they used two ROVs; one to release a liquid target and the other to watch for drift with 2-D SONAR.

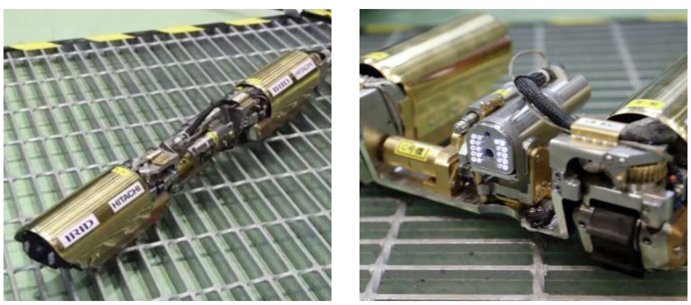


Figure 4.20: An example of the shape-shifting, tread-driven robot that was deployed into the PCV in April of 2015.

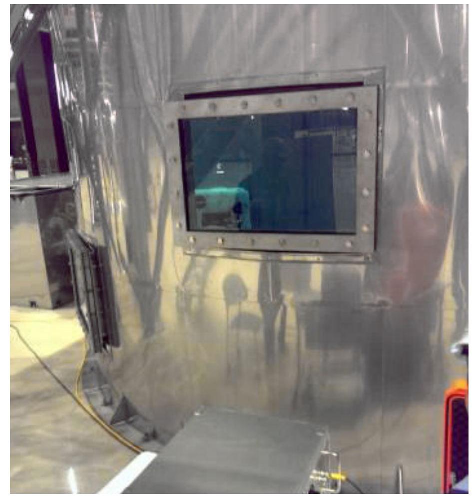
Figure 4.21: Actual image of the first deployed robot inside the PCV from the perspective of the second deployed robot. The first robot died after about three hours.

4.2.8. JAEA/NARAHA TEST FACILITY

The Naraha Test Facility is very impressive, with a 60 m x 80 m x 40 m high bay facility to house such things as a full-scale mock-up of a portion of the Torrus Room from Fukushima. Naraha also has an MOU with Disaster City (Texas A&M University) to share test methods and exchange exercises.

In the following figure, simple teleoperated robot of their own design is climbing a stairwell. A copy of the NIST step field is also available (middle). A large tank for underwater robots is available, as well (right).





The Naraha Test Facility has a customizable stair system to model stairs of different sizes and formats (left).

4.2.9. LESSONS FROM JAPAN TOUR

There are several lessons to draw from the Japanese experience:

- Workforce issues are important - TEPCO refused to use trained iRobot or Qinetiq operators. Instead, trained their own operators for one month
- Toshiba had some 3D laser scans of Fukushima before the tsunami which proved useful. Pro-active scans would be a good idea for all sites
- Communications have frequently dropped, some causing failure
- Operators have poor spatial awareness.
- Cameras gradually failed from radiation, but, in general, electronics did surprisingly well
- Lots of failures due to misoperation - training and HRI are key to operation
- Modularity is valuable due to familiarity, but usability is key to successful application
- Many universities use the Quince platform; commonality breeds leverage
- Active acoustic tapping can classify materials, like WIPP ceiling tapping to assess bolt quality
- Successful use of a consortium for oversight requires strong leadership
- Interoperability and standardization are important

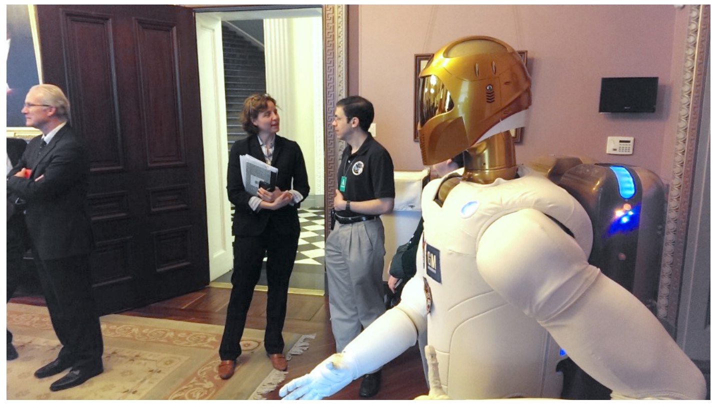
4.3. Report of Sites Visited During the "Texas Two-Step"

