

## Lessons Learned in the Hot Cell at the Transuranic Waste Processing Center - 15336

Jeffrey T. Prince PE\*, and Ronald Gentry\*\*

\*Intervention Design Engineering ([nuctoolguy@gmail.com](mailto:nuctoolguy@gmail.com))

\*\* Wastren Advantage, Inc.

### ABSTRACT

The hot cell at the Transuranic Waste Processing Center (TWPC) has been in operation for seven years. Its mission is to empty, process, and repackage the contents Remote Handled (RH) concrete waste casks. The sequence of operation for processing the RH casks includes using a remotely operated manipulator (manipulator) to remove the cask contents and deliver them to a work table where operators process the waste into RH-TRU, CH-TRU, LLW drums using Master Slave Manipulators (MSMs). The manipulator is the only piece of equipment that can remove material from the cask and represents a single point failure that can shut down hot cell processing should it fail. During the first six years of operation the project processing goals were constantly in jeopardy due to the high frequency and extent of manipulator failures that forced unplanned down time in the hot cell to facilitate repairs.

In 2013 a hot cell maintenance outage was planned and executed to improve the operability and reduce the equipment failure rate. A new remotely operated manipulator, purchased as a spare before the outage, was installed in the hot cell during the outage. Prior to installing the manipulator into the hot cell several major and minor modifications were made to the manipulator to incorporate improvements manipulator reliability and maintainability based upon operating and maintenance lessons learned from the previous years of operation. Additionally a maintenance glovebox was added to the hot cell for servicing the removable manipulator components.

### INTRODUCTION

The mission of the hot cell, located at the TWPC in Oak Ridge TN, is to process 550 cubic meters (m<sup>3</sup>) of Remote Handled (RH) legacy and newly generated debris waste. The RH waste is contained in 9 feet tall cylindrical concrete casks with a nominal volume of waste of 1.66 m<sup>3</sup>. Once the waste cask is introduced into the hot cell, the lid is removed, and the waste extracted using the in-cell remotely operated manipulator. Following visual examination and treatment of prohibited items, the RH TRU waste is the repackaged into certified drums and loaded into the 72-B canisters for disposal at the Waste Isolation Pilot Plant (WIPP) in New Mexico, USA.

The TWPC hot cell has a seven year operating history. Using the hot cell and its remote capability equipment, the TWPC has been able to process and certify for shipment the contents of 152 casks (231 m<sup>3</sup>). Nominally 75 casks of high dose rate material remain to be processed in the hot cell following the current processing campaign. An additional 98 RH casks (163 m<sup>3</sup>) containing low activity RH waste are being processed in TWPC's Cask Processing Enclosure, specifically designed to process casks containing predominately Contact Handled (CH) waste. During the first six years of operation several failures of the vendor supplied manipulator were experienced which resulted in unscheduled down-time and loss of throughput, negatively impacting both project schedule and costs. TWPC analysis determined that most of the manipulator failures were a function of the difficult nature of the waste matrix being processed, but some of the failures were attributed to the design attributes of the manipulator. At the time of TWPC design and construction, the manipulator selected was determined to be best available fit for purposes of processing ORNL's waste, regardless of the design. However, with each failure that occurred during processing the TWPC waste operations and design engineering team learned more about the design performance capabilities and limitations of the manipulator. During processing, TWPC engineering and

maintenance personnel were challenged to be creative and opportunistic in making repairs. While repairs were made with a focus on “keeping it operational”, most of the repair efforts were simply “band aids” or temporary patches.

To understand the importance of improving the manipulator reliability and maintainability, it must be stressed that the in-cell manipulator is a single point failure for almost all significant hot cell operations. However, the single most important function of retrieving waste from a RH cask and placement into reach of the four MSMs used to process the waste, overrides all other functions. Without the manipulator in service, waste processing stops. Figure 1 shows the manipulator entering a cask during post outage operations.



**Fig. 1. Post Outage Manipulator Entering a Cask**

As a result of past manipulator failures, operations and maintenance personnel became very innovative in learning how to quickly, and safely repair the manipulator. To facilitate manipulator repairs, maintenance personnel are required to either enter the hot cell using contamination control means such as a glove bag or work in close quarters extending the manipulator wrist and lower arm through a hot cell drum out port. As such, all manipulator repairs have not only time and cost impacts, but also worker dose consequences.

