The Future is Here: Robotic Catalyst Removal

Christopher Jansen, Program Manager, WorleyParsons, Level 25, 12 Creek St, Brisbane, QLD 4000

Andrew W. Sloley, Principal Consultant, Advisian (WorleyParsons Group), Energy Center II, 575 N Dairy Ashford St, Houston, TX 77079

Scott Schroeder, Senior Technical Consultant, Advisian (WorleyParsons Group), Energy Center II, 575 N Dairy Ashford St, Houston, TX 77079

WorleyParsons has been developing new technology using vacuum catalyst removal from refinery and petrochemical vessels via a remote-operated, screw-propelled vehicle. The development of CAROL™ (Catalyst Amphirol) responds to increasingly stringent requirements to reduce human risk in inert confined-space entry. It is the culmination of a three-year development effort from conception and design to prototyping and testing and represents a potential game-changer in the industry.

The number of fixed-bed catalytic vessels in the global refining and petrochemical industry

is estimated to exceed 58,000. Based on current technology a rough estimate of the number of worker days of risk exposure due to confined-space entry during catalyst unloading exceeds 10,000 days per year. Current practices for catalyst removal from each of these vessels pose a risk to safety and/or the environment. This remains true regardless of whether dumping, vacuuming, or water flooding is employed. CAROL™ provides an alternative option that minimizes risk to workers.

CAROL™ is a simple, one-of-a kind machine that has been demonstrated to achieve vacuum catalyst removal without the placement of workers inside the vessel. A review of operating characteristics in a single bed test vessel is provided. Additionally, two case studies for upcoming plant demonstrations are examined:

Catalyst removal from a narrow naphtha hydrotreater at a refinery in the United States.

Adsorbent removal from a wide dehydration vessel at an LNG plant in Australia.

This paper showcases the challenges associated with current catalyst removal techniques, and the inherent safety advantages that CAROL™ has shown. The presentation includes video of the test vehicle operating characteristics and discussion on industry acceptance progress and preliminary test results.

Keywords:

Engineering & Design: chemical reaction and decomposition hazards; fire and explosion hazards; hazardous area classification; inherent safety; toxic hazards

Systems & Procedures: maintenance; management of non-routine operations

Abbreviations

API	American Petroleum Institute
CAROL	Catalyst Amphirol
HAZID	Hazard Identification
HMI	Human Machine Interface
HPU	Hydraulic Power Unit
IEC	International Electrotechnical Commission
LEL	Lower Explosive Limit
LNG	Liquefied Natural Gas
NEC	National Electrical Code
RSI	Reactor Services International

1. Introduction: The Problem

1.1. Catalyst Unloading

A refinery or petrochemical plant can have up to 100 vessels containing fixed beds of catalyst, adsorbent or other granular material. These beds include reactors, contaminant adsorbers and filters. Vessel entry periods vary from six months to five years. Work requiring vessel entry includes bed replacement, vessel inspection, and internals repair or maintenance.

Catalyst unloading is a potentially hazardous and time consuming activity. Many vessels require inert conditions throughout the catalyst unloading process for various reasons. For example, pyrophoric scale can autoignite in the presence of oxygen. Other hazards include residual hydrocarbon in the catalyst, hydrogen sulfide, mercury, and other toxic compounds depending on the application. Until now, catalyst unloading has typically been performed by catalyst contractors who enter the vessel equipped with breathing apparatus because the inert nitrogen atmosphere does not support life.

Catalyst removal is most commonly achieved by a worker standing on the catalyst and manipulating the end of a high-volume vacuum hose (Figure 1). Material is removed via the vacuum hose to a vacuum truck located adjacent to the vessel (Figure 2).