Yet another, but overlapping, delegation of government DOE personnel, national labs administrators and researchers, and university researchers took a week-long tour of various American facilities in Texas that are engaged in robotics research and development that have relevance to emergency response and clean-up operations. Texas was chosen as the first of several planned states to tour, due to the rich selection of government facilities, universities and non-profits that are engaged in nuclear clean-up R&D. Again, Dr. Rod Rimando organized the visits, which included Richard Voyles, Purdue, Robin Murphy, Texas A&M, Bill Hamel, University of Tennessee, Wendell Chun, CU Denver, Mike McLoughlin, Johns Hopkins University Applied Physics Lab, Mitch Pryor, UT Austin, Phil Heermann, Sandia National Lab, Young Park, Argonne National Lab, and Paul Dixon, Los Alamos National Lab. Presentations were made by Rob Ambrose, NASA/JSC, Josh Mehling, NASA/JSC, Robin Murphy, Texas A&M/Disaster City, Mitch Pryor, UT Austin, Ashish Deshpande, UT Austin, Paul Hvass, Southwest Research Institute (SwRI), Jerry Towler, SwRI, Morgan Quigley, Open-Source Robotics Foundation (OSRF), Debra Sparkman, American Society of Mechanical Engineers (ASME), Patty Loo, ASME, and Patrick Beeson, TRAClabs.

The team met with individuals from one federal facility, two universities, one company and two non-profit entities: NASA Johnson Space Center; Texas A&M University and University of Texas at Austin; TRAClabs; Southwest Research Institute and Open Source Robotics Foundation.

4.3.1. NASA/JOHNSON SPACE CENTER

NASA/JSC performs a wide range of research and development in extra-planetary vehicles and human-assistive robotics, including RoboNaut. RoboNaut-2 was a GM-NASA collaboration for a humanoid robot for astronaut assistance on the International Space Station (ISS). Currently, a version of RoboNaut-2, with legs, resides on the ISS. Valkyrie is a new generation of humanoid, derived from RoboNaut-2, that NASA hopes will find use in industrial applications for the handling of high-consequence materials in radiological and biological applications.



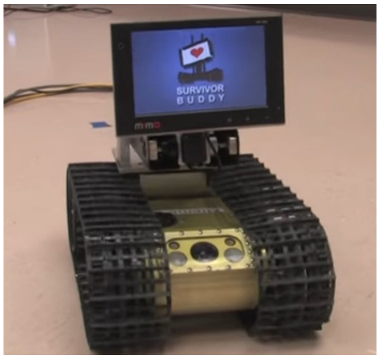
A copy of RoboNaut-2 currently resides on the ISS, with a pair of legs to move around in zero-G, left.Right, the RoboNaut torso is on display and can travel to remote sites, as in this file photo (courtesy Richard Voyles).

Valkyrie is the latest NASA/JSC humanoid that competed in the DARPA Robotics Challenge. Right, the RoboGlove, a "power glove" for human augmentation to reduce fatigue, is derived from Valkyrie. (right image courtesy NASA)

4.3.2. TEXAS A&M AND DISASTER CITY

Disaster City is a 52-acre emergency response "sandbox" operated by the Texas A&M Engineering Extension (TEEX). It is located adjacent to the Brayton Fire Training Field, also operated by TEEX, which hosts over 45,000 emergency responders every year. Disaster City is a unique facility with a wide variety of simulated disaster sites that covers nearly every type of structure, mode of transportation, and environmental hazard to host training exercises, equipment demonstrations, and test scenarios for commercial and research concepts.