In an effort to increase availability, reliability, and maintainability, the TWPC engineering staff closely tracked and evaluated the manipulator failure mechanisms. A plan was developed to sort the failures into

categories of “can be repaired” or “requires modification” to prevent failure. A new manipulator had already been procured as a spare prior to planning the hot cell outage. Outage planning was revised to incorporate a full change out of the existing hot cell manipulator with the spare. In preparation, engineering used the historical failure data to identify and plan modifications to mitigate or eliminate certain of the failure mechanisms. To address certain of the remaining failure mechanisms, engineering and maintenance personnel used the spare manipulator to construct a full mock-up for devising repair techniques, that were then tried and confirmed in a non-contaminated environment. In summary, an extensive list of desired modifications was performed on the new manipulator. While some of the physical modifications were first performed on the in-service hot cell manipulator and then repeated on the spare manipulator, more than half of the modifications were new and were only performed on the spare manipulator. These new modifications included such items as a custom designed wrist assembly, a re-designed end effector, and an overload alarm system. All modifications targeted specific performance issues experienced in the hot cell by operations and maintenance staff. The specific modifications to the manipulator are presented in the following discussions.

In the end, the fundamental reason for the design and upgrade effort on the new manipulator was to improve manipulator reliability, availability, and maintainability and ensure achievement of the TWPC waste processing goals and milestones.

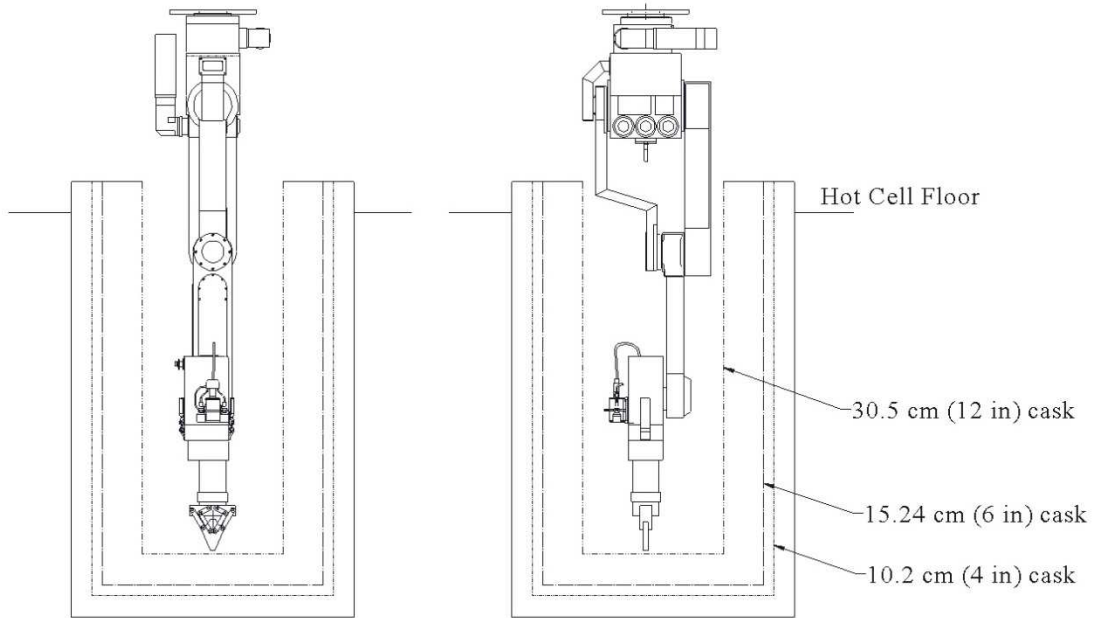
## **DISCUSSION**

The manipulator, as purchased, was a well-made piece of equipment. The general design of the manipulator enabled it to function in multiple environments but it was challenged by the nature of the TWPC RH waste matrix. In particular, the manipulator is not as well suited for the tasks associated with retrieving waste from inside the small diameter RH concrete cask cavity. The in-service performance history shows that the manipulator regularly impacted the cask side walls at the upper and lower arm. This problem is exacerbated as the waste cask is emptied due to the fact that the widest part of the manipulator must be lowered into the cask in order to reach the material in the bottom. Figure 2 shows the relative sizes of the 10.2 cm (4 in.) wall, 15.24 cm (6 in.) wall, and 30.5 cm (12 in.) wall casks with the manipulator inserted into the cask.

