CASE STUDY OF ROBOTIC DISMANTLING OF ETTP BUILDING K-1420 URANIUM RECOVERY AREA B

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ABSTRACT

RedZone Robotics Inc and Decon Recovery Services (DRS) of Oak Ridge, with support from Providence Group and ORNL X-10, recently completely the first full scale commercial deployment of Rosie, a teleoperated robotic worksystem designed by RedZone. The system was used as a dismantlement platform in building K-1420, area B, of the former K-25 site at Oak Ridge National Lab. Building K-1420 was the decontamination and Uranium Recovery Facility for the K-25 site (now the East Tennessee Technology Park). Housed in area B are the calciners and recovery solution feed columns as well as associated equipment such as controls, gages, piping, slab tanks, and pumps. Due to the nature of the materials involved in the UO_2F_2 recovery process, dismantlement methods that reduce worker exposure, as well as reducing other factors such as heat stress and injury, were appealing. The Rosie teleoperated robotic work platform was designed for just such an application. Outfitted with additional robotic end effectors and tooling, as it was for the effort at K1420, it proved a very versatile tool for remote dismantlement of such a facility. This paper will present the results of the deployment of the Rosie system in Area B of building K-1420.

BACKGROUND

The Rosie system as deployed at ETTP building K-1420 is actually a combination of three separate sub-systems. These are Rosie, two Schilling Titan 7F light duty hydraulic robotic manipulators, and a Lukas hydraulic shear.

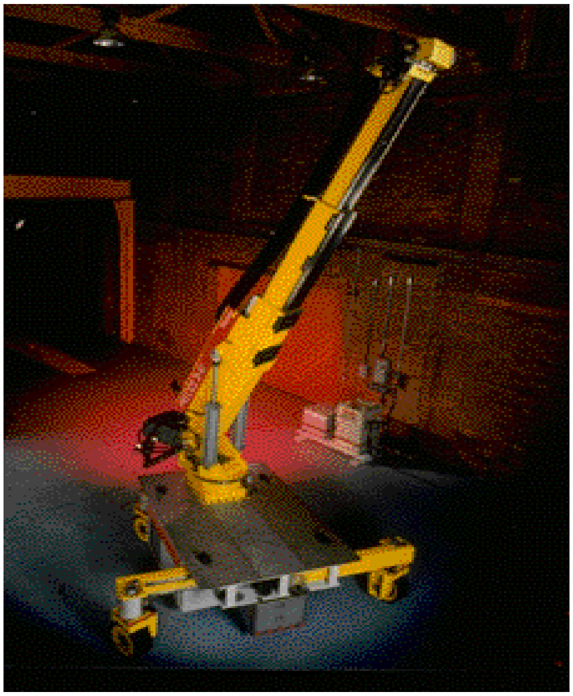

Fig. 1. Rosie System

Table I. Locomotor

Width (extensions in	218 cm	86 in.
Width (extensions o	356 cm	140 in.
Height	107 cm	42 in.
Length	310 cm	122 in.
Obstacle Climb	10 cm (max.)	4 in (max.)
Ground Clearance	15 cm	6 in.
Minimum Turning Radius	0 cm	0 in.
Driving Speed	0 to 0.6 m/sec	0 to 2 ft/sec
Reservoir Capacity	284 l	75 gal
Fluid	Water Glycol	
Reservoir Capacity	284 l	75 gal
Pump Capacity	114 l/min @ 207 bar	30 GPM @ 3,000 psi
Hydraulic Power	45 kW	60 HP
Tether Reel Capacity	50 m	165 ft
Electric Input Powe (to PDU)	480 VAC, 3Ø	@ 125 amps
Weight	3,900 kg	8,600 lb.

Table II. Heavy Manipulator

	Motion	Speed
Waist Rotatic	+201° -153°	±0 to 3 deg/sec
Shoulder Pitc	+90°, -20°	±0 to 3 deg/sec
Forearm Extension	3 to 6 m 10 to 20 ft	±0 to 15 cm/sec ±0 to 6 in./sec
Wrist Pitch	±90°	±0 to 3 deg/sec
Payload Capacity	900 kg with 6,800 Nm	2,000 lb. with 60,000 in.-lb.
Boom Services: Hydraulic Electric	 57 l/min @207 bar 120 VAC	 15 GPM @ 3,000 psi @ 20 amps
Weight	1,950 kg	4,300 lb.
Counterweigh Capacity	0 to 680 kg	0 to 1,500 lb.
Weight	1,950 kg	4,300 lb.

