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CAROL - Robotic Catalyst Removal

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Abstract

WorleyParsons has developed the industry's first commercial robot for catalyst unloading from refinery and petrochemical vessels. The development of CAROL™ (Catalyst Removal Amphiro) 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. 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 from commercial field trials are presented.

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.

Abbreviations

ATEX	Atmosphere Explosibles
CAROL	Catalyst Removal Amphirol
HAZID	Hazard Identification
HMI	Human Machine Interface
HPU	Hydraulic Power Unit
IEC	International Electrotechnical Commission
LEL	Lower Explosive Limit
LNG	Liquefied Natural Gas
RSI	Reactor Services International

Introduction: The Problem 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

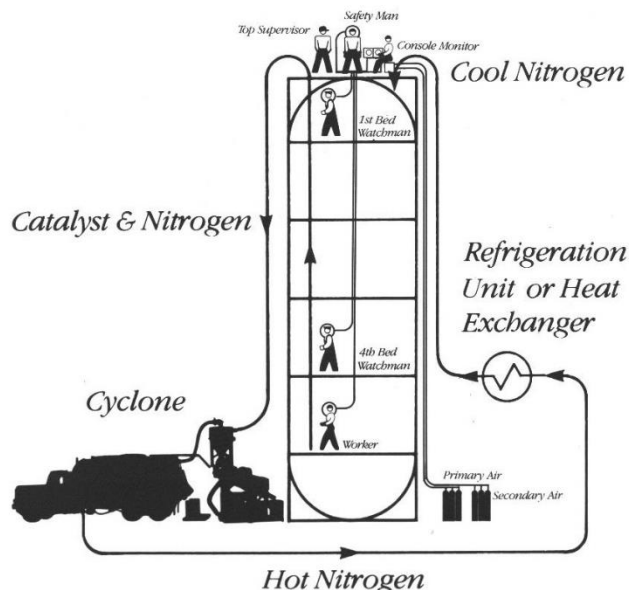


Figure 2: Set up for manual catalyst removal

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 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 fill and empty the vessel which is often required several times. It also poses an environmental impact associated with disposal of the contaminated water.

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 (1). Specialized contractors are usually hired to work in inert atmospheres.

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 m³ of catalyst had to be removed for the body to be recovered.

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.

CAROL Development: The Solution

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 (RSI).

CAROL

Through the use of cutting-edge technology, the project team developed CAROL, the Catalyst Removal 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 a screw-propelled vehicle. This light-weight and simple device is lowered in to the vessel on a winch. It moves with precision on top of the catalyst surface (Figure 3), maintaining an even catalyst surface, controlled by an operator stationed outside of the vessel (Figure 4).



Figure 3: CAROL Prototype

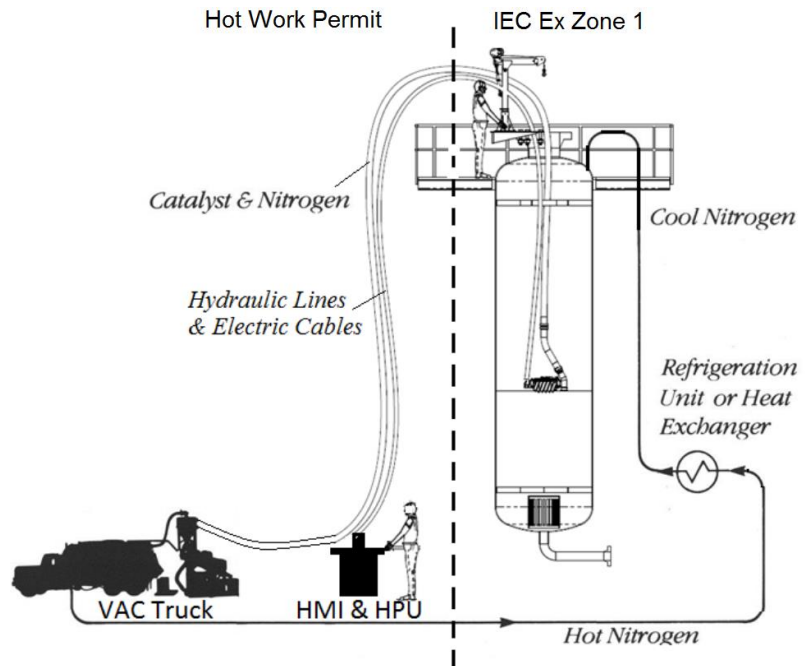


Figure 4: Remote operated catalyst removal system

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 using the winch cable, and then lowered back to be right-sided.

