ACES: A Simulation and Modeling tool for Vehicle Corrosion

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ABSTRACT

This paper describes validation testing of a comprehensive vehicle corrosion simulation and modeling tool under development by US Army TARDEC called "ACES" (Accelerated Corrosion Expert Simulator). ACES is used to predict the initiation and growth of corrosion on Wheeled Vehicles, Aircraft, Ships and other Assets. It is able to simulate coating & corrosion performance under various operating scenarios and to forecast & display deterioration of vehicle systems over time.

ACES has a high degree of correlation to Accelerated Corrosion Deterioration Road Test (ACDRT) data and the original prediction algorithms were correlated using ACDRT data from the Army Family of Medium Tactical Vehicles (FMTV) truck. This paper describes validation testing of the predictions conducted by a third-party stakeholder using a different vehicle, namely the Marine Corps' Medium Tactical Vehicle Replacement (MTVR).

COST OF PRESERVATION

A NACE International study [1] estimates global cost of corrosion at $2.5 trillion annually and a separate study [2] estimated the annual cost in the US to be over $1.1 Trillion in 2016. The war against corrosion is one of the Army's top priorities. Using data from FY2010, the Logistics Management Institute (LMI) [3] estimated the annual corrosion-related cost for Army ground vehicles to be $1.606 billion, or 12.6 percent of the total maintenance costs for all Army ground vehicles. They also estimated the effect of corrosion on non-available days (NADs) for all Army ground vehicle assets. Corrosion is a contributing factor in approximately 662,649 NADs of ground vehicles per year, or 6.6 percent of the total NADs. These days equate to an average of 1.7 days of corrosion-related non-availability per year for every reportable ground vehicle or system. Corrosion impedes performance, hinders readiness, and detracts from safety. Materials, energy, labor and technical expertise that would otherwise be available for alternate uses must be allocated for corrosion control.

Predicting the advent and advancement of corrosion has been described as a "black art" because of its complexity, extensive uncertainty and ambiguity because the environment, materials, coatings, vehicle geometry and use all contribute to the corrosion process. Current approaches that use deterministic, physics-based, electro-chemical models to predict corrosion and the deterioration of complex systems are inadequate. More advanced, non-deterministic alternative approaches, which involve Artificial Intelligence (AI) and statistical methods, appear to offer the best promise for providing the analyst with the tools needed to quantify the corrosion process.

THE ACES SIMULATOR

The US Army TACOM contracted GCAS, Incorporated to produce a complete vehicle simulation and modeling tool called "ACES" (Accelerated Corrosion Expert Simulator) shown in Figure 1 that has a high degree of correlation to an actual full vehicle accelerated corrosion test. The software development contract was initially a Small Business Innovative Research (SBIR) award but is continuing to be enhanced under other contract instruments.

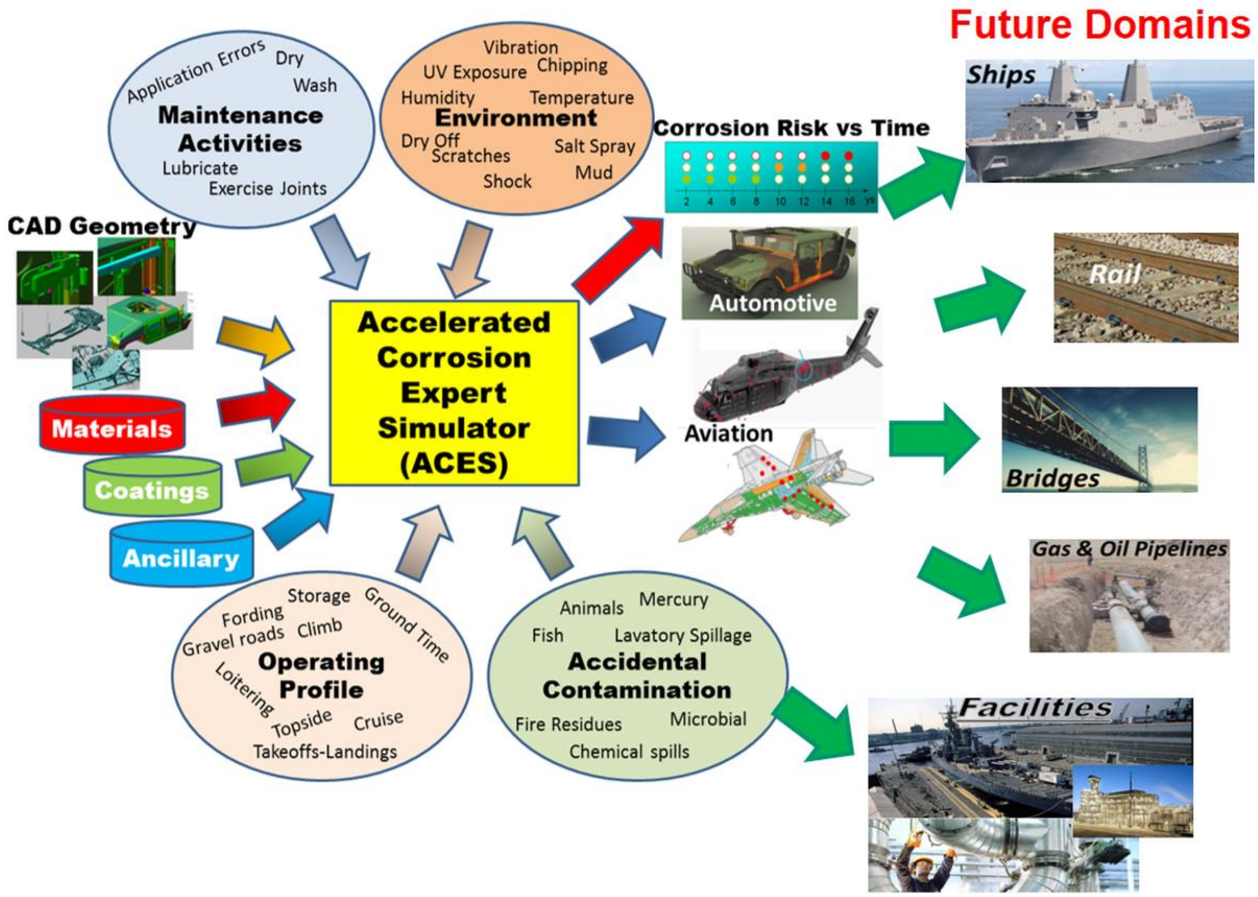


Figure 1: ACES Overview

The ACES system imports existing 3-D geometric CAD models of full vehicles using STEP (ISO 10303) AP214 (Automotive) format, along with part substrate material, coating and other ancillary information. A Software Wizard guides the user through adding fastener and bonding (welds, rivets, etc.) as well as additional coating system detail (i.e., multi-layers, coating at assembly level, etc.), as necessary. Geometry related features such as crevices, areas for poultice entrapment and location of drainage problems are identified for use by the corrosion/coating deterioration algorithms. Vehicle Operating Profiles, Environment and Maintenance Profiles are also defined by the user for use in the vehicle life simulation.

The simulation is executed on parallel processing Graphic Processing Units (GPU) using the full 3-D models of a vehicle's geometry. GPUs are an alternative approach to High Performance Computing (HPC), i.e., Supercomputers, for parallel processing; and use the workstation computer's CPU as well the processor found on the graphics card(s) inserted in the computer. ACES can then be used to perform “What-if?” trade-off studies with alternative designs, materials, operation in different environments, etc.

PREDICTION ALGORITHM CORRELATION

A variety of Predictive Analytics- Statistical Artificial Intelligence (AI) solution methods are used depending on the failure mechanism for corrosion and coating breakdown being analyzed. A knowledge base assembled from Subject Matter Experts, prior ACDRT data, laboratory test data, and field observations are used by the algorithms. The prediction algorithms include mechanisms for Uniform, Galvanic and Crevice forms of corrosion, and the breakdown of the coating system over time [4-7]. Algorithms for Pitting, Exfoliation and Stress Corrosion Cracking (SCC) have also been formulated [8] but have not yet been implemented in code.

The original algorithms were correlated using Accelerated Corrosion Deterioration Road Test (ACDRT) data provided by the US Army on their FMTV (Family of Medium Tactical Vehicles) trucks [9] shown in Figure 2. The FMTV is primarily a steel vehicle with some Aluminum parts. Both CARC and e-Coat coating systems are used as the first line of defense in preventing corrosion.

Figure 2: FMTV 5-Ton Truck with MHE

There have been three ACDRT tests performed on the FMTV design. The first ACDRT was a "10-year test" conducted in 1995 at Transportation Research Center (TRC) on the proposed vehicle prototype provided by the original bidder, Steward and Stevenson (S&S). S&S acquired the design from a European company and the "10-year-test" was intended to qualify the corrosion integrity of the design prior to procurement by the Army. The design was found to have several corrosion issues, including the T-handle door assembly discussed more fully below. S&S addressed each of the Army's corrosion associated concerns, and testing of the redesigned vehicle was performed at the Army's Aberdeen Test Center (ATC) during the 1998 to 2000 time-period. This testing included "22-year-test" of two M1078 model vehicles, one treated with Carwell rust inhibitor and one "as-produced" by S&S. A third ACRDT was also conducted at ATC as part of the vehicle "re-buy", which eventually was manufactured by Oshkosh Defense. This third ACDRT is the source of the most reliable test results used for calibration, as discussed below.