In chronological order the first in-cell modification that was performed on the manipulator was to design a pair of serrated jaws that could readily hold a tee shaped bar made from ½ diameter bar stock. In the sub-sea robotics market t-bar jaws and remote handled equipment are virtually a standard. Unlike many other tool grab schemes, tools equipped with a t-bar can be thrown in a jumbled pile, be re-acquired, and rigidly held in both translation and rotation.

The next modification was within 6 months of commencing operations. This modification involved redesign of a washer and bolt positioned on the end of the wrist extend screw. The existing washer had shattered allowing the extend screw to recede into the wrist at full extension, thereby disabling the extend slip clutch, and thus resulting in loss of the wrist extend function.

Following a connector failure leading to the wrist mounted camera, a hardened wrist camera connector was developed. The original camera connector was a very good quality MIL- spec connector, but in operation the connector was not adequately protected from the high likelihood of impacting the wall of the cask which caused it to break. As a temporary fix, tape was used to hold the camera connector in position allowing time for a permanent fix to be developed and implemented. Figure 3 shows the newly installed hardened connector. The redesigned mount has been in service since May 2009 and has never failed.



**Fig. 2: Relative size of the manipulator and the casks**



**Fig. 3 Hardened wrist camera connector**



From May 2009 until September 2011 no in cell modifications were performed, but numerous wrist and end effector failures, as well as two failures of the wrist pitch joint occurred. As earlier mentioned, there is a lot of work involved in installing a maintenance containment to the CH drum out port to facilitate a repair. The containment setup process usually takes 1 to 2 days to complete before the repairs can be performed on the manipulator. To disassemble the containment takes an additional day of effort. As the manipulator continued to show wear and fatigue, waste operations soon was losing an average of one half to 1 week of operational time each month due to manipulator repair down-time. Due to these failures it was decided to order a spare manipulator.

The next in-cell modification was to repair a crack in the “S” shaped tube steel weldment that is part of the upper arm. A picture of the crack is shown in Figure 4.

This structural crack presented a challenge because no welding (i.e., hot work) is allowed in the hot cell. Engineering decided to fashion a “splint” for the cracked region of the weldment. A finite element analysis (FEA) of the affected area was performed using assumed loads [1] and it was determined that there was a stress riser in the location of the crack both on the top and bottom of the weldment. A second FEA model was prepared and analyzed that included the “splint” pieces and the crack. This FEA was used for determining the shear stress between the “splint” pieces and the weldment. Since two-part epoxy adhesive requires use of an acetone wash prior bonding, an acrylic two-part adhesive was selected that developed,



Fig. 4 Upper arm weldment crack

at cure, a shear strength higher than the required shear stress determined from the FEA. The analysis and the fabrication of the “splint” pieces, ordering of the adhesive, and the installation of the containment occurred in parallel. The ends of the crack were drilled (to stop the crack) and the “splint” was bonded directly onto the weldment. The weldment remained in service for 16 months until the manipulator was replaced. A similar modification was repeated on the new manipulator prior to installation into the hot cell, with the luxury of being able to weld the preventative splint onto the new manipulator.

As mentioned before, there were two wrist pitch joint failures during the period between May 2009 and September 2011. These involved the failure of the wrist pitch bearing retaining rings. In both cases repairs were affected; once by removing the sheared mounting screws for the rings, and once by re-drilling and tapping the screw hole pattern. In June 2012 the wrist pitch joint failed again for the same reason. This time the joint could not be repaired and a design modification was initiated to enable returning the manipulator to service. Once the decision once made to implement the modification, as with the crack repair, the material for the modification was ordered, the modification design was developed, and two sets of parts were made. The first set of parts was used to modify the new spare manipulator as a “dry run” and the second set of parts were used to modify the in-cell manipulator. The manipulator was back in service within ten days from failure to back in service. As with the crack repair, assumed loads were used and a comparative determination of the as-modified strength of the joint was determined. A subsequent report concluded that the joint was 2.89 times stronger in axial loading, 5 times stronger in radial loading and almost 17 times stronger in moment loading [2].