Figure 1: Manual vacuuming

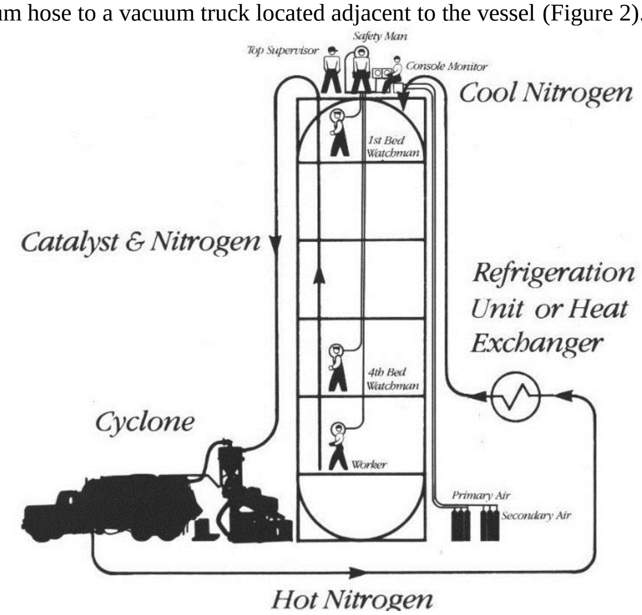

Figure 2: Set up for manual catalyst removal

An alternative method of removing spent catalyst or adsorbents from vessels is gravity unloading through either a side or bottom dump nozzle . Gravity unloading leaves residual material below the dump nozzle or in a talus-like slope extending away from the nozzle. In short, wide vessels, up to 40% of the residual catalyst can remain in the vessel after dumping.

Water flooding is a method to avoid confined space entry under inert conditions. The vessel is filled with water which suppresses the volatile components. The water level is dropped and maintained at a level just below the catalyst surface. The catalyst is then vacuumed in an open air environment. Water flooding typically increases the catalyst unloading duration due to the time it takes to cool the vessel. It also poses environmental challenges associated with contaminated water.

1.2. Potential Hazards

Confined-space entry, particularly with inert conditions, is considered hazardous. Fatalities continue to occur due to asphyxiation, exposure to heat, fire, falling from heights, pressure build-up, and engulfment under catalyst. Specialized contractors are usually hired to work in inert atmospheres.

According to the US Department of Health and Human Services, 670 people lost their lives in confined-space entry accidents during the decade from 1980 to 1990 (1). In the same period, apart from vehicle accidents, confined-space entry was the cause of more multiple fatalities in the United States than any other type of work. The mining/oil-and-gas industry had the highest confined-space fatality rate (per 100,000 persons).

A study conducted by the U.S. Chemical Safety Board identified 85 nitrogen-exposure incidents in the U.S. between 1992 and 2002, resulting in 80 deaths and 50 injuries (2). Despite significant technological advances in the last 25 years, personnel entry into crude oil storage tanks and petrochemical vessels remains commonplace. Maintenance activities at industrial facilities continue to put workers at risk who enter the equipment.

In 2014, a worker was killed at a refinery in Germany. The worker was vacuuming catalyst under inert conditions at the bottom of the reactor. A wall of catalyst collapsed and completely buried him. 10 m^3 of catalyst had to be removed for the body to be recovered.

In 2016, a worker was killed at a fertilizer plant in Lituania. The operator was performing checks at the top of a nitrogen purged reactor. The top catalyst bed was already removed. The operator was not wearing breathing equipment and approached too close to the open top manhole. The operator was killed due to nitrogen asphyxiation.

The industry has an obligation (not just requirement) to maximize personnel safety. The industry should not tolerate manned inert entry as the de facto technique.

2. CAROL™ Development: The Solution

2.1. Roles & Project Objectives

The vision was to apply robotic technology to transform personnel safety and to revolutionize how refinery and petrochemical vessels are unloaded of hazardous materials. WorleyParsons, as program manager, combined the robotics expertise of Canadian company, Mecfor, with the oldest catalyst handling company in the US, Reactor Services International. BP were engaged to provide "voice of the customer" feedback throughout the development process.