Table 1: FMTV Parts for ACES Calibration

Part Name	Material + Coating	Problem
Stowage Door T-Handle Assembly (12418568)	Mg+Zn+SS with CARC	Galvanic Corrosion of Dish and Handle
Engine Brake (12505546)	SS + Iron - Uncoated	Galvanic Corrosion seizure of valve shaft in pillow block
Transmission Cooling Shroud (12424551)	Al - Uncoated	Galvanic and Poultice Crevice Corrosion

Three problem areas shown in Table 1 of the 67 identified in ACDRT testing of the FMTV were selected for use in calibrating the ACES algorithms.

STOWAGE DOOR T-HANDLE ASSEMBLY

The Stowage Door T-handle assembly (Part #12418568) was the first part used for the ACES prediction model development and was used to calibrate the galvanic corrosion Bayesian Network prediction model [6]. The ACDRT 10-year-test showed that the T-handle assembly experienced severe corrosive attack of both the zinc T-handle resulting in white rust, due to corrosion of the underlying zinc, and the zinc plated carbon steel dish (Figure 3), which was successfully cured with the redesign as shown in Figure 4.

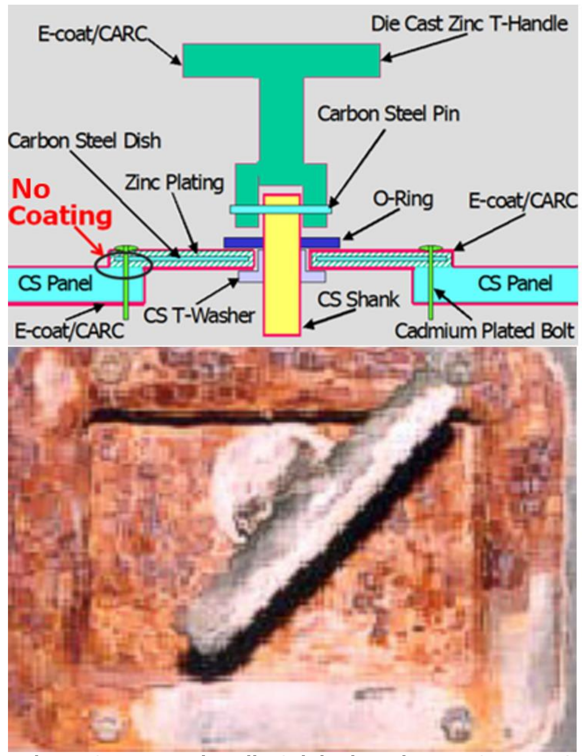


Figure 3: FMTV T-handle Original Design at 10-year ACDRT

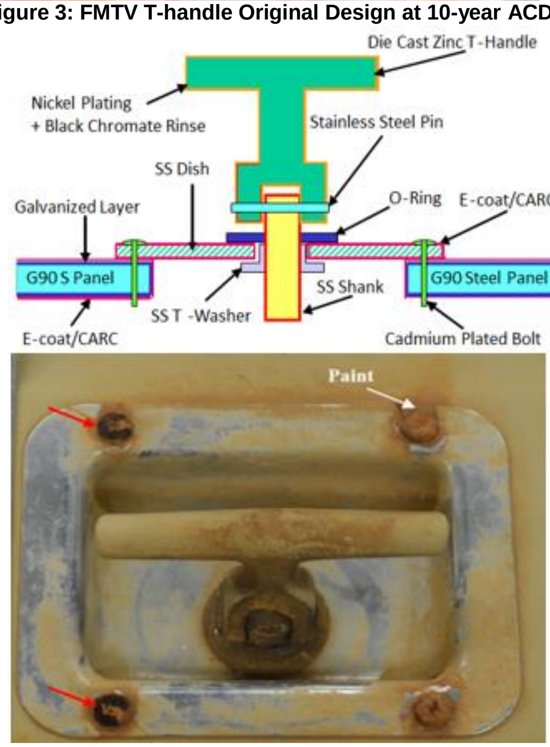


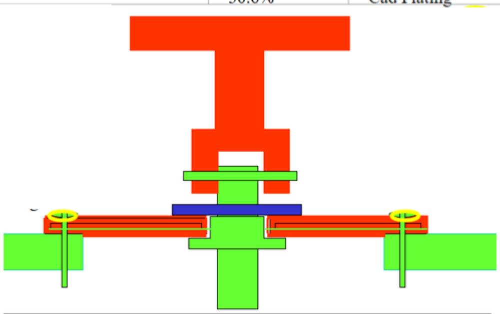
Figure 4: FMTV T-handle Revised Design at 22-year ACDRT

The original T-handle configuration had several design flaws. The primary culprit was the uncoated interface between the carbon steel panels and the zinc-plated carbon steel dish, which created a direct electrical path between two dissimilar metals creating a strong galvanic couple. Another issue with the original design was the e-coat/ CARC coating applied to the die-cast zinc T-handle.

These problems were cured by applying the e-coat/ CARC to the carbon steel panels as individual parts prior to assembly rather than at the full assembly, and replacing the zinc-plated carbon steel dish with a stainless dish. The die-cast zinc T-handle was nickel-plated rather than applying an e-coat/CARC layer.

The ACES software successfully predicted both the "10-year-test" and "22-year-test" results. Figures 5 and 6 show the prediction for the two tests. The details of the predictions are discussed more fully in the previous publications [7, 8].

Interacting Components	Original (10-year ACT) Design	
	Unacceptability	Corroding Part
T-Handle/Pin-Shank & T-Handle/Dish	64.9%	T-Handle
T-Washer/Shank & T-Washer/Dish	11.5%	Zinc plating on Dish@T-Washer
Dish/Panel	59.5%	Zinc Plating on Dish @ Panel
Bolts/Dish & Bolts/Panel	12.8% 30.6%	Panel Cad Plating

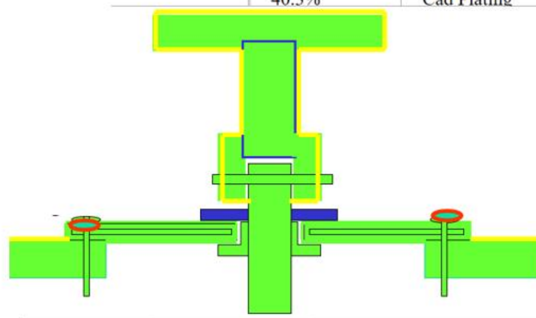


Flag Color	Qualitative Assessment	Level of Unacceptable Galvanic Corrosion
Green	*Acceptable*	Less than 20%
Yellow	*Critical*	20%-40%
Red	*Unacceptable*	Greater than 40%

Figure 5: ACES Prediction for the 10-year Test

An interesting observation of the results in Figure 6 is the prediction that the Cadmium plated screws holding the dish onto the door panel would experience severe corrosion. The test photo in Figure 4 verifies that this did indeed occur.

Interacting Components	Revised (22-year ACT) Design	
	Unacceptability	Corroding Part
T-Handle/Pin-Shank & T-Handle/Dish	16.0% 23.6%	T-Handle Ni Plating
T-Washer/Shank & T-Washer/Dish	0.0%	None
Dish/Panel	15.2% 33.6%	Panel @ Dish G90 Layer
Bolts/Dish & Bolts/Panel	19.0% 40.3%	Bolt Cad Plating



Flag Color	Qualitative Assessment	Level of Unacceptable Galvanic Corrosion
Green	*Acceptable*	Less than 20%
Yellow	*Critical*	20%-40%
Red	*Unacceptable*	Greater than 40%

Figure 6: ACES Prediction for the 22-year Test

In retrospect, the design changes instituted by S&S were over kill for the dish, and the same result would have likely occurred by simply coating the carbon steel door panels before fastening the zinc-plated dish. A key area of concern for the ACES prediction is the order in which coating systems are applied. In general, as good engineering practices, all individual pieces in an assembly are coated first before they are assembled but as illustrated with the T-handle dish example, this does not always occur.

It should be noted that the artist sketches of the T-handle assembly in Figures 3-6 are not geometrically accurate. Figure 7 gives the true geometry as rendered from the detailed 3-D CAD model.

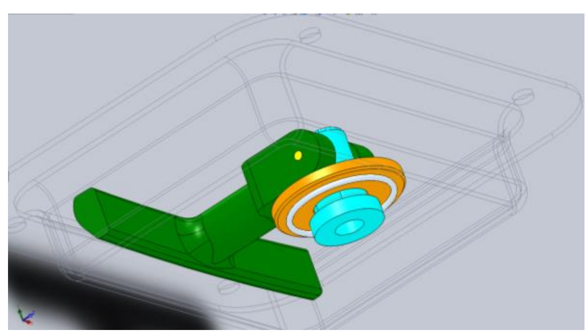


Figure 7: 3-D Model of the T-handle Assembly

Figures 8 and 9 show the ACES finite element model of the full door assembly and a photograph of the assembly at the end of the 22-year ACDRT. The T-handle assembly held up very well and, in general, the door assembly fared better than the adjoining mounting rails. One concern was the lack of paint adhesion on the SS dish, indicating that pre-treatment is required.