Rosie is a hydraulically powered mobile robot worksystem developed for nuclear facility D&D. Its primary function is to perform a variety of dismantlement tasks remotely by deploying tools, sensors, and/or other robotic equipment into hazardous areas. Rosie's capabilities and system design address the need for durability and reliability in these environments, and enable performance of tasks such as piping and process equipment removal, structural demolition, vessel segmentation, waste handling and transport, and wall and floor decontamination.

Rosie measures 6.5 feet wide by 9.5 feet in length (14 feet to the heavy manipulator tip) and weighs about 14,000 pounds. The system includes a tethered robot, a power distribution unit (PDU), and a control console for robot operation. The robot consists of two major subassemblies, the locomotor and the heavy manipulator (HM). The locomotor is a hydraulically powered, omni-directional platform with onboard tether management. It provides mobility to transport the heavy manipulator, tools, or other payloads within the work area. Locomotor specifications are shown in table 1. The HM is a four degree of freedom, high-payload, long-reach mechanism capable of carrying a variety of tools, one or more dexterous manipulators, or any other payload of up to 900 kg (2,000 lb.) throughout a generous work envelope. Rosie is a tele-operated system with low-level automation features that facilitate more efficient remote operations and allow a single operator to maneuver and work effectively. All axes are servo controlled allowing precise, variable speed positioning. The specifications for the heavy manipulator are shown in Table 2.

Located within the locomotor is the hydraulic power supply, which is a 45 kW (60 HP) supply. The hydraulic fluid reservoir is located at the front center of the locomotor. Directly behind it is the hydraulic pump and its electric drive motor. All of the control valving for the system is located above the pump and motor, inside the locomotor frame. Filters, an accumulator, and the hydraulic fluid cooling equipment are all located on the right side of the locomotor, in one of two side enclosures suspended from the frame. The other side enclosure contains all onboard control electronics for the system. At the rear of the machine is the tether reel, which can carry up to 50 m (165 feet) of tether. Up to 100 m (335 ft) of unreeled tether can be included to extend the vehicle's range.

Rosie's operator is provided with extensive feedback information to support remote operations. Audio and video feedback are provided from onboard microphones and up to 12 onboard cameras, with various combinations of focus, zoom, lights, microphone, and pan and tilt motions. All cameras are modular to allow easy replacement or relocation in order to accommodate different tooling or task requirements.

Position readouts of all heavy manipulator and steering motions are displayed at the console. This provides the operator with a clear understanding of the heavy manipulator position and orientation at all times, as well as the steering angles of all four wheels.

Rosie's control system is comprised of an operator control console and onboard control system components linked by a telemetry system. Using this control system, a single operator stationed at the console can control the Rosie worksystem. Primary system functions—locomotor, heavy manipulator, system power, tether, and cameras—are controlled using switches and joysticks on the console panel. Vital system status information is displayed on the console status panel. Less frequently used functions and status information are accessed through the touch screen. Three video monitors, with quad-splitting capabilities, display the onboard camera views. The operator can select any camera view for any of the monitors using the touch screen controls. In this way, each operator can configure the control console monitors to suit his or her particular preferences. These views can be easily and quickly changed during operation of the system, as needs arise. The control system software is transparent to the operator. No keyboard or mouse is required to run the system.

All axes are servo-controlled enabling precise, variable speed motion control for dexterous positioning either by tele-operation or by computer control. This servo-control allows the computer to coordinate the motions of the locomotor wheels in any of three different steering modes enabling the locomotor to move forward and reverse, side to side, and any angle in between as well as to turn about a point.

Rosie is capable of deploying a wide variety of tools and other payloads throughout a generous work envelope. The tip of the heavy manipulator can extend to reach 26 ft above the floor in the straight up position, 14 ft beyond the front edge of the locomotor in the straight ahead position, and at least 15 ft beyond the edges to either side of the locomotor. All wheels are independently driven and steered, making Rosie highly maneuverable in tight or cluttered spaces. Each front wheel can be extended 30 in. to the side for added stability and the locomotor can be driven with these wheels extended or retracted. The pivot-mounted rear axle provides compliance when working on uneven floors and crossing obstacles. As a hydraulic system, Rosie is intrinsically sealed against contamination.