2.2. CAROL™

Through the use of cutting-edge technology, the project team developed CAROL ™, the Catalyst Amphirol. This represents the culmination of a three year development effort from conception and design, to prototyping and testing.

The CAROL™ robotic catalyst removal process is similar to the conventional method. However, instead of a person holding the vacuum, the vacuum hose is connected to CAROL™. This light-weight and simple device moves with precision on top of the catalyst surface (Figure 3). The vacuum hose, hydraulic lines, and electric cables enter the vessel through the top manway (Figure 4).

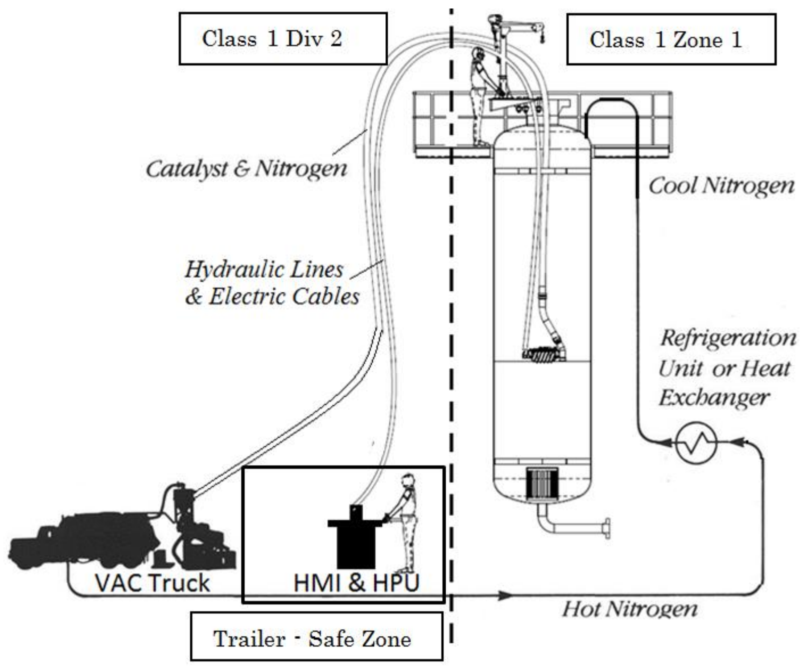

Figure 3: CAROL™ (patent pending) **Figure 4: Remote operated catalyst removal system**

The amphirol (screw propelled vehicle) design allows CAROL™ to move in all directions and to turn on a dime. The screws were manufactured using 3D printing. This allowed for optimization of the ribs and the ellipsoidal ends. The aluminum frame is critical to minimizing the weight. The result is a device that essentially floats on the catalyst, causes minimal damage to the catalyst and rarely gets stuck. It has a low center of gravity to prevent it from flipping over. If it does flip over or gets stuck, then it is easily lifted up using the winch cable, and then lowered back to be right-sided.

CAROL™ is controlled remotely via a joystick and monitored using video screens. Use of hydraulic power means that hazardous area requirements are relevant only to the video cameras, lighting and gas monitors. A specially designed jib crane/winch can be fixed to all manway configurations. This allows for lowering of CAROL™ into the vessel and lifting of CAROL™ out of the vessel. The vacuum head is adjusted remotely to continuously optimize the catalyst to lift-gas ratio.

The hydraulic power unit (HPU) and the human machine Interface (HMI) includes the hydraulic valves, joystick, controller, and video monitors. Both the HPU and HMI are located in a "safe zone". In the United States, all non-hazardous rated equipment is located within an air conditioned trailer (Figure 5). Operation of the "safe zone" equipment will be conducted subject to required hot work permits and with continuous monitoring of the lower explosive limit (LEL) of the atmosphere.