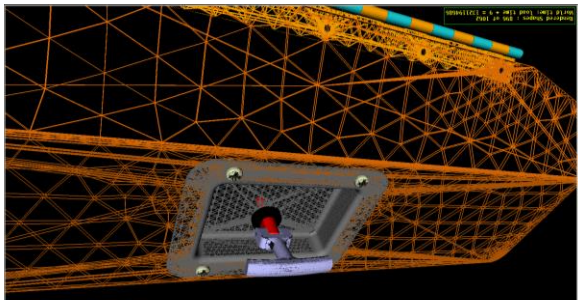


Figure 8: Stowage Door Finite Element Model

Figure 9: FMTV Stowage Door at the End of 22-year-Test

The ACES simulation is a 10-step process:

1. Import the 3-D geometry, material properties, coating and plating systems,
2. Validate Geometry,
3. Part Interactions,
4. Validate Assembly,
5. Part Properties,
6. Part Classifier,
7. Crevice Analysis,
8. Joint Analysis,
9. Zone Analysis, and
10. Corrosion Analysis.

Many of the steps are computationally intense and require processing on a parallel processor to complete in a reasonable time. Once steps 1 to 8 have been performed the actual corrosion analysis requires very little time and is executed on the computer's CPU rather than the GPUs.

A key step for galvanic corrosion is the Part Interaction step which determines the electrical path and electrolytic path between parts of dissimilar metal that are connected either by touching one another (electrical path) or have a small gap (e.g. under 2-mm) separating the parts such that an electrolytic path can occur. The cathode and anode surface areas are also calculated for each part using the "Baboian 2-inch Rule" for the radius of influence. The ratio of cathodic to anodic area is used as an effectiveness measure of the cathodic reaction. The larger the cathode compared with the anode, the more oxygen reduction, (or other cathodic reaction), can occur and, hence, the greater the galvanic current. From the standpoint of practical corrosion resistance, the least favorable ratio is a very large cathode connected to a very small anode. The electrical and electrolytic interaction calculations for the T-handle door assembly are shown in Table 2. A total of 21 "direct" electrical path (no gap) contacts and 26 "indirect" electrolytic path contacts were found.

Table 2: Electric and Electrolytic Interactions

Part1	Part2	Area1	Area2	Gap
12418568_DISH	Phillips Pan Head [_6]	11227	249	
12418597-001 Door	Phillips Pan Head [_6]	15057	274	
12418597-001 Door	Phillips Pan Head [_7]	8250	275	
12418597-001 Door	12418568_DISH	50027	29173	
12418568_DISH	Phillips Pan Head [_10]	11217	248	
12418597-001 Door	12418595_DOORSIDE	46068	11347	
12418595_FrameSIDE	12418595_HingePin	13479	2004	
12418595_DOORSIDE	12418595_HingePin	13159	1725	
12418568_DISH	Flat Washer ISO 7089	25726	245	
12418568_SHANK	12418568_T_HANDLE	849	2645	
12418568_DISH	Phillips Pan Head [_7]	11153	247	
12418568_DISH	12418568_T_WASHER	27624	653	
12418568_DISH	Phillips Pan Head [_11]	10974	247	
12418597-001 Door	Phillips Pan Head [_11]	14914	275	
12418595_DOORSIDE	12418595_FrameSIDE	13528	13537	
12418568_T_HANDLE	Shank_Pin	2690	84	
12418597-001 Door	Phillips Pan Head [_10]	7595	275	
12418568_SHANK	12418568_T_WASHER	803	763	
12418568_SHANK	Shank_Pin	896	89	
Flat Washer ISO 7089	12418568_SHANK	303	894	
12418568_DISH	12418568_SHANK	25702	891	
12418568_T_WASHER	Flat Washer ISO 7089	877	328	2
12418597-001 Door	Shank_Pin	7790	114	21
Shank_Pin	12418568_T_WASHER	114	877	9
Flat Washer ISO 7089	12418568_T_HANDLE	328	1717	12
12418568_T_HANDLE	12418568_T_WASHER	2717	877	6
12418597-001 Door	12418595_HingePin	35380	2535	4
12418597-001 Door	12418568_T_WASHER	7966	877	17
12418597-001 Door	12418568_SHANK	6345	918	17
12418568_DISH	12418568_T_HANDLE	32469	2717	9
12418568_DISH	Shank_Pin	27178	114	14
12418597-001 Door	12418595_FrameSIDE	36482	14002	3
12418597-001 Door	Flat Washer ISO 7089	5908	328	23
12418597-001 Door	12418568_T_HANDLE	21719	2717	12
12418568_T_HANDLE	Phillips Pan Head [_6]	825	288	33
12418568_T_HANDLE	Phillips Pan Head [_7]	1403	288	19
12418568_T_HANDLE	Phillips Pan Head [_10]	1399	288	19
12418568_T_HANDLE	Phillips Pan Head [_11]	821	288	33
Phillips Pan Head [_10]	12418568_SHANK	288	852	38
Phillips Pan Head [_10]	12418568_T_WASHER	288	701	36
Phillips Pan Head [_10]	Shank_Pin	288	108	35
Phillips Pan Head [_10]	Flat Washer ISO 7089	288	266	40
Phillips Pan Head [_7]	12418568_SHANK	288	843	38
Phillips Pan Head [_7]	12418568_T_WASHER	288	687	36
Phillips Pan Head [_7]	Shank_Pin	288	108	35
Phillips Pan Head [_7]	Flat Washer ISO 7089	288	264	40
Shank_Pin	Flat Washer ISO 7089	114	328	15

The definition of the interactions between coating layers and the substrate continued to be a problem. The latest iteration found severe corrosion between the zinc T-handle and the applied nickel plating. The prior versions showed the nickel plating was effective in preventing corrosion (see Figure 6).

ENGINE BREAK SEIZURE

The second FMTV part to be used for ACES corrosion algorithm calibration was the Engine Brake (Part #12505546) shown in Figure 10 where there was seizure of stainless steel valve shaft in the iron pillow block due to galvanic corrosion. This failure was of particular importance because it represented a corrosion-related failure of high risk assembly that could have resulted in loss of the vehicle or even human life.

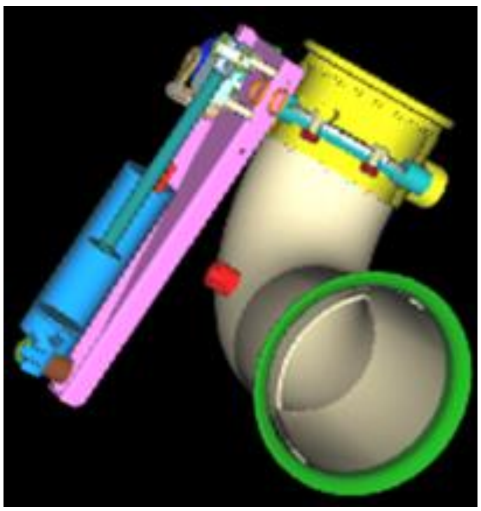


Figure 10: FMTV Engine Brake (Part #12505546)

The engine exhaust brake assembly consists of a tubular 90° bend with flanges on each end to connect to the various engine and exhaust system components.

Testing indicated that seizure of the butterfly valve shaft in the pillow block resulted in the failure of this Part. The engine exhaust brake was sectioned and disassembled to permit an examination of the internal butterfly valve shaft as shown in Figure 11. The shaft is in the as-received position as shown and is immovable. The shaft is supported in a blind hole on one end (left) and in a pillow block on the other end (right).

The butterfly valve shaft was cut at mid-length (indicated by red arrow in Figure 11a) to permit independent rotation of each end of the shaft. This revealed that the end of the shaft in the blind hole (left) rotates freely, however the end of the shaft in the pillow block (right) was seized in place. The butterfly valve shaft and one half of the pillow block is shown in Figure 11b after sectioning to permit examination of the bearing surfaces of these components. The shaft exhibits two split seal rings that are apparently intended to retain grease in a machined groove at the center of the pillow block. No remnants of grease or other lubricants are present.

The pillow block was produced from an unalloyed, hypoeutectic (carbon equivalent less than approximately 4.3) ductile iron. The butterfly valve shaft is produced from Type 303 free-machining austenitic stainless steel

The majority of the corrosion damage occurred to the ductile cast iron pillow block, rather than the austenitic stainless butterfly valve shaft. No seals of any kind are present to prevent the infiltration of moisture or other corrodants into the pillow block assembly. Furthermore, no grease or other lubricants were present within the pillow block which would have improve the lubricity of the joint and repel moisture and corrodants, retarding the corrosion rate of the surfaces within the pillow block.

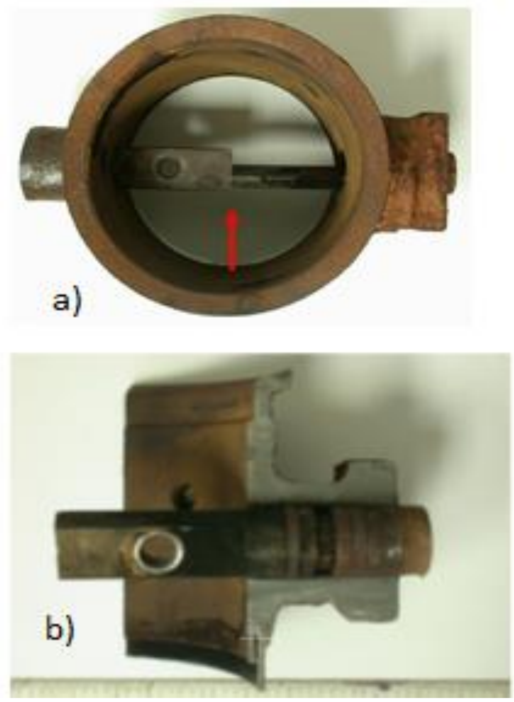


Figure 11: Dissected Butterfly Valve Shaft

The outboard split seal ring shown in Figure 11b above is shown at higher magnification in Figure 12a. The seal is adhered to the valve shaft and a significant amount of corrosion products are present adjacent to the split seal ring in the groove of the mating billow box as seen in Figure12b.