Disaster City is a 52-acre complex adjacent to Texas A&M University. (right picture courtesy TEEX website)

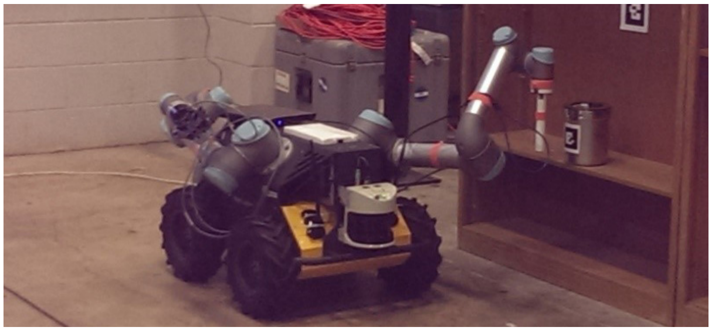


Dr. Robin Murphy's "Survivor Buddy." (courtesy Robin Murphy)

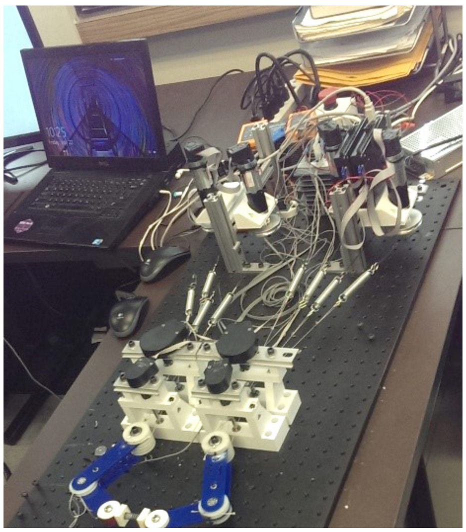
To bolster the activities at Disaster City, researchers at Texas A&M explore many aspects of emergency informatics. Robin Murphy explores human/robot interaction with "Survivor Buddy," a bi-directional emotive interface to reduce the stress of emergency survivors. Dylan Shell explores robotic information collection and sharing around spatial fields, representing such things as nuclear contamination.

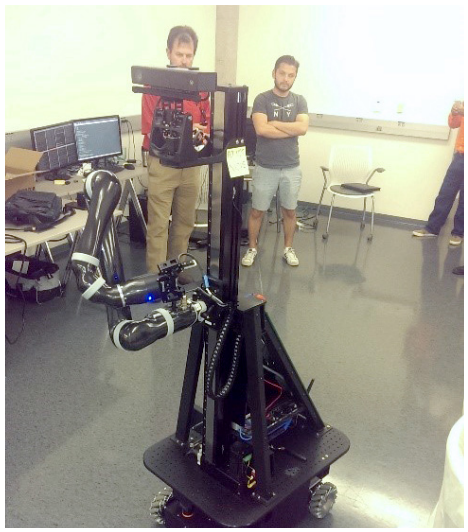
4.3.3. UNIVERSITY OF TEXAS AT AUSTIN

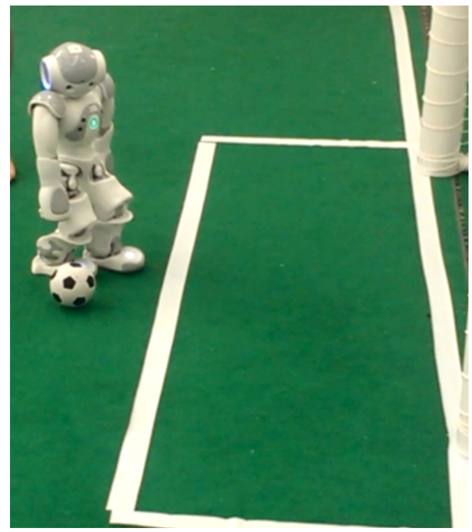
The University of Texas at Austin has particular strengths in both compute science and nuclear engineering. The nuclear engineering program is housed within the Mechanical Engineering Department and researchers study the remote sensing and characterization of nuclear samples and the facilities in which they reside.