Figure 5: Control systems located in an air conditioned trailer

An additional advantage in some applications is that CAROL™ can be used in temperatures not suitable for human entry. Catalyst contractors or local regulations set occupancy duration limits for traditional catalyst removal techniques based on conditions. Typical personnel exposure limits are a maximum of two-three hours for temperatures exceeding 30°C (86°F). Entry is prohibited if the vessel temperature exceeds 40°C (104°F). CAROL™ can be operated in temperatures of up to 80°C (176°F).

2.3. Hazardous Area Considerations

For the development of CAROL™, the hazardous area classification requirements were determined based on the explosive atmosphere standards applicable to each territory. As per the OSHA confined space entry standard (8), for installations in the United States and Canada, the API-500 (division classification) and API-505 (zone classification) standards have been applied. For installations in all other territories, IEC-60079 standards have been applied.

Catalyst unloading is often conducted with a nitrogen purge of the vessel to maintain hydrocarbon concentrations at less than 10% of LEL. There are also occasions where the catalyst is unloaded in an open-air environment. Examples include a reformer catalyst that has undergone an oxygen burn stage or a vessel that has been flooded with water. For application of the hazardous area classification standards, the inert and/or hydrocarbon-free conditions are considered the 'normal' operating conditions for a vessel during catalyst unloading.

Conditions in the vessel are continuously monitored remotely including temperature, lower explosive limit and oxygen levels. Continuous readings are displayed on the HMI with audible alarms sounding at 10% of LEL, 2% oxygen concentration and 80 °C (176 °F).

It is possible for the 10% of LEL set point to be exceeded occasionally. For example when an agglomerated part of the catalyst bed which has not been sufficiently purged is disturbed. At this point, power to all electrical equipment and the vacuum is shut-off. The purge is increased and operations do not commence until the hydrocarbon levels have reduced back to less than 10% of LEL. Similar actions are taken if high oxygen or high temperature alarms are activated. Such elevated ignitable atmosphere conditions are expected to be infrequent.

The classification of hazardous areas in the International (IEC) and American (API) standards are summarized in Table 1. With atmospheric monitoring, the presence of an explosive atmosphere inside a vessel during catalyst unloading is considered "Intermittent" or "Abnormal".

Table 1: Comparison between the Australian/IEC Zones and the American Hazardous Area Classifications (7)

Classification of hazardous areas			
Explosive atmosphere	**Continuous**	**Intermittent**	**Abnormal**
Australia	Zone 0	Zone 1	Zone 2
IEC			
U.S.A.			
U.S.A.	Division 1		Division 2

For the United States and Canada, all electrical equipment used on CAROL™ and inside the vessel is classified as Class 1 Zone 1 as per API 505 (6) or Class 1 Division 1 as per API 500 (5). For the rest of the world, all electrical equipment used on CAROL™ and inside the vessel is classified as Zone 1 for international applications as per IEC 60079-10-1 (4). All electrical equipment on CAROL™ employs protection techniques appropriate for the hazardous (classified) location.

The mechanical components of CAROL™ are designed to be free of inherent sources of ignition. This is made possible by the materials of construction, the low velocities inherent in the operation of the machine, and the use of a hydraulic power source for the motors and adjustable vacuum head. Potential static build-up at the vacuum head is dissipated through the vacuum hose to the vessel superstructure

2.4. Risk Assessment

While the key driver for this technology development is improving safety during catalyst unloading, it is important that newly introduced risks are identified and mitigated. The WorleyParsons risk management process (Figure 6) has been adopted to generate a risk register for robotic catalyst removal technology. The risk register was created for testing the first prototype, and amended and expanded for subsequent tests and throughout the development process.