The current ACES Galvanic Corrosion algorithms do include elevated temperature as a parameter for predicting the brake failure.

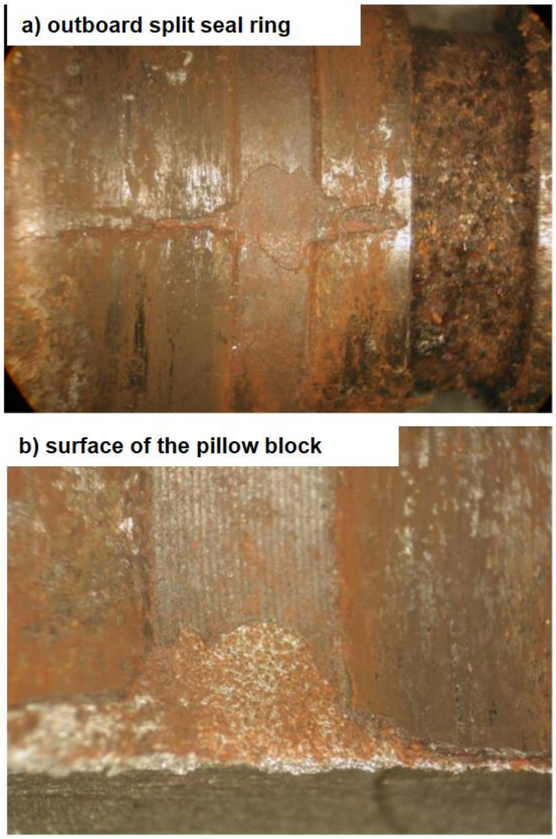


Figure 12: Magnification in the groove at the split seal ring

There were a few constraints which limited the ability to perform a complete analysis of all connected parts. First, the 3-D geometric model was missing several parts which were obvious from the presentation of the included parts which appeared as floating in space. These missing items were discovered to include the rubber suspender connecting to the 5 hole bracket, an (assumed) aluminum flex tube, cut to length from bulk and secured with hose clamps, and a number of missing parts which may (or may not) impact the corrosion. (see Figures 13 and 14).

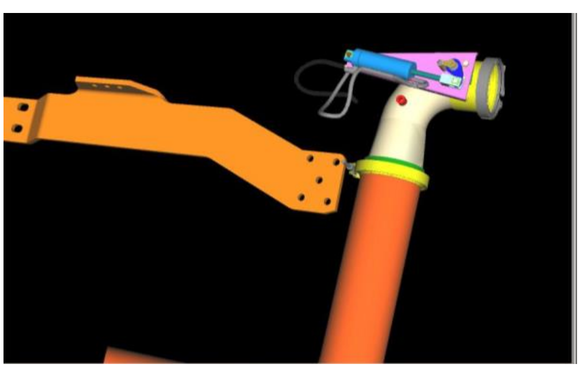


Figure 13: Engine Brake Assembly in 3-D Model

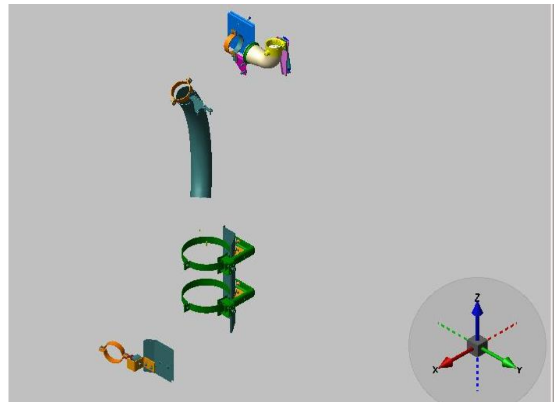


Figure 14: Engine Break Assembly floating in Space

The material and coating system (finish) for each part in the assembly extracted from the 2-D drawings as summarized in Table 3.

Table 3: Engine Break Assembly Material & Coatings

Part Number	Part Name	Material	Coating
19207_12414289-002_1	SUPPORT, ENGINE-TRANSMISSION-RIGHT	ASTM A572	
19207_12414307-123_1	BOLT, HEX FLANGE		
19207_12414634-002_1	CLAMPING-CLAMP V-BAND	ASTM A240	
19207_12414634-003_1	CLAMPING-CLAMP V-BAND	ASTM A240	
19207_12418003-901_1	HOSE ASSEMBLY	SPECIAL	
19207_12418003-902_1	HOSE ASSEMBLY	SPECIAL	
19207_12419172-003_1	CLAMP, LOOP, V-BAND	ASTM A240	
19207_12419172-004_1	CLAMP, LOOP, V-BAND	ASTM A240	
19207_12419172-005_1	NUT, SELF LOCKING, HEXAGON	STAINLESS STEEL	
19207_12421919-001_1	CLAMP	ASTM A240	
19207_12423115-001_1	TUBE	ASTM A269	
19207_12423115-002_1	FLANGE	ASTM A167	
19207_12505546-002_1	BRAKE ASSEMBLY, EXHAUST (all)	304L	None
19207_12505546-003_1	BRAKE ASSEMBLY, EXHAUST (flange)	ASTM A536	Method-6
19207_12505546-004_1	BRAKE ASSEMBLY, EXHAUST (inspection port)	STEEL	Method-6
19207_12505546-005_1	BRAKE ASSEMBLY, EXHAUST (butterfly shaft)	STEEL	Method-6
19207_12505546-006_1	BRAKE ASSEMBLY, EXHAUST (arm)	STEEL	Method-6
19207_12505546-007_1	BRAKE ASSEMBLY, EXHAUST (butterfly)	SAE 8670	Method-6
19207_12505546-008_1	BRAKE ASSEMBLY, EXHAUST (cylinder)	STEEL	Method-6
19207_12505546-009_1	BRAKE ASSEMBLY, EXHAUST (pipe plug)	STEEL	Method-6
19207_12505546-010_1	BRAKE ASSEMBLY, EXHAUST (washer)	STEEL	Method-6
19207_12505546-011_1	BRAKE ASSEMBLY, EXHAUST	STEEL	Method-6
19207_12505546-012_1	BRAKE ASSEMBLY, EXHAUST (capscrew)	SPECIAL	
19207_12505546-013_1	BRAKE ASSEMBLY, EXHAUST (valve bolt)	STEEL	Method-6
19207_12505546-014_1	BRAKE ASSEMBLY, EXHAUST (valve nut)	STEEL	Method-6
19207_12505546-015_1	BRAKE ASSEMBLY, EXHAUST (clevis)	STEEL	Method-6
19207_12505546-016_1	BRAKE ASSEMBLY, EXHAUST (clevis pin)	STEEL	Method-6
19207_12505546-017_1	BRAKE ASSEMBLY, EXHAUST (e-clip)	STAINLESS STEEL	None
19207_12505546-018_1	BRAKE ASSEMBLY, EXHAUST (filter)	STAINLESS STEEL	None
19207_12505546-019_1	BRAKE ASSEMBLY, EXHAUST (washer)	STEEL	Method-6
19207_12505546-020_1	BRAKE ASSEMBLY, EXHAUST (lock washer)	STAINLESS STEEL	None
19207_12505546-021_1	BRAKE ASSEMBLY, EXHAUST (bolt)	STEEL	Method-6
19207_12505546-022_1	BRAKE ASSEMBLY, EXHAUST (plug)	STEEL	Method-6
19207_12505546-023_1	BRAKE ASSEMBLY, EXHAUST (piston)	STEEL	Method-6
19207_12505546-024_1	BRAKE ASSEMBLY, EXHAUST (bracket)	SAE 1020	Method-6
19207_12505546-025_1	BRAKE ASSEMBLY, EXHAUST (anchor pin)	STEEL	Method-6
19207_12505546-026_1	BRAKE ASSEMBLY, EXHAUST (stop)	STEEL	Method-6
19207_12505546-027_1	BRAKE ASSEMBLY, EXHAUST (bushing)	STAINLESS STEEL	None
19207_12505546-028_1	BRAKE ASSEMBLY, EXHAUST (spacer)	STEEL	Method-6
19207_12505546-029_1	BRAKE ASSEMBLY, EXHAUST (valve body)	ASTM A536	Method-6
81343_4-2_070202C_1	90 DEGREE MALE ELBOW		
81343_SAE-J-30R7-401	HOSE, RUBBER, FUEL AND OIL	RUBBER COMPOSITE	None
96906_MS20500-[illegible]	NUT, SELF LOCKING, HEXAGON	STAINLESS STEEL	
????	?????Rubber suspender????		
????	????Flex Tube, cut to length?????		