The Schilling Titan 7F is a high velocity, spatially correspondent, remote manipulator system. Developed approximately fifteen years ago, it is comprised of a hydraulically powered seven degree of freedom slave arm, a slave arm controller, a master controller, and associated electrical cables, hydraulic hoses, and junction boxes. The operator uses the master controller keys and "mini master" arm to control the functions and movements of the slave arm. The master controller inputs are processed and compared to the slave controller slave arm position data. The slave controller then sends electrical signals to the appropriate servo valves on board the slave arm which releases hydraulic fluid to the actuators, resulting in the desired movement. The mini master axes correspond to the slave arm axes and include shoulder asimuth, shoulder pitch, forearm pitch, wrist pitch, wrist yaw, wrist rotate, and gripper. The slave arm weighs approximately 150 pounds in air, has a maximum reach of 78 inches with a lift capacity of 250 pounds at full extension. The jaw is capable of grasping objects up to 4 inches in diameter and has a grip force of 350 pounds. The jaw grippers are supplied with a milled 3/8 inch diameter T slot which facilitates positive gripping and positioning of tooling outfitted with mating T handle. The wrist has two rotate modes, a slaved ±135 degree rotate mode and continuous 0-90 rpm rotate mode. Wrist torque is 110 foot pounds. The speed of all the axes is scalable and each axis can be locked in position by disabling the corresponding servo valve. The slave arm requires a hydraulic power supply capable of delivering 3.0 gallons per minute at 2000-3000 pounds per square inch. Because some of the slave arm hydraulic return lines also serve as conduits for position signal wires, the hydraulic fluid must be oil based. The slave controller requires either 120/240 VAC or 20-30 VDC power input. The master controller is powered by 120VAC.

The Lukas 600 LSI shear is a heavy duty, high cutting force hydraulically powered unit. It employs a linear actuator to drive opposed hardened steel blades, which deliver almost 61,000 pounds of force at the cutting surface. The unit weighs approximately 50 pounds. The maximum cutting diameter varies with material. For example, it is capable of shearing 1 inch diameter solid steel rod, 2.3 inch diameter x 0.125 inch wall steel tubing, or 2.5 inch x 2.5 inch x 0.25 inch steel angle. The shear is powered by an Enerpac Titan 10,000 pounds per square inch low flow hydraulic power supply.

THE FACILITY

Building K-1420 was previously the Decontamination and Uranium Recovery Facility for the K-25 Site (now known as the East Tennessee Technology Park (ETTP)). The facility is located on the northeast corner of ETTP. Building K-1420 has not been used for decontamination and uranium recovery for several years and the entire facility is being decontaminated and decommissioned. During normal operation of K-1420, various pieces of equipment, contaminated primarily with UO_2F_2, were brought to K-1420 and washed with nitric acid solution. The contaminated solution was collected in slab tanks and holding columns. Following various volume reduction methods, the uranium solution was calcined in order to facilitate uranium recovery. The resultant material from the calcining operation was stored in Area C. The equipment in Area B - ten feed columns, the two uranium recovery columns, floor pans, and associated piping and equipment - were part of the uranium recovery process. Any product material in the columns, piping and equipment was assumed to have evaporated to sludge during the last several years. A figure showing the facility is attached at the end of this paper.

Area B measures approximately 180 feet East-West by 40 ft North-South. There is a second floor steel grate mezzanine approximately 15 feet above floor level and the ceiling rafters are 22 feet above that. The solution and feed columns that are part of the column array in Area B of Building K-1420 all have outer diameters of 5.563 inches. Columns 1 through 10 are the feed columns. These columns are 26 feet 3.5 inches tall. The solution columns have an east/west separation distance of 96.5 inches and a north/south separation distance of 93 inches center to center. Columns 11 and 12 are the uranium recovery columns. The uranium recovery columns are 24 feet 7.5 inches tall. The feed columns have a separation distance of 84.5 inches center to center. There are two holding tanks, which are 5.563-inch in diameter by 146 inches long. They are located 4 to 6 ft under the 10-solution columns midway between the two rows. There is one corridor approximately 7 feet wide that runs East-West the length of Area B that is clear of process piping and equipment, but the rest of the facility is a maze of process pipe, tubing, and electrical conduit. The floor pans (1.5" deep), columns, and other equipment are all constructed of 304L stainless steel.