In late October 2011 engineering began design of a different wrist assembly. There had been numerous failures of the existing wrist assembly and ultimately sequential failures occurred to three different wrist assemblies. It was decided that the exiting wrist design could not withstand the rigors required for waste processing in the hot cell. It should be re-stated that the failure mechanisms experienced were not because the vendor supplied wrists assemblies were in any way sub-standard, they simply were not designed to deal with operational requirements and tasks required in TWPC the hot cell. Secondly, and perhaps the more important reason for a new wrist design is that the original wrist assembly was very hard to maintain using the four sets of protective gloves required for a maintenance technician to place hands into the containment. The features designed into the new wrist assembly included use of a face type slip ring for transferring power to the grip motor and clutch, limit switches for the extend/retract function, application of commercially available gearmotors with robust gearboxes, and attributes for ease of maintenance. These design features were derived directly from lessons learned from each of the wrist failure events. The prototype face type slip ring is shown in Figure 5.



Fig. 5 Face Type Slip Ring



A prototype wrist was built and tested on the new manipulator and was placed in service with the new manipulator as part of the hot cell outage. Although it was 3.65 inches longer and weighs 15 lbs. more than the original, the new design features and the added strength of the wrist assembly advantageously offset the added length and weight. The new wrist has held up well following restart of hot cell operations with only a single grip gear motor failure in 14 months of operation.

Prior to testing and placing the prototype wrist in service, the maintenance staff assembled and disassembled the wrist several times. It was quickly realized that some of the features were not as easy to re-assemble desired, so a second more modular design was developed. Two of these wrist assemblies were built as spares. Figure 6 shows the final wrist assembly.



**Fig. 6 Final Wrist Assembly**

Lessons learned also prompted the engineering staff to re-design the end effector(s). The original end effectors were a struggle to remove and replace due to the push pull nature of the locking collar. Further, it was recognized that the end effectors failed at a notch connection between the linkage that opens and closes the end effector and the acme screw that drives the linkage. Since the arm receives load by the end effector an effort was made to also include what could be called a “mechanical fuse”; a feature that would break when over loaded but at the same time would be easy to replace. The mechanical fuse for the end effector is the bolt that connects the drive plate to the drive screw. If this bolt breaks a new drive screw and bolt can be installed in less than an hour in the maintenance glovebox. To address the difficulty of removing and replacing the end effector a different locking collar was made that rotated from the locked to unlocked position. This allowed the locking collar, when rotated to the unlocked position, to stay in the unlocked position. A parallel acting, and non-parallel acting end effector were designed and tested. Both types of end effectors are currently in service in the hot cell. Another advantage of the re-designed end effectors is the extensive use of anodized aluminum. The end effectors weigh 67% less than the original vendor supplied end effectors while maintaining the strength and corrosion resistance of the original. Figure 7 shows the re-designed parallel acting end effector.



**Fig. 7 Re-Designed Parallel Acting End Effector**

The final significant modification of the manipulator was the installation of a means to detect an arm overload condition. As supplied by the vendor, the manipulator is equipped with slip clutches for the shoulder, elbow and wrist pivot axes, as well as the shoulder and wrist roll axes. These are well designed and work well, but they can only prevent overloading if the overload force(s) is parallel to the plane of motion of these axes. The manipulator can be overloaded by forces that are perpendicular to the plane of motion, so called “out of plane forces.” These forces can readily be imparted to the manipulator because the manipulator mast is connected to a bridge that moves horizontally north, south, east, and west. TWPC engineering and operations personnel suspected that this out of plane loading is the primary contributor to the wrist pitch joint fail. To preclude failure from out of plane overload, an overload alarm system was designed and tested on the spare manipulator mock-up. The system replaced the original manipulator mounting which included a means to remotely disconnect the manipulator from the manipulator mast.

When the manipulator was first placed in service, it was thought that being able to remotely disconnect and re-connect the manipulator would be a valuable feature. This feature was never used by TWPC during the 6 year service period of the original manipulator. Also, as the project became more familiar with the system it was realized that it would require a manned entry into the hot cell in order to remove and replace the manipulator. Based on that experience, the remote disconnect feature was removed and the overload sensing switch installed at that location. Figure 8 shows the lower portion of the overload alarm assembly on the spare manipulator mock-up. The overload alarm is triggered by the presence of excessive bending moment reacting at the point where the manipulator attaches to the mast, and is sensitive to both in plane and out of plane force(s). Operationally, when the overload alarm is triggered a



visual and audible alarm annunciates. When this occurs the operator will move away from the perceived source of the overload until the alarm goes silent.



**Fig. 8 Partial View of the Overload Alarm Assembly**

The electrical connection for the overload alarm was made possible by another minor modification which removed the tool power connector feature from the wrist housing; it was also never used. This meant that the in-place wiring that was already installed from the mast to the manipulator controller could be re-purposed; two of these wires were used to connect the overload alarm to the control cabinet outside the hot cell.