The cells shown in Blue in Table 2 are blank meaning there was no information on these items. The table; content summarizes the state of parameter definition as:

- 14 of 43 parts have sufficiently defined material specifications.
- 27 of 43 parts have sufficiently defined coating/plating specifications.
- 2 missing parts are apparent. At least one of the missing parts may be important to the analysis.

Figure 15 shows the ACES results for the available connected parts using a 20-year Montreal environment. The analysis correctly predicted the severe corrosion of the bellow box and an acceptable level of corrosion of the stainless butterfly valve shaft.

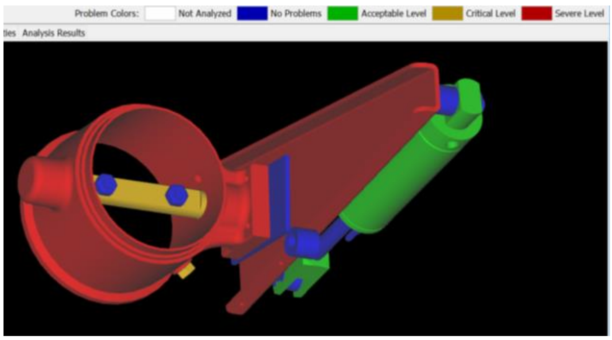


Figure 15: ACES Prediction of the FMTV Engine Break

TRANSMISSION COOLER SHROUD

The Auxiliary Transmission Cooler Shroud (Part #12424551) experienced severe galvanic and poultice corrosion of aluminum shroud as shown in Figure 16.

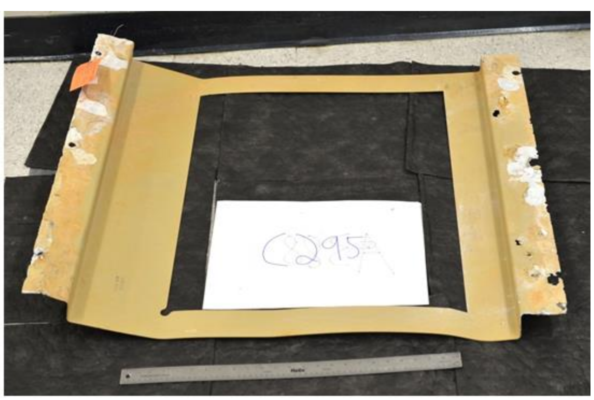


Figure 16: Aux. Trans. Cooler Shroud after ACDRT.

The crevice corrosion was so severe that it ate through the metal at the bolt attachments as shown by the right side of Figure 16. The crevice corrosion was intensified by the collection of electrolyte at the mating face between the shroud and the frame rails which acted as a water trap as seen by the red arrow in Figure 17.

Figure 17: Location of Water Trap associated with the FMTV Auxiliary Transmission Cooler Shroud.

The Transmission Cooler Shroud is displayed in the model assembly tree as a single leaf part only (that is with no subparts) shown in Figure 18.

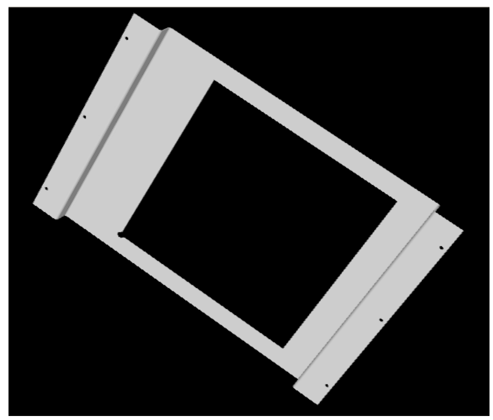


Figure 18: FMTV Transmission Cooler Shroud

The part interactions analysis found a total of 22 direct contacts and 15 gap contacts. Figure 19 show these contacting parts.

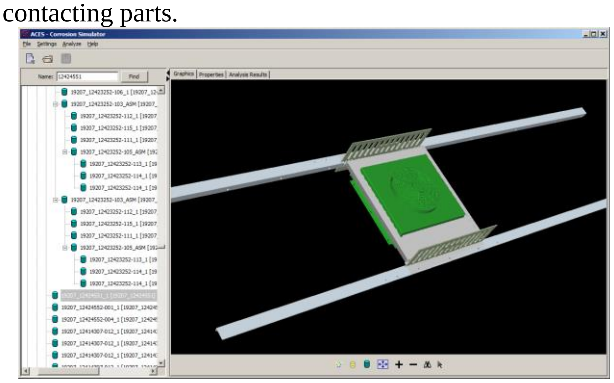


Figure 19 – Shroud Plus Interacting Parts

Figure 20 shows the results of the galvanic corrosion analysis. Ironically, ACES predicted no crevice corrosion even though it was the most dominate failure mode and led to catastrophic failure clearly indicating that algorithm changes are necessary.

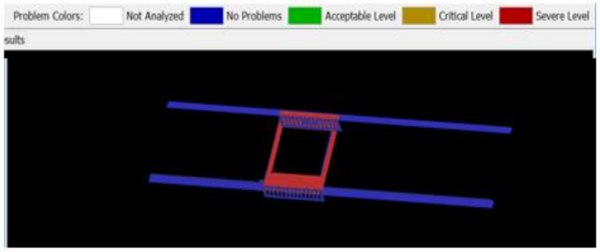


Figure 20: Shroud Galvanic Corrosion Prediction

CONCLUSIONS FROM CALIBRATIONS

An effort was made to improve and calibrate the existing ACES corrosion prediction algorithms using the results from three part assemblies that experience catastrophic corrosion failure during ACDRT of the FMTV. The analysis indicated there was a need for additional basic improvements to the algorithms as follows:

1. The new galvanic corrosion algorithms did not properly predict the improvement obtained for the zinc die casted T-handle design with nickel plating. This indicates that the ACES algorithms need to include the effect of sacrificial cathodic coatings such as nickel which “seal” the surface of the substrate material (such as zinc) from the atmosphere. The current algorithm flagged the sacrificial galvanic reaction between the nickel and zinc as a severe adverse condition. The test results of the new T-handle design were properly predicted with the prior ACES algorithms.
2. The new galvanic corrosion algorithms did properly predict the performance of the all the other parts in the T-handle assembly.
3. The new galvanic corrosion algorithms did correctly predict the failure of the reported the Engine Brake Pillow Block which resulting in seizure of the butterfly valve stem. All neighboring part corrosion were also correctly predicted.
4. The new galvanic corrosion algorithms correctly predicted severe corrosion of the aluminum Transmission Cooler Shroud due to connecting steel parts. However, the algorithms did not consider the fact that aluminum spontaneously forms a thin but effective oxide layer that prevents further oxidation, so the true severity of the corrosion is much less. This effect needs to be included in the next generation algorithms.
5. The ACES crevice corrosion algorithm failed to predict the catastrophic failure of the aluminum shroud at the bolted connections which was immersed in electrolyte and poultice due to poor drainage.
6. A needed enhancement to the ACES code is to develop a method for modeling electrolyte entrapment including drainage problems. This would include algorithms for the microenvironment surface wetting.
7. Both the existing galvanic and crevice corrosion models are not time dependent. That is, they fundamentally predict of the likelihood of corrosion at any time in the future, rather than the likelihood of corrosion over time. To correct for this short coming, a “patch” solution was implemented where some simple "piece-wise-linear" scaling with time is performed connecting likelihood values derived from ACDRT data and subject matter expert opinions.
8. The crevice corrosion algorithm which does include time variation has been enabled. It is however limited to a very narrow set of circumstances, namely: for Hem Flanges (for Al-Al and Low Carbon Steel (LCS)-LCS), "Coach Joint", for Al-Al, LCS-LCS and G60-G60) and Lap Joints (for Al-Al, G60-G60, G90-G90 and Hot-Dip-Zinc (HDZ)-HDZ). The previous version had a crevice corrosion prediction algorithm for the likelihood was not time dependent. It however gave results for other types of mating (fasteners, gaskets, spacers, moving joints, T-joint, sandwich, butt-joint, ell-Joint), as well as likelihood specified for two other mating interfaces: "Fastening" and "Moving Joint". These types of connections need to be moved into the time-dependent algorithm. Note that this is the reason that no crevice corrosion was predicted for the transmission cooler shroud.
9. The calibration effort was handicapped by the fact that ACES predicts the relative likelihood of corrosion occurring rather than the relative severity level of corrosion. A desirable future enhancement would be to predict the likelihood of achieving the various ASTM D610 stages of corrosion [10].
10. The version of the ACES product presented here does not have a coating deterioration algorithm to account for the breakdown of the protective coating layer over time. This is particularly important in the prediction of the Transmission Cooler Shroud which had a coating system applied (see Figure 16), namely IAW 12420325 Method 2 (e-Coat). To add this capability to ACES, a recent subcontract award from PPG (via ARL) was awarded to create prediction models within ACES for coating breakdown over time using field inspection data as the basis for the prediction [11].

ACES VALIDIATION TESTING ON THE MTVR

An Office of the Secretary of Defense (OSD) demonstration project was awarded to the US Army TARDEC to demonstrate the predictive capability of ACES on the MTVR vehicle over time. The MTVR (Medium Tactical Vehicle Replacement) shown in Figure 21 is a USMC vehicle designed to replace the 5-ton truck (Army M939/ USMC M809). The vehicle was designed and built by Oshkosh Corporation, which, unlike the

FMTV, retained the vehicle drawing package and other intellectual property associated with the vehicle. This situation was advantageous to the validation process in that a third-party company from the software developer, namely Oshkosh Corporation, was contracted to perform the validation and this increases the tool credibility.