Excluding the Calciners, NDA data indicated that the residual U^{235} in B Area may be in excess of 285 grams or approximately 13% of a safe mass. The Characterization Report indicated surface contamination levels as high as 40,000 dpm/100 cm squared Alpha and 2,600,000 dpm/100 cm squared Beta. Loose contamination levels were measured as high as 13,000 dpm/100 cm squared Alpha and 700,000 dpm/100 cm squared Beta. Whole body doses reach 10mR/hr Beta in some areas. Personal protection equipment required included double coveralls, booties, double shoe covers, double gloves, skull cap, hood, and full face respirator. Prior to beginning any removal of equipment, the electrical service was disconnected and the piping systems in the area was verified to be drained and open to the atmosphere. Any piping, conduit, or equipment not to be removed was blazed green.

INITIAL REPAIR, MAINTENANCE, AND TESTING

Reassembly of Rosie and system testing was performed the last week of February 2000 by a team of RedZone and DRS personnel in an area referred to as the "spool destruct", a three side shelter adjacent to the main K-1420 building. Prior to the project at K-1420, Rosie was deployed at Argonne National Lab in Chicago to assist in the dismantling of the CP-5 graphite reactor. Following the completion of that project, Rosie's heavy manipulator was removed from the locomotor and the two assemblies were put in a land-sea container for storage. The system was unpacked and the heavy manipulator was mounted to the locomotor. The power distribution unit, electronics rack, and operator control console were set up in a lab area just on the opposite side of the East wall of Area B, approximately 200 feet from where the robot was staged in the spool destruct shelter. The Schilling operator console was placed beside the Rosie console in the same room. Because Rosie's on board tether had been contaminated during work at ANL CP-5, the clean spare tether was strung from the lab through the K-1420 building to the spool destruct. The spare tether was then connected to the robot via a tether reel bypass junction box. The tether reel cannot be used in this configuration. In addition, nearly the entire length of the spare tether was used for the run through the building. These two factors limited driving motions but otherwise enabled a comprehensive system check and subsequent testing and training. All Rosie system operation anomalies were addressed before the RedZone support personnel left site. Rosie was delivered to DRS in February of 2000 and uncrated and inspected. Some minor damage to the system was discovered and addressed.

Nine of the thirty tapped holes in the locomotor frame used to anchor the heavy manipulator to the frame were damaged. The threaded inserts had partially pulled out or were stripped. The first concern was that this had been caused by excessive loading at the threads in question, but because they were randomly spaced around the square bolt hole pattern and not biased to just one side, as would be expected in an overloading scenario, it was determined that the helical inserts had been damaged when the heavy manipulator was removed, either because the fasteners had corroded or because they were removed too fast and had galled (i.e., they were zipped out with an impact wrench). The damaged holes were drilled out and repaired with solid threaded inserts. The three hydraulic lines from the locomotor manifold to the heavy manipulator were cleaned out (they had been plugged at the last disassembly using what appeared to be cotton paper towels) and the o-rings on the face seal fittings were replaced. (One of these same o-rings failed during testing - attributed to a loose fitting - and was again replaced and all fittings then torqued to spec.) The HM was then installed onto the locomotor.

The camera mounted to the hydraulics enclosure cover on the right side of the machine had been pushed forward in its housing. The camera was removed and inspected. Two leads had been cut and were repaired. Still, the picture from this camera remains snowy. Two other camera connectors were damaged. Both are Remote Ocean Systems custom molded cable connectors. These were repaired with electrical tape in lieu of ordering two new cable assemblies from ROS and remain operational. Several of the bulbs for the camera lights were either broken or missing. All were repaired. The connectors for both the heavy manipulator waist and shoulder joint position feedback resolvers were damaged. Several leads in each of the connectors were broken at the pins. These were repaired and remain functioning.

The left side wheel extension operated properly only intermittently. This was likely either a problem with the onboard electronics or a malfunction of the limit switch on that side. Due to time contraints no reason for this problem was identified. A brief electronics check was not definitive. Because the expected boom payloads were well below those, which would necessitate using the wheel extensions, the left wheel extension was simply strapped in the retracted position.

In addition to these repairs, some minor routine maintenance to Rosie was performed. This included changing the three low pressure hydraulic filters (one return and two kidney loop) and one high pressure hydraulic filter. All the accessible mechanical bearings on the system were lubricated. The boom extension linear slides, boom waist bearing, the tether drum bearings, and the tether fairlead linear slide were all greased. The fittings for the two front wheel extension grease fittings are not readily accessible, so these bearings were not lubricated. A sample of Rosie's hydraulic fluid was sent out for testing, cleared, and the hydraulic reservoir was topped off. One of the on board electronics cards failed during testing - likely due to moisture in the electronics enclosure after the cover was left off one night - and was replaced.