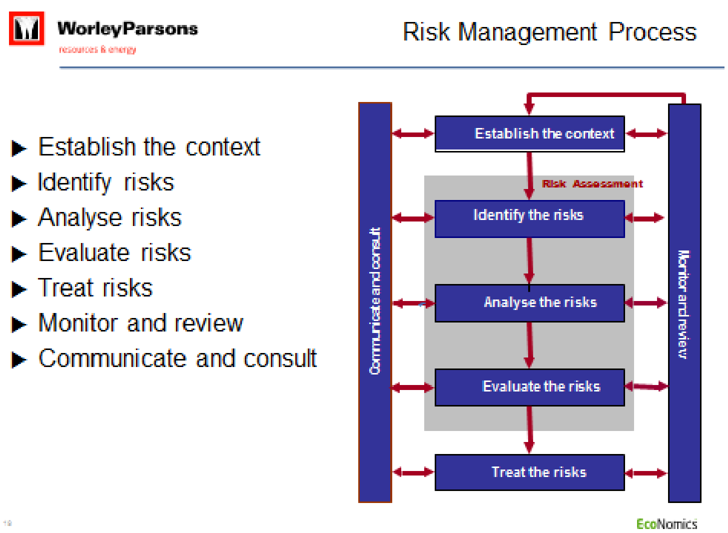

Figure 6: WorleyParsons risk review process

Figure 7 shows an example excerpt from the risk register.

RISK REGISTER

Document Number: 760100-12422G-CI-LST-0001-v1.4

WorleyParsons resources & energy

Likelihood	Consequence				
	Insignificant	Minor	Moderate	Major	Catastrophic
Almost Certain	High	High	Extreme	Extreme	Extreme
Likely	Moderate	High	High	Extreme	Extreme
Possible	Low	Moderate	High	Extreme	Extreme
Unlikely	Low	Low	Moderate	High	Extreme
Rare	Low	Low	Moderate	High	High

Item No.	Date Item Opened	Category	Issue / Cause	Risk Description	Mitigation	Consequence	Likelihood	Mitigated Risk Level
11	30-Aug-16	Schedule / Cost	Ruptured hydraulic lines inside the vessel	Ruptured hydraulic line leading to hydraulic oil in the reactor, contamination of the catalyst.	- Hydraulic lines have a hard cover, resistant to wearing. - Inspection plans & preventative maintenance. - Hose pressure rating of 6000 psi, operating pressure is 1000 psi. - Encapsulated umbilical. - Hose bun protects against wear against the manway. - Low level alarm and trip on HPU oil tank	Unlikely	Moderate	Moderate

Figure 7: Excerpt from the Robot Catalyst Removal Risk Register

An important consideration when using robots or remote-operated equipment is the risk that the equipment could operate outside of its normal operating behavior or when a person is not expecting it. If a person is located within the robots environment, they can be at risk of injury. Management of this risk is one of the key safety recommendations from a NIOSH alert based on its field evaluation of robot-related fatalities in the United States (3). The CAROL™ development team mitigated the risk of injury to workers from unexpected engagement of the screw motors through use of a lock-out, tag-out system on the power supply to the HPU.

Safety modifications continue to be made based on the risk review processes and customer feedback.

2.5. Review of Operating Characteristics

"Man" versus machine trials indicate that the robot can achieve a removal rate at least equivalent to that of the current human operation over the total catalyst unloading period. The screws can assist in breaking up slightly agglomerated material. The video monitoring and hydraulic controls were effective in achieving an entirely remote operation.

CAROL™ Prototype 2.0 testing was conducted in a single bed test vessel of diameter 2.7 m (9 ft) and height 4.9 m (16 ft) at a test facility in Griffith, Indiana (Figure 8). The vessel was partially filled with carbon pellets having a bulk density of 770 kg/m^3 (48 lb/ft^3) and an average size of 3mm (1/8"). The carbon material was successfully removed from the vessel using CAROL™. No worker entry was required while lowering CAROL™ into the vessel, vacuuming the material, or retrieving CAROL™ out of the top manway. Vision was provided to the operator on video screens via cameras on CAROL™ and at the top of vessel.