Figure 21: MTVR

The MTVR has undergone three ACDRTs: the original test during procurement at ATC [12], a second test at ATC under ONR contract, and a test at NTC under ONR contract. Unfortunately, all the data and records from the two ONR tests were either lost or destroyed but the original 22-year ACDRT procurement data, including the vehicle that underwent testing were still available for review.

A Focus Area List (FAL) of 27 corrosion hotspots were identified as candidates for ACES validation testing:

1. Steel hydraulic, cooling, air and fuel fittings
2. Aluminum electrical fittings
3. CTIS tubing
4. Cab shock fastener
5. Frame rail flange
6. Stave pocket interiors (Phase 15)
7. Cargo body crevices (Phase 15)
8. Dropside crevices (Phase 19)
9. Dropside cracking (Phase 19)
10. Fuel tank straps
11. Longitudinal structural angle on cargo body
12. Hood hold down metal clips (Phase 15)
13. Door latching hardware
14. Mirror hardware
15. Cab fasteners
16. Hood fasteners
17. D-ring fasteners (Phase 19)
18. T-bolt fasteners
19. Hydraulic tank straps
20. Air tanks
21. Air tank exterior
22. Radiator surge tank
23. V-channels welded to cargo bed
24. Cargo bed forward edge
25. Suspension Springs
26. Hood Springs
27. Inter-vehicular connector (front & rear)

Oshkosh engineering then organized these FAL items into four assemblies containing twelve (12) of the 27 FAL items as candidates for ACES analysis. All 12 items are in the Under Body (UB) vehicle zone:

1. Frame Assembly (Figure 22)
   a. FAL #5: Frame Rail Flange

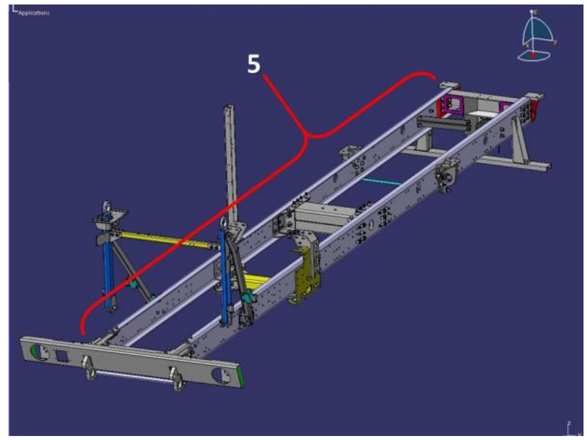


Figure 22: Frame Assembly showing FAL item #5

2. Cargo Body Top (Figures 23) and Bottom (Figure 24)
   a. 6) Slave Pocket Interiors
   b. 7) Cargo body crevices
   c. 8) Dropside Crevices
   d. 9) Dropside Cracking
   e. 17) D-ring fasteners
   f. 11) Longitudinal Structural Angle on Cargo Body
   g. 23) V-channels welded to cargo bed
   h. 24) Cargo bed forward edge

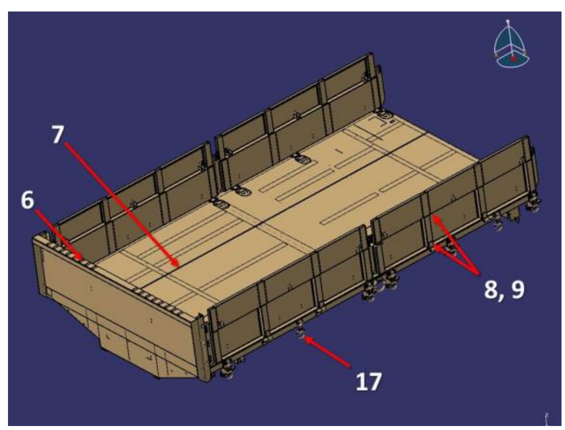


Figure 23: Cargo Body - Top showing FAL items #6 - 9 and 17

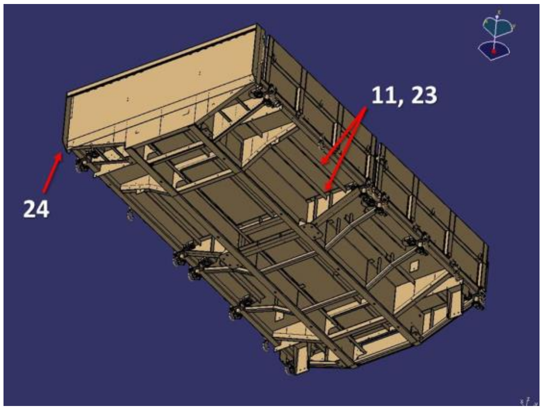


Figure 24: Cargo Body - Bottom showing FAL items #11, 23 and 24

3. Air Tanks (Figure 25)
   a. 20) Air tanks
   b. 21) Air tank exterior

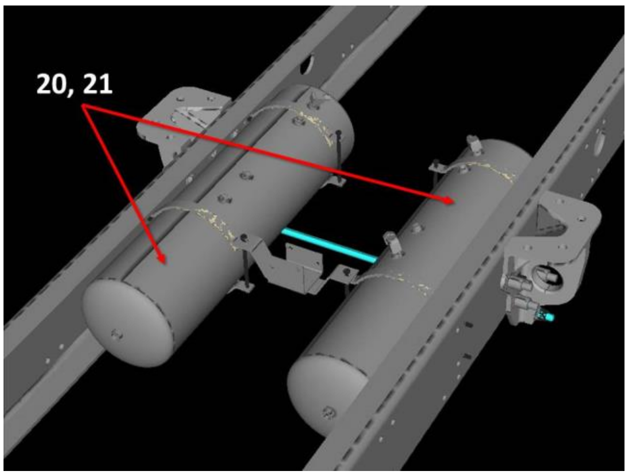


Figure 25: Air Tanks showing FAL items #20 and 21

4. Fuel Tank (Figure 26)
   a) 10) Fuel tank Straps

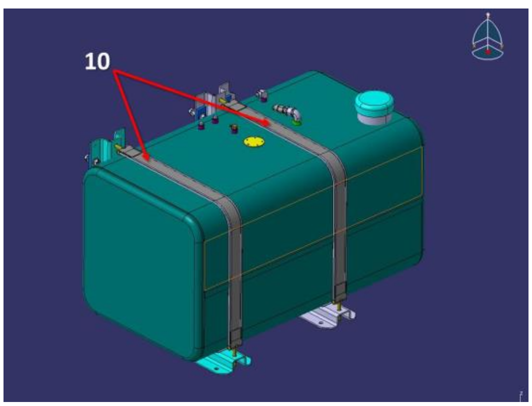


Figure 26: Fuel Tank showing FAL items #10

The balance of 15 FAL items which have not been analyzed are listed in Table 4:

Table 4: Remaining (Unanalyzed) MTVR FAL Items

FAL Item #	Description	Vehicle Zone
1	Steel hydraulic, cooling, air and fuel fittings	UB
2	Aluminum electrical fittings	
3	CTIS tubing	
4	Cab shock fastener	
12	Hood hold down metal clips (Ph-15)	
13	Door latching hardware	ATB
14	Mirror hardware	ATB
15	Cab fasteners	
16	Hood fasteners	ATB
18	T-bolt fasteners	
19	Hydraulic tank straps	
22	Radiator surge tank	UH
25	Suspension Springs	UB
26	Hood Springs	UH
27	Inter-vehicular connector (frt & rear)	BTB

FRAME ASSEMBLY ANALYSIS

A more detailed view of the Frame Assembly Model is shown in Figure 27.

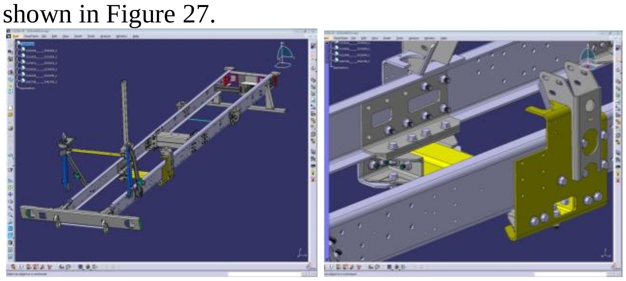


Figure 27: MTVR Frame Assembly Model

The truck frame, particularly around fasteners, has repeatedly been identified as a prime target area as shown in Figure 28.