A bi-manual mobile robot for inspecting radiological samples in a warehouse environment, left. Another warehouse inspecting robot "sniffs" the floor to look for possible spills and other forms of localized contamination, right. This robot tirelessly searches the entire floor and maps evidence of contamination for future comparisons.





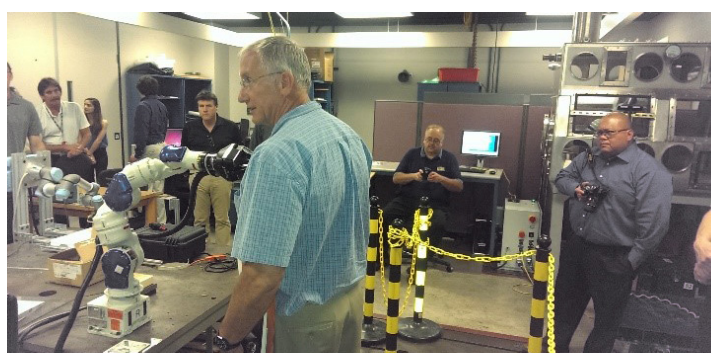


Ashish Deshpande's lab, left, examines human grasping and control. Andrea Tomaz's lab, right, explores human-centered robotics and natural interfaces.

A small humanoid robot in Peter Stone's lab has learned to play soccer on a robot team. They can kick, pass, and even use mis-direction to fool opponents.

4.3.4. SOUTHWEST RESEARCH INSTITUTE

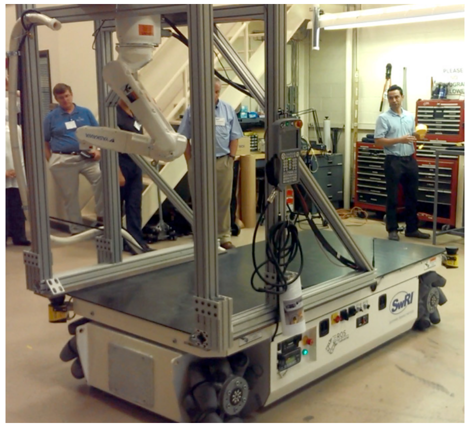
SwRI also represents a wide range of research interests, spanning many key topics of national significance. For example, SwRI leads the ROS-Industrial (ROS-i) initiative, which is an industrial consortium promoting the hardening of ROS packages and basic components to make them more suitable for incorporation into commercial products. Morgan Quigley, of OSRF, presented status on the ROS 2.0 and ROS-i software developments, including a description of the benefits of open-source development for for-profit entities. SwRI uses ROS for much of its robot-related development, including several DOE projects. The team was also given a primer on software quality assessment standards and their relationship to nuclear quality assessment.

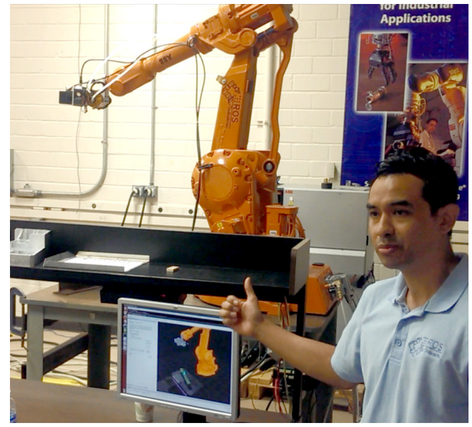


Left, the SwRI autonomous vehicle took attendees on a fully autonomous drive on a closed test course on the SwRI grounds. Right, Philip Heerman, center, and Rod Rimando, right, look on as SwRI personnel demonstrate a glove box robot.