Figure 8: Test vessel set up

The rate of removal was recorded and compared to a human trial under the same conditions. Using CAROL™, a 1.2 m^3 (42 ft^3) super sack was filled in under 13 minutes providing a catalyst removal rate of greater than 5 m^3/h (180 ft^{3}h). With a worker on the end of the hose, a super sack was filled in 11 minutes. The removal rates were limited by the size of the vacuum truck and the diameter of the hose. CAROL™ achieved an instantaneous rate of removal comparable to that of a human. Once worker fatigue and breaks are accounted for, CAROL™ should not add any additional time to the total turnaround duration.

A key challenge in the development of CAROL™ was effective operation on a range of material types. CAROL™ sinking or getting stuck in the material would create challenges in terms of efficiency. CAROL™ Prototypes 2.0 and 2.1 (refer to Figures 9-14) have had their amphirol movement successfully tested on a number of different media. Bulk densities for the test media ranged from 625 kg/m^3 (39 lb/ft^3) to 1310 kg/m^3 (82 lb/ft^3). Test media size ranged from 1mm diameter (0.04 inch) for ICR 130 catalyst to 25 mm (1 inch) for ceramic balls (catalyst support). In all cases the movement of the machine was effective.

Figure 9: ICR 130 catalyst, 660 kg/m^3 (40 lb/ft^3)

Figure 10: Corn, 695 kg/m^3 (43 lb/ft^3)

Figure 11: Sorbead WS 2050, 625 kg/m^3 (39 lb/ft^3)

Figure 12: Fused Carbon, 770 kg/m^3 (48 lb/ft^3)

Figure 13: Ceramic balls, 1310 kg/m^3 (82 lb/ft^3)

Figure 14: Support rings, 450 kg/m^3 (28 lb/ft^3)

An endurance test was conducted using a reservoir and re-circulating the catalyst (Figure 15). Continuous operation was achieved for 12 hours. This verifies that CAROL™ can be used continuously over the duration of a full shift.

Figure 15: Endurance test with material recirculated back into the reservoir

2.6. Case Studies

Plant trials are scheduled for early 2018. Below are details of two plant trials.

Case Study 1 - US Refinery

One trial is scheduled for a refinery on the West Coast of the United States. The demonstration will involve the open air removal of catalyst from a long and narrow single bed reactor vessel. The demonstration will occur in a live operating part of the plant. All equipment outside of the trailer is to be rated for a Class 1 Division 2 hazardous area. The vessel has an 18” manway which has necessitated the production of a smaller CAROL™, Prototype 3.0.

The aim of this trial is to demonstrate that CAROL™ can achieve instantaneous catalyst removal rates comparable to that of a human whilst reducing the time spent by workers in the vessel and the number of inert entries required by more than 80%.

Case Study 2 - Australian LNG Facility

A second trial is planned for Australia. Preparations are underway to deploy it in an adsorbent vessel at an LNG facility. The plant has nine large, single-bed dehydration vessels that require catalyst change-out on an 18-month cycle. Because the vessels are short and wide, dumping is not effective. A HAZID study was conducted by the plant operator which did not identify any risks exceeding the tolerable level for the site.

The current method for catalyst removal is vacuuming via human entry which takes a full shift to accomplish. To avoid inert confined-space entry, the vessel is flooded with water. The water level is controlled just below the surface of the catalyst. The catalyst is then vacuumed out. It takes several days to fill the vessel with water and to reduce the temperature to allow for human entry. With ambient temperatures exceeding 32°C (90°F), risk of fatigue and heat exhaustion limit the time any one person can spend in the vessel.

The aim of this trial is to demonstrate that using CAROL™ avoids the requirement for inert confined-space entry therefore negating the need for water flooding of the vessel. This will avoid clean-up of the contaminated water and should reduce the total shutdown time.

Acceptance for the use of CAROL™ at the in-plant trials detailed above represents the culmination of extensive reviews by two blue-chip oil-and-gas operators. A number of modifications to the original design have been implemented based on this operator feedback, including automated shut-off of the HPU for low oil level, Zone 1 ratings on all electrical equipment inside the vessel (including cameras, lighting, cabling, etc.), trailer built to house the control equipment (US operations), and procedural updates.