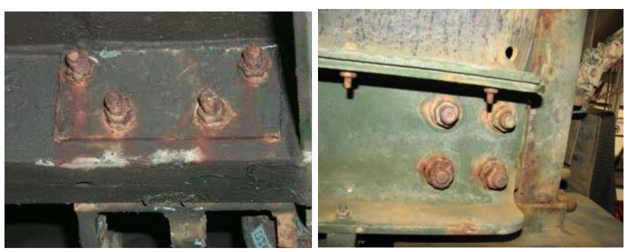


Figure 28: MTVR Truck Frame Fastener Corrosion

During validation testing, there was an upgrade of the version of ACES used for the analysis from version 1.2 to version 1.3. The most significant difference between the two versions was the change in the crevice corrosion algorithm. As discussed previously, the initial version 1.2 used the prediction algorithm for the likelihood that was not time dependent but did have a broad range of mating features including fasteners, gaskets, spacers, moving joints, T-joints, sandwiches, butt-joints, ell-Joints; as well as likelihood specified for "Fastening" and "Moving Joint". mating interfaces. The new crevice corrosion algorithm found in version 1.3 is time dependent, but rules are currently only encoded for Hem Flanges, Coach Joints, and Lap Joints; and those only for limited materials and coatings.

of the fasteners during ACDRT. The latest version 1.3 however did not predict these results. This apparent step-backwards was a result of abandoning the traditional “Crevice Propensity” prediction model used in version 1.2, which had no time dependency. Clearly additional calibration of the ACES crevice corrosion prediction models is needed.

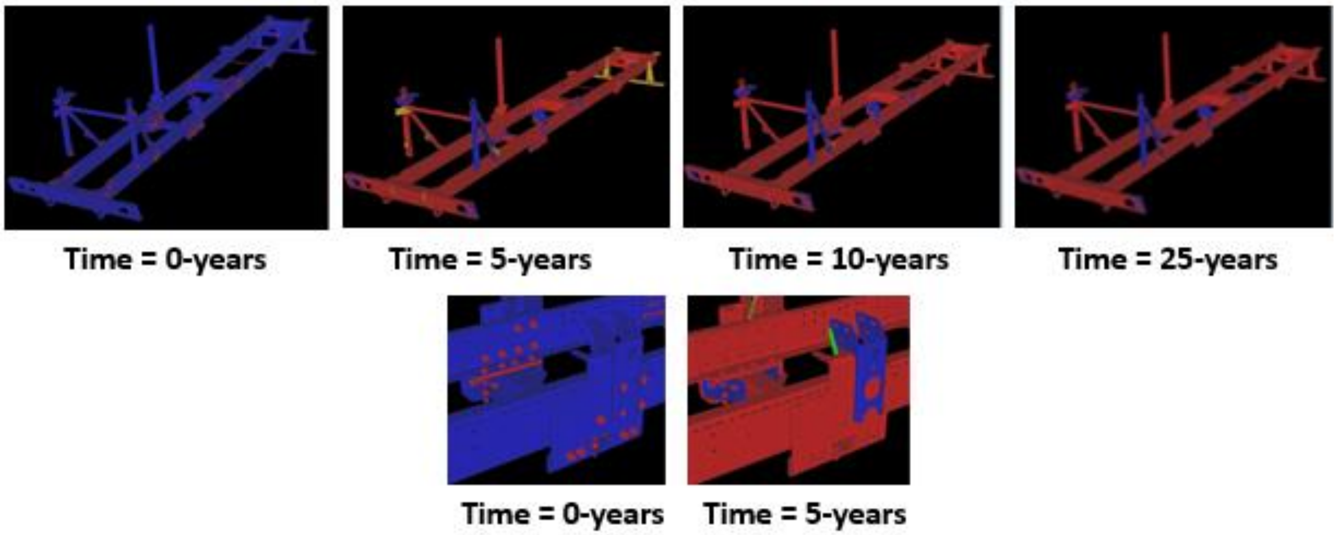


Figure 29: ACES Version 1.2 Prediction of MTVR Frame Corrosion (Montreal) at Different Points in in Time.

The initial validation testing analysis using version 1.2 was a “Zero-years” simulation, which immediately flagged the fasteners as seen in Figure 29. The analysis assumed only zinc phosphate and oil coating on fasteners. During the simulation, it was noted that currently ACES has no interface for the user to add substance/ coating to 3D threads on a fastener. The 5-year simulation of the frame in the figure showed that most of frame has been elevated to a “severe” rating. Changing the simulation time resulted in little change as seen by the 10-year and 25-years simulation.

Oshkosh then performed simulations on the MTVR frame assembly using ACES version 1.3 as shown in Figure 30. As seen by the side photos in Figure 28, the frame assembly experienced extensive crevice corrosion

The Oshkosh predictions in Figure 30 using the new version shows only the front bumper with severe corrosion and no crevice corrosion on any of the fasteners. As discussed above, the previous version showed the fastener corrosion immediately (even at 0-years) because there was no time dependency in the earlier algorithm. Based on the Oshkosh validation test results, additional refinement is needed to the current time-dependent algorithm to include the very early corrosion of the fasteners that was observed in the test data.

CARGO BODY ASSEMBLY ANALYSIS

MTVR Cargo Body shown in Figure 31 has many of the FAL items. The future simulation may require analysis or assumptions for material properties.

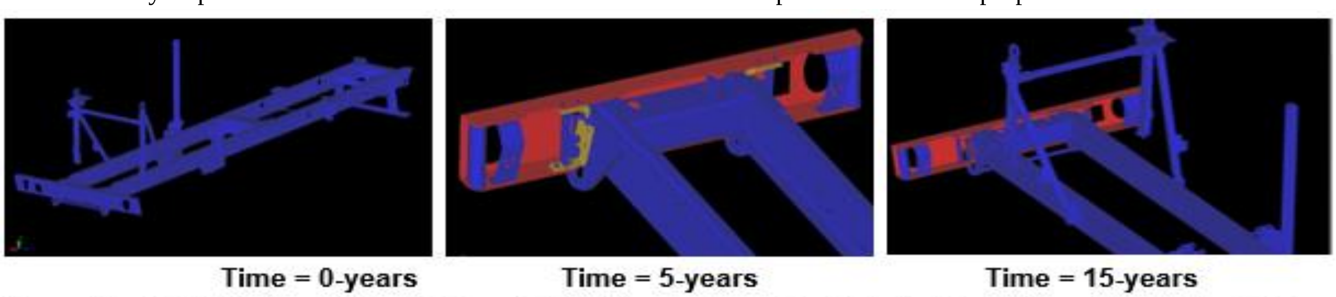


Figure 30: ACES Version 1.3 Prediction of MTVR Frame Corrosion (Montreal) at Different Points in in Time.