SwRI treated the team to rides in their self-driving car on a closed test track. This project is of direct relevance to DOE needs as fork lift automation is under consideration to improve worker safety and reduce accidents. Some of SwRI's self-driving car technology and expertise have been integrated into a self-driving fork lift that was demoed at the Portsmouth Site in August of 2016 as part of the Science of Safety program.

The team also saw several projects for the safe handling of high-consequence materials in or around glove boxes.





In a project similar to that at the Sellafield site, above, SwRI researchers are creating a virtual representation of the robotic workcell to test programs and operations.

4.3.5. LESSONS LEARNED FROM THE "TEXAS TWO-STEP"

After the tours, a "Robotics Retreat" was held in San Antonio to discuss the trip and to plan future actions leading toward a robotics roadmap for DOE/EM.

4.4. Summary of the ISOFIC Visit, South Korea

A small delegation of United States individuals took a week-long visit of a few sites in South Korea in connection to their nuclear waste handling activities. The tour was organized on the U.S. side by Dr. Young Soo Park, Argonne National Lab, and on the South Korean side by Dr. Jisup Yoon, and included Dr. Richard Voyles, Professor, Purdue University, Dr. Wendell Chun, Professor, University of Colorado at Denver, Prof. Leo Lagos, Professor, Florida International University, and Dr. Mitch Pryor, Research Scientist, University of Texas at Austin.

The team presented talks on their own research and development work on nuclear waste handling at the International Symposium on Future Instrumentation & Control for Nuclear Power Plants (ISOFIC), meeting numerous individuals from universities and government entities. They also visited a Korea Atomic Energy Research Institute (KAERI) facility and met with two representatives of the Korea Ministry of Science and ICT (Information and Communications Technology). The team also was given a tour a several cultural sites important to the Republic of Korea.

4.4.1 ISOFIC SYMPOSIUM

ISOFIC is an international symposium held every three years in South Korea. Started in 2002, the symposium brings together experts from around the world to report on challenges and solutions for instrumentation and control of nuclear power plants, their safety systems, and related facilities. The team exchanged information with the Korean hosts on robotics roadmapping efforts in both countries. The Korean roadmap was presented by Dr. Kyung-Hoon Kim, Program Director of the Korean Evaluation Institute of Industrial Technology, a part of the Ministry of Trade, Industry and Energy (MOTIE). The Korean roadmap is in its second 5-year period with an investment at around $60M per year. (The roadmap is available on the web in Korean only with no English translation -- http://www.korearobot.or.kr.) Korea sees the need to take a leadership role in robotics, starting with manufacturing and expanding towards the service industry.

Members of the US delegation join the ISOFIC conference in Gyeongju, South Korea.

For Korea, robotics is considered a Next Growth Engine and one of 12 Industrial technologies for industrial restructuring . For example, Hyundai uses a combination of their own robots and Robotstar robots (cheap and modular to assemble individual joints one at a time). Korea is expanding into the service sector with robotic vacuums and medical robots. There is AI shock in Korea, and the country has embraced the coming 4th Industrial Revolution. For the next generation of robotics, they are working on collaborative robots, dual arm robots, and plan for 20,000 Smart Factories.

Dr. Jisup Yoon presented the status of the Nuclear Robotics Laboratory at KAERI. They are chartered with the maintenance and inspection of nuclear power plants. A major focus in their lab are on emergency response systems (K-R2D2, ATV with multi-rotor copter, high extension mobile robot), D&D robots, Calandria robot, and a Raman LIDAR for hydrogen detection.

4.4.2 KAERI FACILITY

Left, the US delegation joins the Korean KAERI delegation in Daejeon, South Korea. Right, presentations by the US and Korean delegations focused on nuclear materials handling and policy.