2.7 Limitations

For many vessel types, CAROL™ is not currently able to completely eliminate the need for human entry throughout an entire catalyst unload. In order to access the catalyst bed, various bolted reactor internals such as the inlet distributor, typically need to be removed by personnel. As robotic catalyst removal gains industry acceptance, vessel designs should be adjusted, to facilitate removal of internals from outside of the vessel.

The final clean-up, including removal of residual catalyst and support material, still requires human entry. However, in many cases the remaining catalyst and/or support can be removed under open air conditions where the volume of material is small enough for flammable conditions to be avoided.

3. Future Work

As discussed in section 1.1, catalyst can be unloaded by dumping the majority of the material through a nozzle located at the bottom of the vessel. This process leaves behind a catalyst talus at its angle of repose, which depends on the material characteristics and vessel dimensions. The talus could measure to 40% of the total catalyst amount. Furthermore, if the material is slightly agglomerated, shelving can occur in the vessel whereby catalyst becomes stuck against the wall. Currently, human entry is required to knock down the shelving and/or to vacuum up the residual talus.

Future testing and plant trials will include operations during or after a catalyst dump operation. Preliminary testing of CAROL™ on a material with a steep angle of repose has provided promising results. With the vacuum head operated in the horizontal position, CAROL™ is directed towards the built-up material, effectively knocking it down. The screws help convey material into the vacuum, and moving CAROL™ from side to side helps even out the catalyst surface. Further work is required to validate operation in these environments.

Future testing and plant trials will also assess the equipment on agglomerated catalyst. In some cases, catalyst can be fused, normally as a result of a process upset prior to the shutdown. In in-house tests, CAROL™ has broken through a layer of crust created using a carbon and mortar mixture. The screws ground through the hard material, and movement of the vacuum head helped break off larger pieces. Further testing in different types of agglomerated materials is required to verify CAROL's ability to operate in such environments.

4. Conclusions

WorleyParsons and its partners have developed the industry's first screw-propelled remote-operated catalyst unloading machine, CAROL™. CAROL™ will reduce the associated risk with placing people inside vessels by phasing out the current manual-labor-intensive process.

CAROL™ has a simple design with few moving parts. By using screws for propulsion, CAROL™ moves freely on the surface of loose material. It is light weight and easy to maneuver inside the vessel using a joystick and live video feedback. CAROL™ facilitates effective vacuum removal of catalyst with no requirement for human entry during the bulk catalyst unloading phase of vessel change-out.

WorleyParsons have challenged the status quo that catalyst unloading must rely entirely on personnel–CAROL™ has the potential to radically alter what has been done the same way for almost 75 years.

5. References

1. MacCarron, C 2006. 'Confined-space Fatalities', Doctor of Philosophy thesis, Edith Cowan University, Western Australia

2. Malewitz et al. (2015). A Deadly Industry. Available at: http://www.ehstoday.com/safety/deadly-industry [Accessed 10 Jan 2018]

3. OSHA (1987). Guidelines for Robotics Safety. Available at: http://www.hyrobots.com/safety.htm [Accessed 11 Jan 2018]

4. IEC 60079-10-1 Ed. 2.0 (English 2015) : Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres

5. API Recommended Practice 500, third edition, December 2012, Recommended Practice for Classification of Locations for Electrical Installations at Petroleum Facilities Classified as Class I, Division 1 and Division 2

6. API Recommended Practice 505, first edition, November 1997, Recommended Practice for Classification of Locations for Electrical Installations at Petroleum Facilities Classified as Class I, Zone 0, Zone 1, and Zone 2

7. Council of Standards Australia HB 13-2007, fourth edition, December 2007, Electrical equipment for hazardous areas

8. Occupational Safety and Health Administration Standards - 29 CFR, 1910.307, Hazardous (classified) locations