The two Schilling manipulators also required maintenance. One of the arms was exhibiting intermittent sporadic movement. Several servo valves in that were removed and cleaned. The hoses in the same arm were replaced and both the arms and power supply were flushed.

Once the repair, maintenance, and reassembly of Rosie was complete, RedZone departed the site and DRS proceeded to implement the tooling and support systems. One of the biggest issues was how to power the Schilling 7F manipulators. As supplied, Rosie uses a water-glycol hydraulic fluid. Because theses particular arms require an oil based fluid, a separate hydraulic power supply had to be acquired and was hung in place of one of the heavy manipulator counter weights. Hydraulic lines from this power supply were run through he E-chain of the heavy manipulator to a manifold at its tip to supply the necessary hydraulics to the arms. The shear power supply was mounted to a shelf installed above the counterweights at the rear of the heavy manipulator and the pressure and return hydraulic lines for the shear were also run through the E-chain to the tip. The shear was fitted with a "T" handle for use in the Schilling arm grippers. The Schilling arms were mounted to a 6" x 6" steel tube approximately 6 feet apart and their power supply hung from the rear of Rosie's HM.

Two months later, system testing and operator training began. RedZone trained and certified a total of four operators, two from Providence Group and two from DRS. Training consisted of a short classroom session to familiarize the operators with Rosie and approximately 15 hours of hands on system operation. Approximately two weeks was spent modifying the tooling package and cleaning up cabling and hose runs and another two weeks was spent on hands on operator training. A small mock up was constructed in the spool destruct area and trainees practiced operating the heavy manipulator and Schilling arms. The focus of this training centered on the shear. Two other pipe cutting methods were briefly tested and subsequently rejected because of reliability issues. Many of the modifications and tooling packages were rejected when RedZone returned to site for system testing and operator training. For example, there was a large (approximately 60" x 48" x 3/8" steel plate with several 12" section of steel tubing protruding from it. This was then mounted to the HM tip. The plan was to use this as a t tool deployment platform of sorts. All the tools would be hung from the tubing and could be retrieved by one of the Schilling manipulators as needed. The main problem with this particular arrangement was that it blocked many of the onboard camera views. In addition, none of the cameras provided an adequate line of sight to support grasping a hanging tool with a Schilling arm. Therefore, the plate was removed.

Two tools that were to hang from the plate; a portable band saw and a reciprocating saw, both to use in cutting pipe and other material that was too large for the shear. These were fitted to large steel jaw clamping mechanisms designed by DRS. A single hydraulic cylinder was employed to drive the jaws closed around the workpiece. The tool pivoted on the clamping device allowing a pneumatic cylinder to drive the tool blade into the workpiece with a constant force. In testing, the mechanisms worked well when deployed by hand, but were difficult to position with the Schilling arms. It took almost 30 minutes to position and clamp the tool for a single cut. The clamping cylinder was plumbed into Rosie's hydraulics, but still required the addition of valve, solenoid, and associated wiring for the remote actuation. To power the pneumatic cylinder, a small AC compressor was mounted at the rear of Rosie's HM and hoses run through the e-chain to the boom tip. This also required another a set of valves. There were also two small AC powered oil misters mounted at the boom tip to lubricate the cutting blades. All the electrical devices were plugged into a switch box also mounted at the boom tip, which in turn was wired to a relay box that was tethered to a control panel at the Schilling arm console in the set up next to the Rosie console. All the additional wiring and plumbing made Rosie's HM tip a very busy, cluttered area, further blocking camera views and decreasing the range of motion of the HM wrist joint. The extra wire and hose bundles were very exposed and at a high risk for damage. Because of these issues, and because the shear was capable of cutting the majority of pipe in the work area, the saw tooling packages and much of the support elements were removed. There was some interest in redesigning the saw tooling, but there was sufficient piping to occupy the shear for the duration of the planned operations, so no redesign was performed.

After a brief round of cold testing, the entire system was disconnected, craned onto a flatbed truck, and transported to the far end of Building K-1420. Rosie was removed from the truck and placed just outside Area B highbay door. Most of Rosie's tether was pulled off the tether reel manually and taken to the far end of Area B and passed through a hole the wall between Area B and the Rosie/Schilling operator control room. The tethers for the Schilling arms and the tool control relay box, as well as power and signal cables for two overview cameras that had been installed in Area B, were also passed into the control room. All the connections were made and a systems check performed during which the Lucas shear would not actuate. The problem was in the connector of the tool control tether on the robot side. Apparently it had snagged on something as it was pulled through the building from the spool destruct and five pins had pulled out of the connector backshell. The connector was repaired and the system deemed operational.