The team was able to see first-hand the many robots presented at the ISOFIC conference. For example, the K-R2D2 robot of Dr. Sun Young Noh was presented that is being developed for emergency applications. The team also observed Dr. Jongwon Park's collaborative robotic ATV with a large multi-rotor drone carried on its tail for a two robot team by a teleoperator. The teleoperator would drive the ATV to a site, then switch to flying the drone. He is also preparing for an underwater robot challenge with a UUV in Australia later this year. The KAERI robot group is led by Dr. Kyungman Jeong, supported by Dr. Young Soo Choi and Dr. In Soo Koo. They showed two generations of a large hydraulic manipulator, a mobile robot that has an extendable mast that can rise over twenty feet, and various ground robots with articulated tracks. Of note is a full-scale mockup of a facility for an emergency response challenge, similar to the DARPA Robotics Challenge. A robot must climb a ladder or stairs two stories to a top floor where the robot must close a large valve. They also showed a medical imaging mechatronic device/robot used in the past, and a clever mechanism to exchange cylindrical fuel rods. In addition, there was a second warehouse of older robots, including an old PUMA manipulator and KUBO humanoid robot.

4.4.3 MINISTRY OF SCIENCE AND ICT

The last day included a meeting between the visitors and Mr. Woochul Kim from the Ministry of Science and ICT. He schedules US-Korea relations, and discussed opportunities for collaboration. Mr. Kim has open line opportunities for D&D activities including robotics, and would like to add another new line item for both countries to collaborate on. He has some candidate Korean entities that they would fund from their side that matches US investments.

4.5. Future Opportunities for DOE

The US DOE used to be a leader in robotic nuclear waste handling in the 1980's and 90's, when a greater premium was placed on technology development. In the early 2000's, EM emphasis shifted to site closure, based largely on the "low-hanging fruit" opportunities created by extensive technology development. Now that these remediations enabled by prior technology efforts has been harvested, it is time to refocus on the next generation of technologies that will enable the next leaps forward. It appears, from comparisons to other international sites, DOE is now behind the curve, so this is an important area of R&D for both efficient and safe processing of nuclear waste and for the control of the massive costs of nuclear processing.

DOE could experience substantial benefits in economics and efficiency from a comprehensive program of research and development in robotics for nuclear waste processing and remediation. In turn, investment in such a program will return quality of life benefits for many US citizens employed in the nuclear waste processing and remediation industries and the environmental health of the nation will also be enhanced. This program should consist of a mix of the following:

- Use-inspired extramural research engaged with the academic community through the National Robotics Initiative
- A university/industry center of excellence (COE) focused on robots and sensors for nuclear waste management
- Development of open testbeds for the evaluation of new technologies by industry, academia, and the national laboratories
- A workforce development program, that stresses the STEM Continuum "from HS to MS," and includes curricular development, student recruitment and placement, and targeted media
- National labs
- SBIR topics
- The formulation of a set of grand challenges for the re-processing industry

This could start in FY16 with modest investment of $5-10M in the NRI, plus some initial foundations for the broader program, such as the CoE and grand challenges. In FY17, a $40-50M program could:

- Continue investment in NRI projects
- Compete and award the center of excellence
- Initiate the workforce development program
- Launch some SBIR topics

Subsequent years could build programs at the national labs and initiate testbeds at the COE and at national laboratories.

4.5.1. NATIONAL ROBOTICS INITIATIVE

To participate in the NRI in FY16, existing money would have to be carved out, the MOU draft must be finalized and signed, and text must be written for the solicitation. FY17 money could be hashed out in the budget process. Some potential solicitation text:

In the evermore interconnected world, our nation has to address high consequence but low probability events across multiple disciplines. What might be needed in one high consequence situation could be applied to another. The potential synergistic application of robotics has the potential to provide greater safety in handling biological, extra-planetary, radionuclear, and environment materials in ways never imagined before and allow for sharing tools and benchmarks. Generalizations of worker studies could lead to greater understanding of the science of safety.