CAROL is controlled remotely via a joystick and monitored using video screens. The motors are hydraulically powered and the cameras and sensors have a Zone 1 hazardous area rating suitable for use globally with IEC Ex, ATEX and AEx (Class 1 Zone 1) approvals.

One advantage over the traditional manual process is that CAROL can be used in temperatures not suitable for human entry. Typically, human entry is prohibited if the vessel temperature exceeds 40°C (104°F). CAROL can be operated in temperatures of up to 75°C (167°F).

While the key driver for this technology development is improving safety during catalyst unloading, it was important that newly introduced risks were identified and mitigated. The WorleyParsons risk management process has been adopted to generate a risk register for robotic catalyst removal technology. HAZID reviews by tier 1 operating companies have confirmed that no risks of unacceptable consequence and probability have been introduced.

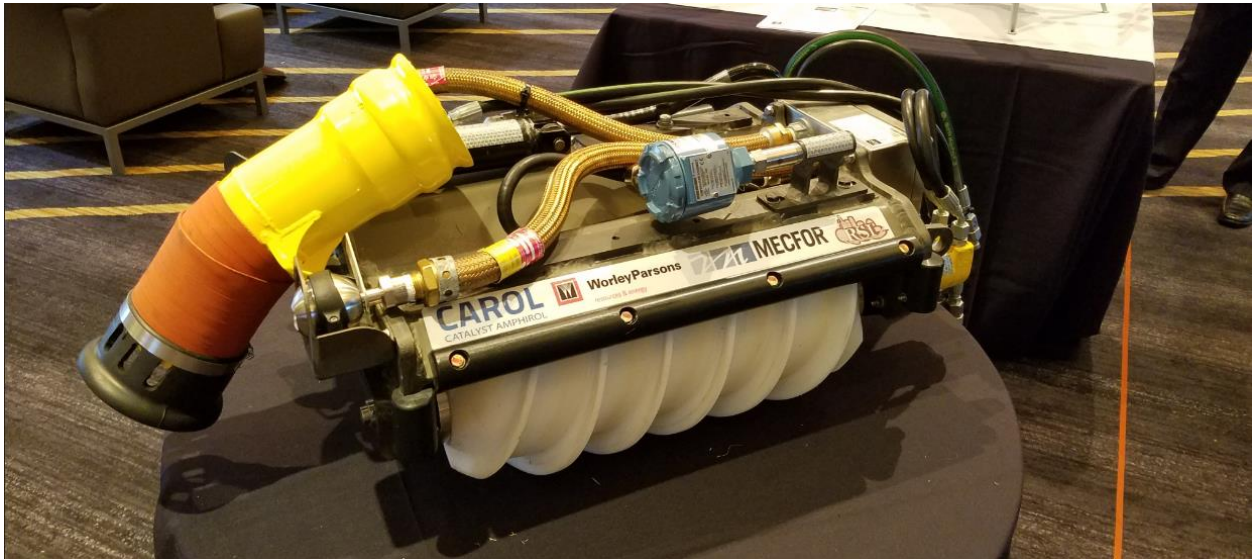


Figure 5: CAROL at the Energy Robotics & AI Network Conference in Houston, TX

Review of Operating Characteristics

Extensive testing has been carried out at test facilities in the United States and Australia. Rate of catalyst removal trials indicate that CAROL can achieve a removal rate that is at least equivalent to that of the current human operation with the same vacuum equipment. Over the total catalyst unloading period, it is estimated that 20-30% time savings can be achieved once worker fatigue and the requirement for breaks is considered.