OPERATIONS

Rosie was brought online using the on board tether, was driven into Area B through a highbay door at the East end of the room and maneuvered between the structural support columns to the South and the Uranium recovery columns and the calciner room to the North. The West end of the building had been designated as "work area one". Because there was only about 4 inches of clearance on either side of the vehicle, the control velocities of the locomotor were adjusted to just 10 percent of maximum via the operator touch screen interface. Both the crab and four wheel steer modes were used to maneuver Rosie through the building. Two thirds of the way down this corridor to work area one, it was necessary to cut away an out cropping of piping and gages that was in the path of Rosie's left shoulder mounted camera. Ideally, Rosie's HM would be rotated counter-clockwise, centering the pieces to be cut between the two Schilling manipulators, but because of the space constraints, only about ±10 degrees of rotation was possible before the Schilling arm power supply hanging at the rear of the HM hit either structural columns or process piping to one side or the calciner room to the other. Fortunately, the work envelope of the arms is such that the arm on the side of the obstruction - which was holding the shear - was able to it to reach the piping needing to be cut out of the way. However, the opposite arm was too far away to be able to reach and hold the pieces that needed to be cut. This presented a problem because the work plan stated that the piping was to be held during cutting operations by one of the arms and then placed on a pallet. After some debate, the work plan was modified to allow pipe to fall to floor as long as it did not accumulate to a height greater than 12 inches, ensuring there was no chance of achieving critical mass. On August 15, 2000 the first section of piping was cut. The third cut resulted in the discharge of approximately two gallons of liquid. This was somewhat unexpected as all the piping in Area B had long before been air gapped and all valves opened. A litmus test of the liquid revealed that it was of near zero pH, most likely Nitric acid used in the Uranium recovery process that had pooled in low spots and behind blockages in the piping. This was the first of many such discharges from piping cut in Area B. It and all subsequent releases were neutralized with sodium bicarbonate spread on the spills by DRS personnel. After a number of sections of pipe were dropped, they were picked up and placed on either fabricated steel pallets or in buckets positioned around Rosie just within the reach. These were periodically removed from the area manually. Generally, the work proceeded in this manner, cutting a path through the process piping, until something forced a halt to it.

Only two of the steel pallets were "filled" before abandoning them in favor of 55 gallon steel drums. The pallets took 2 days each to construct and were very heavy and had to be positioned manually with a pallet jack. In addition, cut piping often fell into the gaps of between base slats or slid off the edge. The 55 gallon drums were easier to load, could be moved with a Schilling arm, and actually had greater capacity than the pallets. The bottoms of the steel buckets started to corrode from the low pH process solution spilling from the valves. No plastic equipment was available, so a layer of sodium bicarbonate was put in the bottom of both buckets and barrels.

On the second full day of operations, the T handle used by the manipulator to hold the shear broke while cutting a piece of steel angle. It was replaced with a spare, which also failed while making a similar cut. These first T handle brackets were both stainless steel, so a new one was fabricated of carbon steel. The carbon steel version bent instead of breaking when too much force was applied to it. On two occasions when the T bent, a high pressure hose on the shear was pinched between the body of the shear and the wrist of the Schilling arm, both times requiring replacement of the hose. A subsequent design added gussets welded to either side of the T. This version also incorporated rubber dampeners to allow some compliance and reduce the loading. This worked very well, as it allowed some motion of the shear relative to the arm, but not so much to allow damage to the shear hoses. The compliance motion allowed the operator to see when the shear was in contact with something and prevented excessive force to the arm. The dampeners also facilitated better alignment of the shear blades to the workpiece in the same fashion, allowing a cleaner cut. Four shear blades were broken and replaced in the course of the operations. One blade broke each time. A combination of blade wear and of routinely pushing the shear to the limits of its capacity were sighted for each of the breaks. A three position switch installed on the operator control at the Schilling console to open, stop, and close the shear blades was replaced by a foot switch which was easier and faster to use.