4.5.2. WORKFORCE DEVELOPMENT

Existing sites employ a large number of STEM workers at all levels and a comprehensive program should be initiated to feed the pipeline for the generations of workers that are needed for this critical industry. A key aspect of this work is raising the profile of the opportunities and benefits of working in hazardous waste cleanup through a media campaign. Coupled with this must be an effort to improve the image of the value and working conditions of this industry.

Curricular development at the AS, BS and MS degree levels could be helpful in raising the profile of the industry. The recruitment of potential students, including scholarships for candidates sponsored both by government and industry, would feed several national priorities.

4.5.3. CENTER OF EXCELLENCE

Establishing a national center of excellence on Robotics Handling of High Consequence Materials at a leading university or collaboration of universities could serve as a focal point for curriculum development in nuclear materials handling; as a catalyst for technology transfer between universities, national laboratories, and private companies; as an innovation incubator; and as a hub for research and results dissemination.

KEY FINDINGS AND OBSERVATIONS

Based on the observations from the four primary U.S. site visits (Hanford, INL, WIPP, and SRNL), a summary of the committee member's experience related to other DOE activities, and the collective previous experiences working with the DOE Complex and recent participation in other related workshops and meetings, the committee makes the following recommendations:

- There are DOE-EM activities that – in the short term (1-4 years) – can be completed using robotic technology available today and that will have quantifiable and positive impact on the DOE-EM mission as it relates to safety, cost, and reduced mission time.
- These short-term activities can be used to not only demonstrate and deploy robotic technological solutions, but also used to develop the next generation of DOE lab and site engineers in the medium term (3-6 years) that ensure that the DOE complex has the internal capabilities utilize and further develop automation and robotic technologies.
- Given the 50+ year extended timeline for DOE-EM, this workforce is then well-positioned to look at the DOE-EM mission needs with the clean slate to develop and deploy solutions in the long-term (6-20 years) that utilize the rapidly advancing capabilities seen in robotics today.

These recommendations provide impact in the short-term and – with the continuous dedication of DOE – provide momentum that ensures robotic and automation technologies can and will positively impact the many sites and challenges remaining across the complex for decades to come.

5.1. Specific Recommendations

The 1945 publication of Science the Endless Frontier, at the behest of the Roosevelt administration, was a watershed moment for research and development in the United States. World War II represented the first investment in private research and development as a national resource by the federal government and the first recognition of R&D as an infrastructural priority. The resulting public/private partnerships produced incredible advances in the war effort, including radar and atomic technology, and Science the Endless Frontier paved the way for continued investment in that infrastructure.

Nearly 75 years later, that tradition of investment in R&D has grown stronger and much more significant and has infused civilian and military agencies. NSF, NIH, DARPA, DOE and many others invest considerable resources into public/private partnerships in both direct R&D and also the infrastructure that begets R&D. The laser, Google search, battery advancements, and stealth aircraft have all been born of federal investment in private research and have all had enormous benefit to the American economy. Many examples of robotic technology have been amplified by federal investment for the greater good.

One such example is the Robotics Operating System (ROS). ROS is properly described as "software infrastructure" that has enabled many researchers and even corporate developers to "stand on the shoulders of giants" by sharing code, applications and data sets and has substantially reduced the need to "reinvent the wheel." While ROS was popular among developers and researchers, leading to significant advances, it floundered in the commercial world as corporate interests preferred proprietary systems. But a forward-thinking consortium of government agencies, consisting of NSF, NASA, DARPA and the Army, saw the value in the common infrastructure that ROS provided and the economic multiplication of their research investments as fewer researchers were reinventing the wheel.

The recognition that investment in research and research infrastructure is good for federal agencies, for financial stewardship, and for the American economy is an important cornerstone of what the participants in this survey activity view as key to their recommendations. The DOE has a long and successful history of funding R&D and DOE-EM, in particular, has reaped the benefits of strategic investment in future technologies that have reduced the cost of operations and improved the safety of workers engaged in the EM mission. The R&D investments made in the 1980s and 90s laid the foundation for the exceptional cleanup efforts that DOE-EM has achieved over the past 15 years. But, the operational budget priorities that have resulted in these stunning cleanup efforts have become out of step with the developmental budget priorities needed to achieve the cleanup efforts of the next 20 – 50 years. The top recommendation of this report is the return of budgetary support for R&D and R&D infrastructure at levels commensurate with the 1990s: roughly 5.5% of the total DOE-EM budget.