Numerous additional minor modifications were made to increase the ease of maintenance. For example, the remote connect connector used for connecting the wrist wiring to the arm wiring was replaced with a more friendly and reliable molex™ connector. The remote connect feature was a good idea, but when a wrist repair is performed it was difficult to trouble shoot following reinstallation. Should the wrist not work, it was very difficult to determine whether it was nonfunctioning wrist or if it was not functioning because the connector improperly mated. Another simple change was made to prevent the upper wire guard from getting knocked off. The mounting screws were modified from #6-32 to 1/4 -20, and beveled the end of the wire guard. The wire guard has not been knocked off post outage.

During the service life of the original manipulator, maintenance had to change the drive belts twice. To change the drive belts the lower and upper arm covers must be removed. All of the arm covers were secured by over one hundred button head cap screw of various sizes. The button head screws would get

abraded as a function of working in the cask. Many of the screws had the sockets worn down to the point where the screws could not be removed. The solution to this was to change all the cover mounting screws to one size, and use hex head screws. Additionally, an in-line set of MIL-spec connectors was installed in the wrist and camera wiring harnesses in the center of the lower arm weldment. This change was required because when the lower arm drive belt needed to be changed, the wrist would have to be pulled out and the two wiring harnesses removed from the wrist housing and most of the lower arm. These activities were time consuming and exasperating for the maintenance staff. With the new connector in place they only need to be de-mated and the wiring harnesses pulled out of the lower part of the lower arm in order to facilitate a belt replacement.

Also in order to facilitate maintenance on the belts, TWPC installed polycarbonate windows over one of the two pulleys and pulley sets in the upper and lower arm so that the belt movement can be observed from outside the hot cell. These windows allow the operations and maintenance staff to observe whether the belts are loose or not tracking on the pulleys correctly. This in-turn provides a predictive tool for the maintenance staff. Figures 9 & 10 show some of these modifications.