A week into the decommissioning effort, the Schilling arm in which the pressure hoses had been replaced failed. Several erratic motions of the slave arm were followed by the wrist going hard over and leaking oil. An inspection revealed a missing hose hold down clamp at one of the combination hydraulic return line/signal line bulkhead fittings as well as damage to that line. The arm was removed, washed down, and placed in the spool destruct area. No funds were available to repair the arm, so it was stored until such time. Meanwhile, the remaining Schilling arm had to both cut and pick up the pipe. The shear was used for both operations because of the logistics involved in removing and reinstalling it each time cut pipe needed picked up. Basically, the shear doubled as a gripper. It was closed around the piece to be retrieved enough to grasp it without completely shearing it. Unfortunately, the second arm was never again installed on the system. It was eventually sent to Schilling for repairs, but required a very comprehensive rebuild that was not completed until after the contract commitment had expired.

One of the hoses in the second arm blew the third week of September. Several other of the hoses had bulges or soft spots in them, so a complete set of replacement hoses was ordered. At this point the first arm had been shipped to Shilling for refurbishing, so the second arm was removed and placed on a shop bench in a shelter outside K-1420 and repaired on site. This effort - removal of the arm, hose procurement, hose replacement, and arm reinstallation - took over two weeks.

The Rosie platform experienced two failures of consequence enough to cause work stoppages. The first was a blown hose in the locomotor hydraulics enclosure. This was the main pump pressure hose, prior to the accumulator, so its age and number of pump startup cycles it had endured are thought to have caused the failure. The failure was quickly detected by onboard pressure transducers, which prompted the system software to shut down the system. Very little hydraulic fluid was lost and no damage to the hydraulic system occurred. It took a day to procure a replacement hose and a day to install it. The second failure occurred with only a week remaining in the four months of scheduled operations. A section of pipe fell directly onto Rosie's tether after being sheared. The pipe pierced the outer jacket of the tether, slicing through two main power leads which, as later discovered, caused damage to several components on the system's starter motor board housed in the power distribution unit in the operator control room. The damaged tether was removed from the system and the spare tether installed. A new motor starter was procured and installed which restored the system to operational status.

CONCLUSIONS

As outfitted, the system proved to be a very capable tool for the removal of process pipe and associated equipment. Although the shear was not large enough to remove all piping in the facility, it was able to shear approximately 95 percent of it in work area one. A total of about 20 gallons of low pH process solution was released in the four months of operation. It's estimated that 1200 linear feet of process pipe was removed during three months of operations. In addition, approximately 70 valves, gages, unions, and tees were removed as well as 150 feet of pipe hanger.

Unfortunately, the full efficiency of the system was never realized. Most of the operation proceeded with only one of the two Schilling manipulators installed. They both proved to be unreliable and prone to break downs because of their age. Because of the problems with the Schilling manipulators, the original work plan, which called for one arm to hold the pipe while the other used the shear to cut it, had to be abandoned. This greatly slowed operations, as one arm had to cut and then pick up the pipe. It also led to the tether being damaged, which caused another significant delay in operations as well as damage to the system. The usefulness of Rosie's on board tether management was all but negated by the additional tooling tethers that were required for the Schilling arms telemetry and their power supply. Arms compatible with Rosie's water-glycol hydraulic system would have greatly improved up time and eliminated the need for the oil based power supply because the arms could have been plumbed directly into the heavy manipulator tip hydraulics. Unfortunately, no such arms were available.

Communications between all the parties involved in the effort were initiated late. Many of the modifications to the system, which were ultimately removed or rejected would most likely have been discouraged, saving valuable time and money, had all parties been involved from the onset. A larger shear would have reduced down time caused by the blades breaking. A tour of the facility by experienced remote operators prior to procurement of the tooling would most likely have pointed out that the amount of piping present could occupy the shear for the duration of the contract period, so the added expense of additional tooling could have been eliminated.

There were several operational issues, which arose in the course of the project that also affected efficiency. Two of the initially trained four operators were pulled from the project prior to deployment due to a staffing shortage. One of the other operators was rarely available because of other project needs, including being appointed Project Manager of the entire K-1420 clean up effort shortly after Rosie's deployment. This left a single operator to work full time on the decommissioning effort. In addition to the robot operator shortage, DRS was experiencing a labor shortage and many hours were spent waiting for support when there was a system failure.