5.1.1 RESTORE TECHNOLOGY DEVELOPMENT INVESTMENTS TO PRE-2000 LEVELS

DOE made a conscious effort over the past 15 years to accelerate the pace of cleaning up and shutting down a large number of aging, highly contaminated facilities. This effort has been highly successful, both in objective measures of progress and in subjective measures of community citizenship. However, the remaining difficulties are complex and long-term (multiple generations of engineers and technologists) and demand technological solutions that do not currently exist. Current EM stakeholders must devise a long-term plan to realize these solutions.

5.1.2 STUDY THE IMPLICATIONS OF WORKFORCE DEVELOPMENT AND TRAINING ON THE INTRODUCTION OF ROBOTIC SYSTEMS

Robots can have a profound impact on the workforce, both physical, mentally and emotionally. The pride of employment at a government lab or site, the fear of losing a job, the drudgery of menial jobs that only “feed” a robot, and the lack of proper training for new technologies are all important concerns for robotic adoption. It was clear from many site visits that workforce implications at DOE installations are critical to decisions on robotics and other technologies, but are rarely made explicit. These aspects should be examined and explored in greater detail.

For example, most robotic systems require some training for them to be operated safely and effectively. This training should not be neglected or underemphasized. As robotic tools become more prevalent at EM sites, site managers should consider providing general robotic safety courses, in addition to system-specific training. Dual-use applications, such as inspection robots that can double as emergency response tools, can increase the efficiency of training. In addition to training the workforce, site managers should actively solicit feedback from the workforce to ensure that the systems are meeting their needs and that potential improvements can be identified and fed back to TDO and developers. Proper training and preparation will help avoid the misuse of technology which can cause skepticism among the workforce and reduce openness to new capabilities.

5.1.6 ENGAGE THE R&D ECOSYSTEM

It is necessary that technology providers gain an in-depth understanding of the EM site needs and challenges and carefully consider the implications of that knowledge in order to make implementable proposals. Most academic and corporate researchers have little appreciation for the environments and complexities faced at DOE sites, as the relationships needed to grow this appreciation are difficult to nurture. Yet it is in DOE’s interest to expand the pool of performers that can adequately respond to DOE site needs, both short term and long term. DOE should do more to purposely engage the R&D community as this can not only result in more successful implementations, but can also significantly reduce long-term operational costs through more efficient competition.

Likewise, it is important that the DOE complex stay in intimate contact with innovators outside its reach. It was apparent, in certain contexts, that DOE capabilities have fallen behind those of others within the national sphere or the international community. It is vitally important that a vigorous and engaging climate maintain familiarity with and the ability to harvest these developments that are happening outside the normal DOE purview.

5.1.7 PLAN FOR TECHNOLOGIES OF THE NEXT SEVERAL DECADES

Technology is advancing at such a profound rate that it is difficult to foresee opportunities on the time scales that DOE-EM regularly faces. Looking back over what has transpired in the past 40 or 50 years presents only a glimpse of the magnitude of changes expected in the next 40 or 50 years. “Planning for the un-plannable” should be a mantra at DOE. An example is “black cells” with no access for future robotic systems. Building in access ports for systems we can’t yet conceive seems like low-cost insurance for a difficult-to-foresee future.

Contributors

A large number of individuals from universities, companies and government agencies contributed their time, their insights, and their expertise to produce this report. Numerous visits to domestic and international sites involved expert observations and comments, discussions amongst visitors and site personnel, as well as demonstrations and physical artifacts that were invaluable to the effort. The editors listed below could not have completed this report without their valuable observations and notes.

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