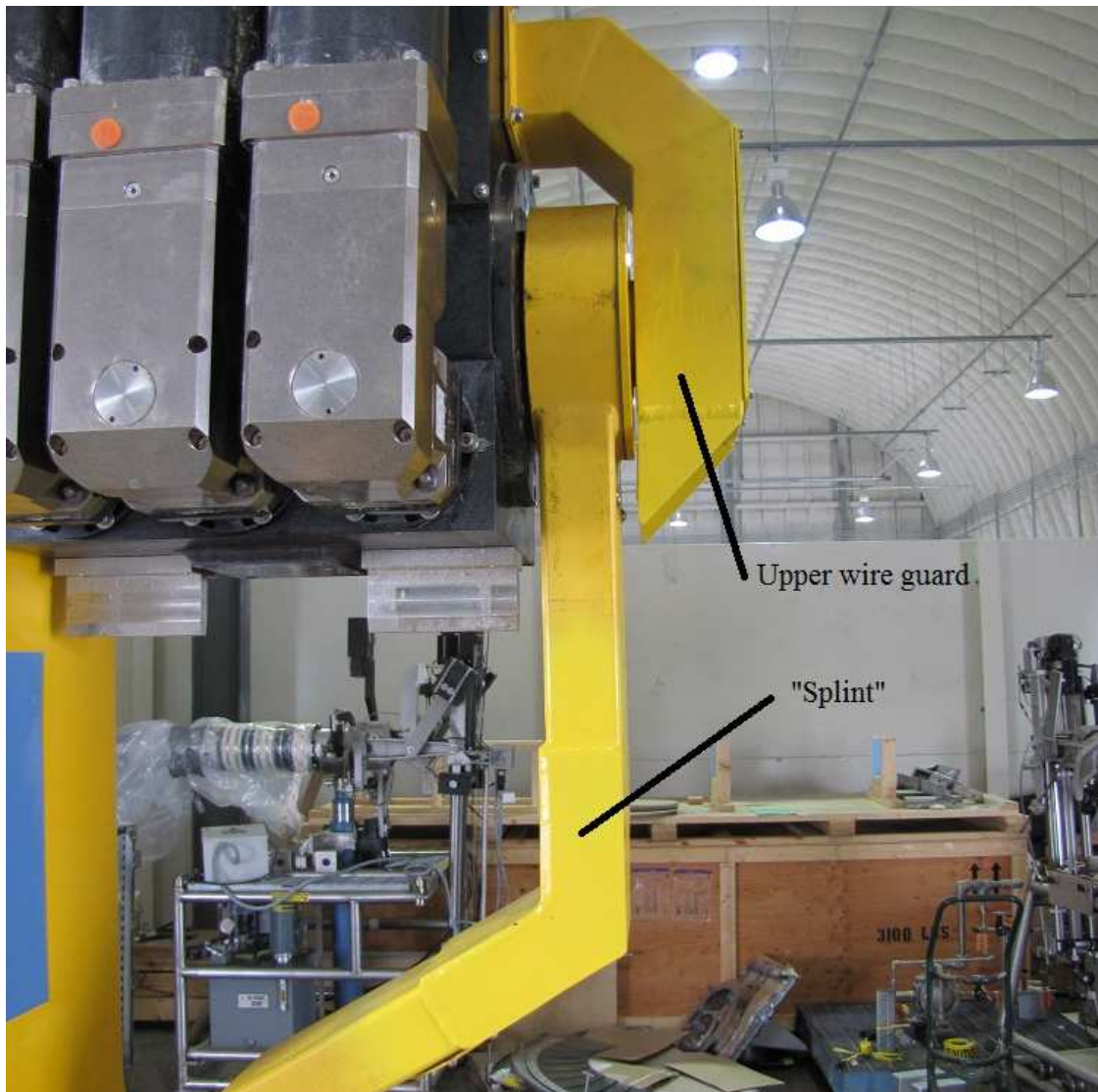


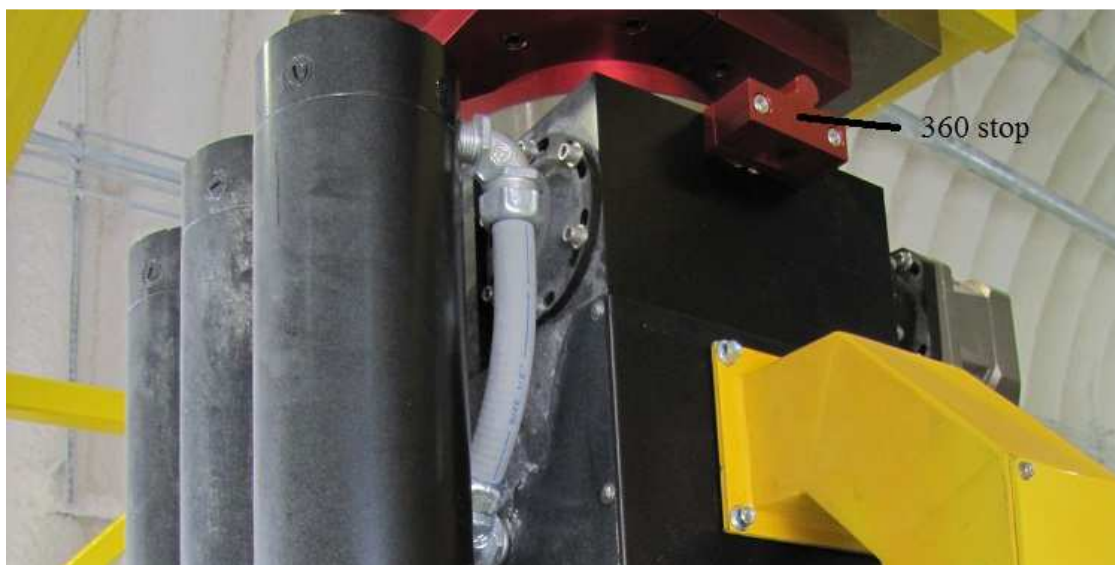
Fig. 9 Other Modifications





**Fig. 10 Belt Windows**

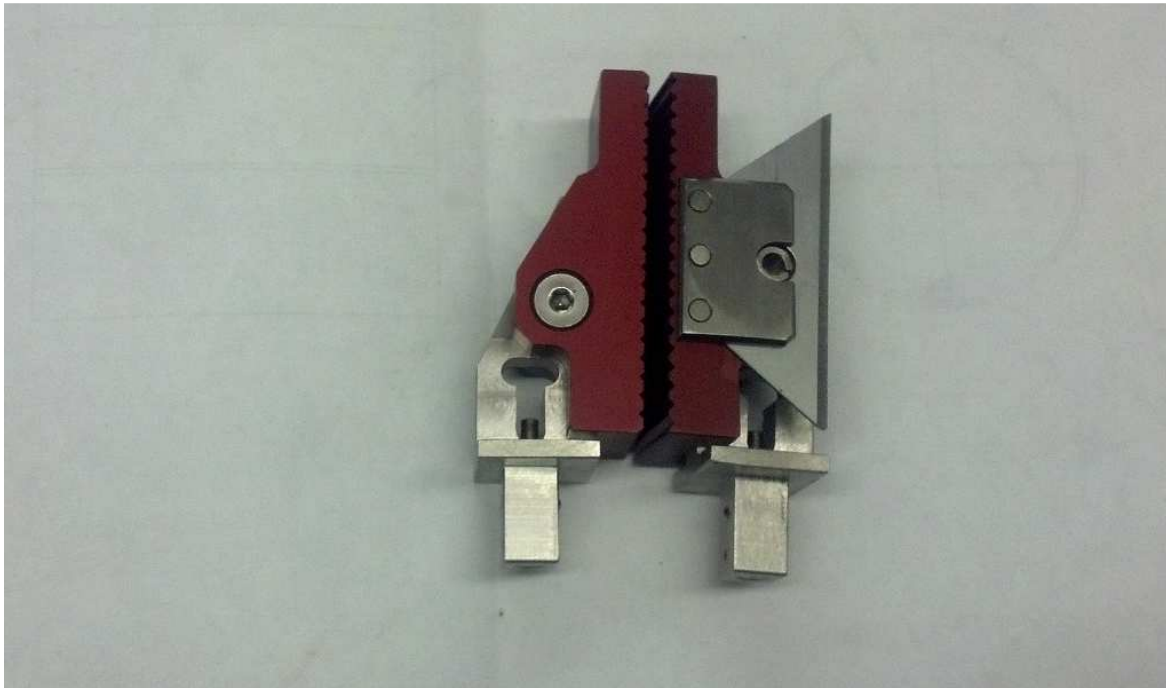
The last minor modification was to change the original shoulder roll hard travel stop. The original stop limited the shoulder rotate function to 330 degrees creating a shadow area that could not be entered unless the manipulator pitches were inverted, but in doing so it would create the same shadow on the opposite side of the manipulator. The hard stop was re-designed to allow a full 360 degrees of motion. The 360 degree hard stop is shown in Figure 11.



**Fig. 11 360 Degree Stop**



The last lesson learned relates to the ability of the manipulator to grip thin, slippery surfaces such as plastic sheets and bags. While it may be easy to physically grab a plastic sheet with the manipulator end effectors, it is entirely another thing to be able to pull on it with necessary force to move or lift. Some of the RH waste casks have been filled with lots of plastic bags and plastic sheeted items. Even when exerting a tight grip force, both smooth and serrated manipulator jaws that did not intermesh demonstrated a tendency to slip when pulling on plastic. To address this issue the design of the t-bar jaws was revised to make them intermesh. Similarly, TWPC's MSM tongs were reverse engineered and designed with intermeshing fingers. One of the MSM fingers contains a spring loaded utility knife attachment that allows a utility knife blade to be installed onto the finger. When a lot of plastic bags and sheeting are being processed in the hot cell, it saves time to be able to invert the MSM hand and cut the plastic. The MSM tongs and fingers are shown in Figure 12.