Of a possible 370 hours of operation time, only 71 hours were realized. The Schilling arm failures accounted for 126 hours of down time. Problems with the shear and T handles caused 77 hours to be lost. The two Rosie failures required the system to be down for 42 hours. Another 54 hours was lost to the support issues mentioned earlier as well as other to non-system related factors that required system shutdown. These included a number of "off gassing" incidents during which the control room had to be cleared of personnel, the need to perform manual labor in the area of Rosie, a power outage, and an evacuation drill. Still, when the system was operating it did so very efficiently. DRS personnel familiar with the manual process for similar tasks estimated that the remote operations performed by the Rosie system proceeded three to four times as fast and greatly reduced worker exposure to both the radiological and other hazards - acid, falling objects, injury, heat stress - in the process.

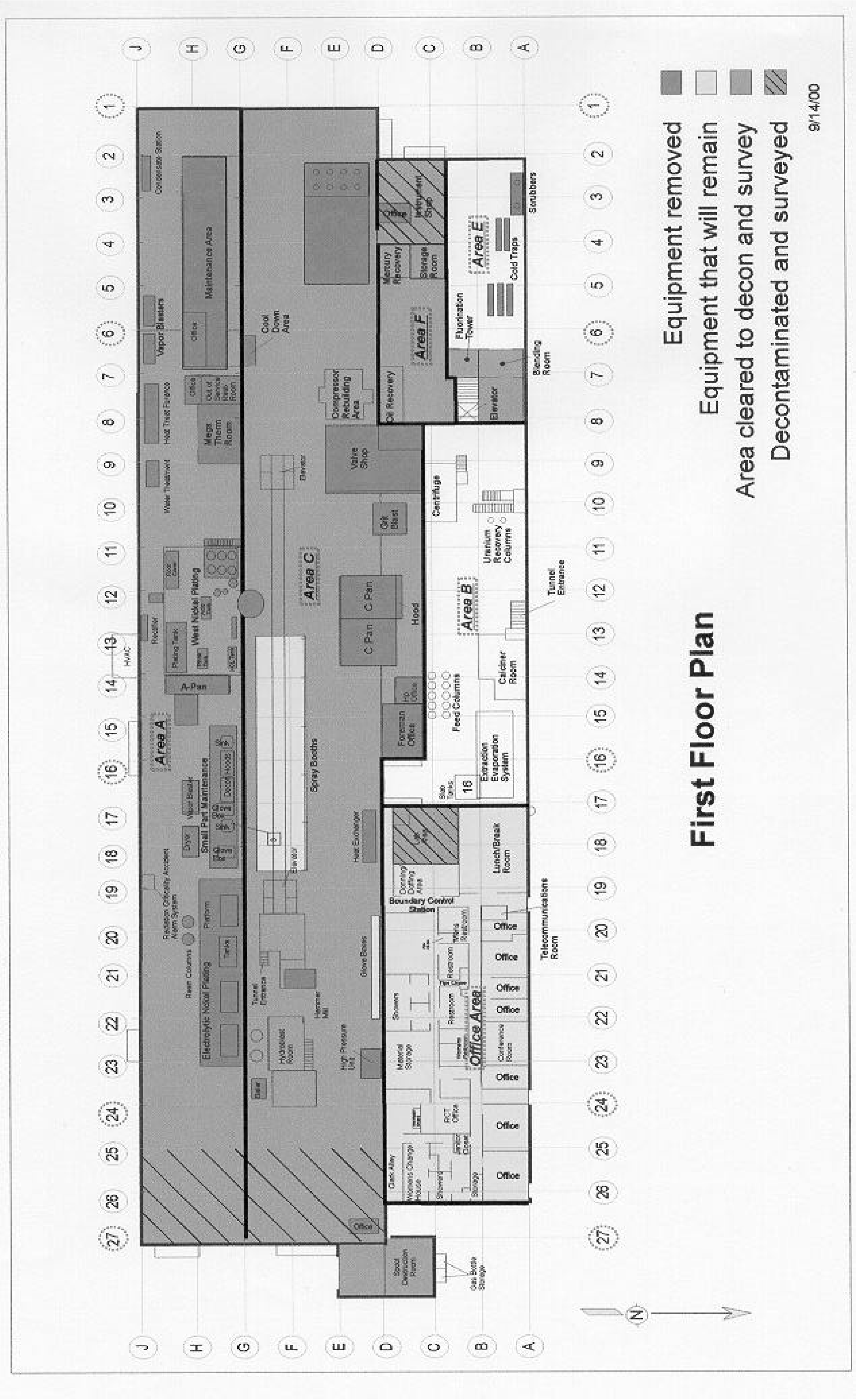

Fig. 2. K-1420 Building Layout