CAROL has been tested on a range of material types. Bulk densities for the test media ranged from 625 kg/m³ (Figure 6) to 1310 kg/m³. Test media size ranged from 1mm diameter for ICR 130 catalyst to 25 mm for ceramic balls (catalyst support). The screws were shown to be effective operating on loose/random tower packing (Figure 7), on ceramic balls (Figure 8) and in

breaking up a slightly agglomerated material created using carbon and concrete. An endurance test was conducted using a reservoir and re-circulating the catalyst (Figure 9).



Figure 6: Molecular Sieve



Figure 7: Loose/random tower packing



Figure 8: Ceramic Support



Figure 9: 12 Hour endurance test set-up

Case Studies

Two commercial field trials are presented.

Case Study 1 - Australian LNG Facility

CAROL was used to remotely remove adsorbent from a dehydration vessel, avoiding the need for worker confined space entry under inert conditions.



Figure 10: Dehydrator Vessel



Figure 11: Control Station

Customer Challenge

The dehydration vessels, which remove water from gas before it is liquified, have previously been unloaded using a water flood method. The adsorbent is deactivated using water after which workers enter the vessel equipped with breathing apparatus and manipulate the end of a vacuum to remove the material. Other vessels at the plant must be unloaded under inert conditions – a nitrogen environment. The Client is seeking to minimize confined space entry, particularly under inert conditions.

The dehydration vessels at the Gorgon LNG Plant provide some unique challenges for the robotic catalyst removal technology. The manway is off-center, which means the robot needs to travel a long distance to the outer edge of the 4.1-meter diameter vessel. The top ceramic balls are on a steel mesh screen, and there are moisture probes located towards the bottom of the vessel, which the robot needs to navigate around.

Our Solution

CAROL was used to unload one of the dehydration vessels under inert conditions. This was the first time that CAROL had been used in a live operating plant. The use of CAROL removed the need to water flood the vessel and the associated issues of disposing of potentially contaminated water, while also minimizing the time spent by workers in the confined spaces.

Value delivered

CAROL remotely removed more than 95 per cent of the adsorbent from the vessel including the ceramic support material at the top of the bed. Inert conditions were maintained throughout and the requirement for confined space worker entry in the oxygen deficient atmosphere was eliminated. CAROL was also successfully deployed in another vessel under water flood conditions.

The successful trial of CAROL at the LNG Plant has demonstrated that WorleyParsons' robotic catalyst removal provides an alternative to inert confined space entry during catalyst unloading. It also provides an alternative to water flooding and the associated disposal of the potentially contaminated water. Lessons learned from the trial have been implemented in the revised procedures and design. Once implemented, CAROL should also provide schedule advantages compared with the current methods

Case Study 2 - USA Syngas Power Plant

CAROL was used to remotely remove built-up catalyst at its angle of repose with vessel temperatures exceeding 50 degrees Celsius.



Figure 12: Reactor and control system trailer



Figure 13: Top view of CAROL in reactor

Customer Challenge

Catalyst from the Gas Shift Reactor vessels is removed in the first instance using a dump nozzle located at the bottom of the catalyst bed. This allows for catalyst to be gravity dumped from the vessel however not all catalyst is removed. The residual catalyst can be up to 40% of the total vessel volume. It is difficult to unload manually by people entering the vessel with a vacuum hose because the material is built up around the vessel walls. Workers need to manually break down the mounds of catalyst whilst trying to avoid getting buried in the falling material. The pyrophoric material also tends to heat up if the nitrogen purge is insufficient to maintain inert conditions.

Our solution

CAROL was used to unload the residual catalyst material (post dumping) in one of the Gas Shift Reactor vessels. CAROL was operated in temperatures exceeding 50 degrees Celsius thereby reducing delays caused by the requirement to cool the vessel for the traditional worker entry technique. This was the first time that CAROL had been used in a live operating plant in the USA.

Value delivered

This use of CAROL demonstrated that the robotic catalyst removal technology can be used effectively in combination with gravity dumping, to minimize the time spent by workers inside confined spaces during catalyst unloading. In many cases, this will reduce the outage duration because CAROL can be used in vessel temperatures and toxic environments that are not suitable for worker entry.

Conclusions

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

CAROL has a straightforward 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.

References

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