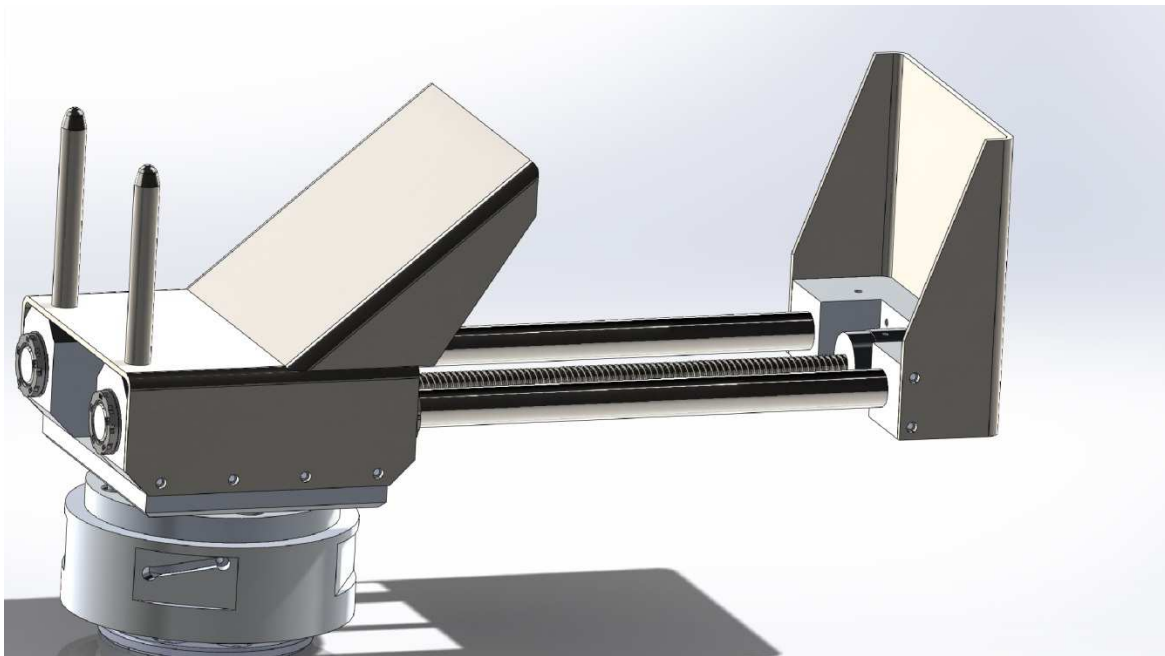
**Fig. 12 Intermeshing MSM Jaws with Knife Holder**

### On-going work

It is a TWPC RCRA permit requirement that the RH waste cask be verified as empty as a part of processing. This includes the bottom of the cask to the wall of the cask (i.e. the lower corner). It can be seen from Figure 2 for a 30.5 cm (12 inch) wall cask there is not much room for moving the manipulator into a position where the lower corner can be cleaned. During the years of waste processing the operations staff tried many approaches to move the waste from the lower corner of the casks into the middle of the cask. These include vacuums, scrapers, dust pans, etc. and all have met with little or marginal success. It is known that cleaning the cask to its lower corner is where the most damage to the manipulator occurs. A current project is approved and underway to build an offset end effector (shown in Figure 13). This end effector will off-set a scraping jaw 38 cm (15 inches) from the centerline of the manipulator allowing the blade to reach the lower corner of a waste cask. The blade operates on a linear bearing so it can remain in contact with the bottom of the cask when closing; this will scrape the material away from the corner and pile it in the center of the cask. We hope to have this and two more end effector types ready to test by the end of calendar 2014.

Another project is to attach battery powered range finders to the end effectors that can be seen through the wrist camera (Shown in Figure 14). These will allow the operators to gather 3D information from the 2D wrist camera. Testing will begin in December 2014.

**Fig. 13 Intermeshing MSM jaws with knife holder**



**Fig. 13 Offset End Effector**



Figure 14: laser depth modules

## CONCLUSION

The manipulator is a cross between a custom designed piece of equipment and a standard product. Its support structure (mast, bridge crane, etc.) are close to custom designed piece due to the fact that they have to fit in the room at the correct height and so on. The manipulator portion is a standard existing design with little customization. We have had a two week down time replacing the mast linear bearings once, but we have had a total of 45 weeks of down time attributable to manipulator repairs, 21 days in the



last ten months of operation of the first manipulator . The labor cost to operate the hot cell averages \$13,185 a day, so the manipulator down time has cost \$2,373,300. After the hot cell outage with the improvements to the manipulator, and commissioning the maintenance glovebox, we have had 36 hrs. of down time attributable to manipulator failure.

At TWPC the engineering staff has made an effort to modify a standard manipulator so that it can function better in its challenging environment. Also we made great effort to minimize the time to repair, and since we now have the protection of the overload alarm, perhaps the risk of failure has dropped. The performance metrics show that we seem to have been successful in increasing the availability of the hot cell, only time will tell.

Again, it must be said that the manipulator is a great piece of equipment and well made, it's just not the right piece of equipment. It is true that even today there is no commercially available right piece of equipment. That being said perhaps the most important lesson is for future remote system development. Perhaps it would be better to custom build or at least customize remote systems so that they are as close to being the correct piece of equipment, rather than be concerned about what is commercially available.

## **REFERENCES**

1. J.T. Prince, Report "RH-R-ME-001-R0 PaR Arm Crack Repair Evaluation" (2011)
2. J.T. Prince, Report "RH-R-ME-003-R0 Comparison of Bearing Strength for the PaR Wrist Pitch Joint", (2012)