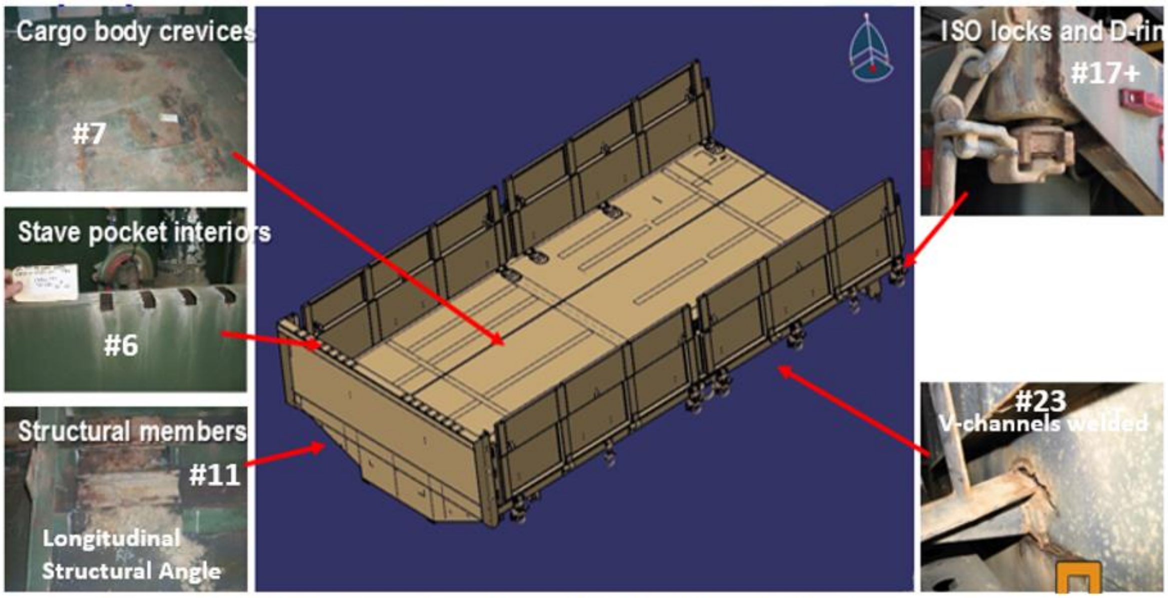


Figure 31: MTVR Cargo Bay Assembly Model and FAL Corrosion Areas

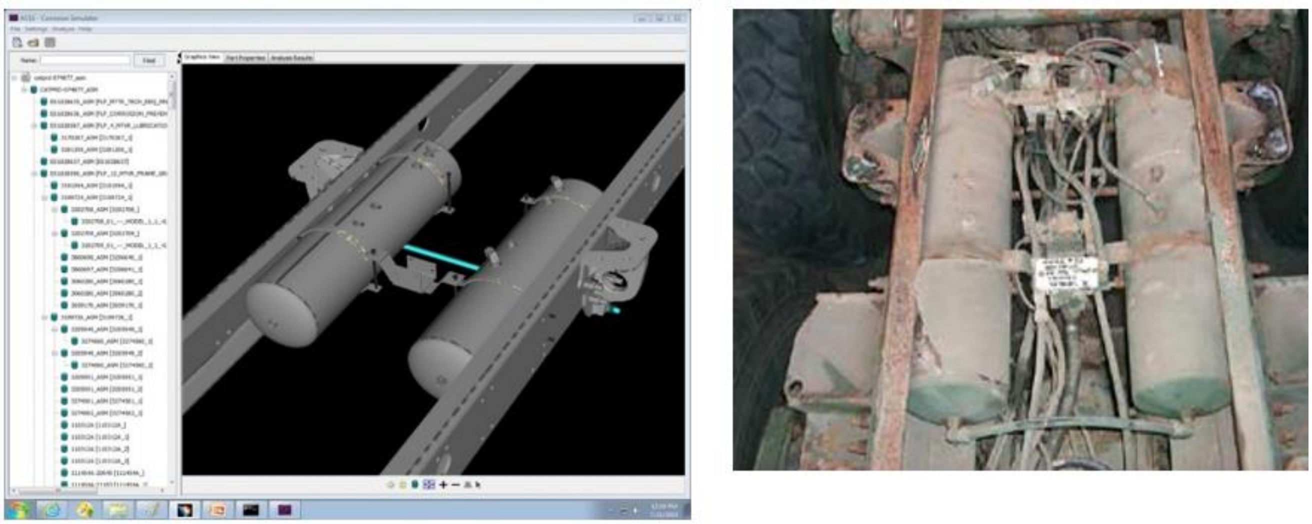


Figure 32: MTVR Air Tank Assembly a) ACES Model and b) ACDRT Result

AIR TANK ASSEMBLY ANALYSIS

The MTVR Air Tank Assembly Model and corresponding ACDRT result are shown in Figure 32. Small Air Tank Assembly built to include tanks, fittings, mounting hardware, and adjacent frame components.

FUEL TANK ASSEMBLY ANALYSIS

The analysis of the Fuel Tank Assembly using the original version 1.2 showed immediate fastener corrosion (Figure 33). The main interest of analysis was the deterioration of both of the tank restraining straps observed during ACDRT as seen in Figure 34.

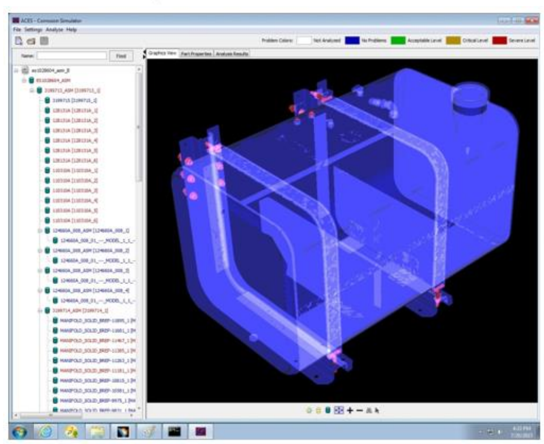


Figure 33: MTVR Fuel Tank Assembly Model

Figure 34: Corrosion of the MTVR Fuel Tank Straps

The ACES simulation however predicted only one strap corroded as shown in Figure 35.

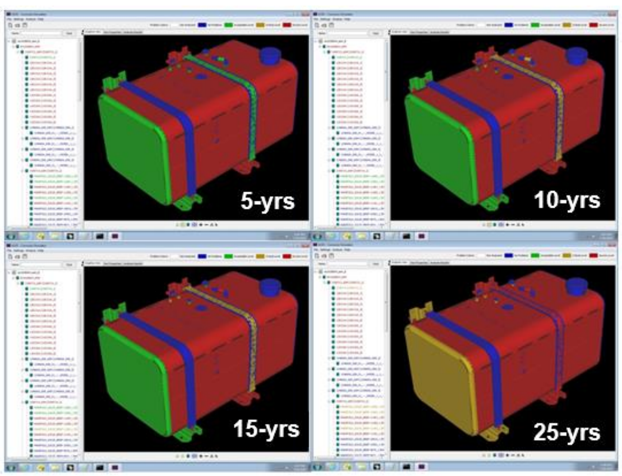


Figure 35: ACES Simulation of MTVR Fuel Tank over Time

The Materials and Coatings data files accompanying the model showed the tank material to be aluminum: 5XXX (uncoated), and the attachment bands made from 10XXX steel (uncoated) over a rubber insulator. There were also uncoated yellow brass pipe/tubing fittings. That is, the materials specified for the fuel tank parts in the assembly showed no coatings or plating on any of the materials.

Galvanic corrosion (only) analysis of the assembly produced similar results to that seen in Figure 35 above with band #1 showing severe corrosion (Figure 36) and band #2 showing "No Problems" (Figure 37). Examination of the interacting parts showed that the band #1 has additional interacting parts due to the close proximity to one of the brass fittings.

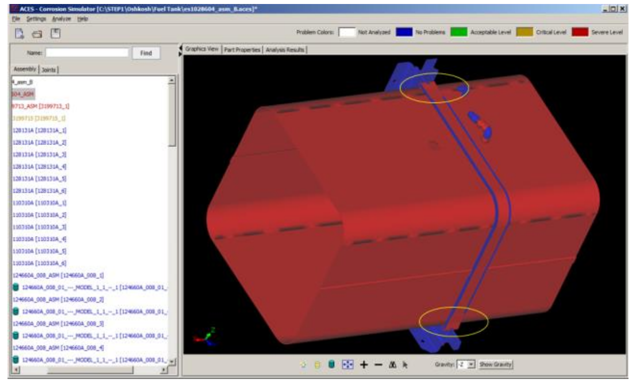


Figure 36: Fuel Tank – Band #1 Interacting Parts

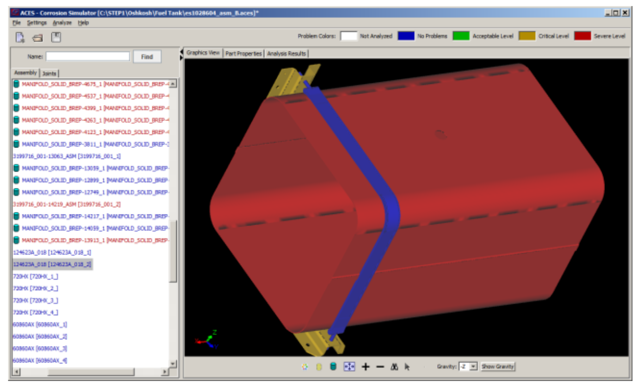


Figure 37: Fuel Tank – Band #2 Interacting Parts

The detailed corrosion analysis scoring report for band #1 listed three sub-problems for three of the brass fittings (part numbers: 56846AX_01, 3054528_01 and 47386AX_01) which were galvanically interacting with the band (part 13913_1). Note that there was no detailed report for band #2 because there were no reported problems. The report indicated that the fuel tank galvanic corrosion of band #1 were due to the close proximity to brass fittings. To better understand the cause, the strap – tank connection geometry was examined in more detail. The ACES "Show Connected Parts" indicates that the straps are in contact with the tank, and close examination of the ends seems to confirm this (Figure 38).

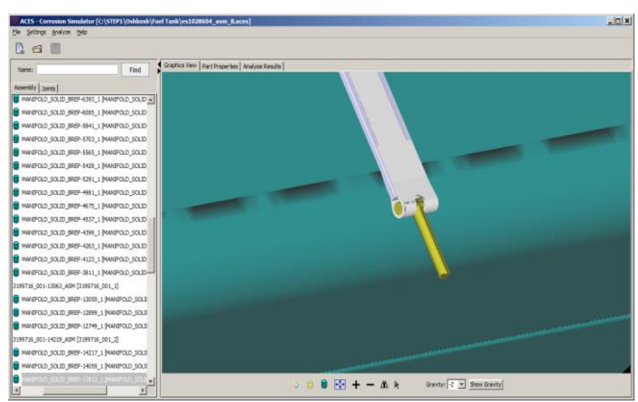


Figure 38: Fuel Tank - Connected Parts

However, an even closer examination shows that there is a very small gap between the tank and the steel straps (Figure 39). (Perhaps subject to manufacturing tolerance). This small gap is reported as a "direct contact" because the distance is less than the default contact distance of 3mm. Changing contact distance to 1-mm still reports a direct contact.

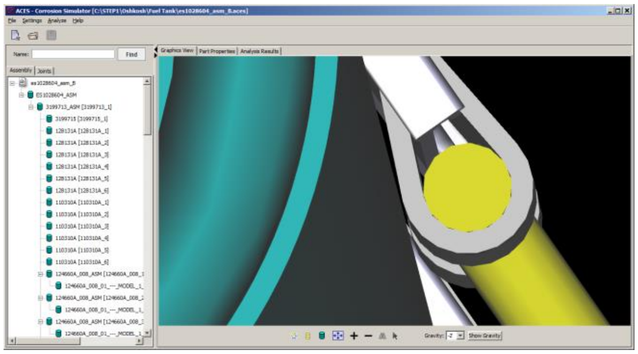


Figure 39: MTVR Aluminum Fuel Tank / Steel Strap Band gap

The original fuel tank project file (provided by Oshkosh) was examined in a text editor, where it was noted that some of the parts had no assigned coatings. The missing coating methods were added and the corrosion analysis was repeated (galvanic only) which gave an "Acceptable" galvanic corrosion of the bands as shown in Figure 40. Note however that the detailed report does show three minor interactions with the brass fittings.

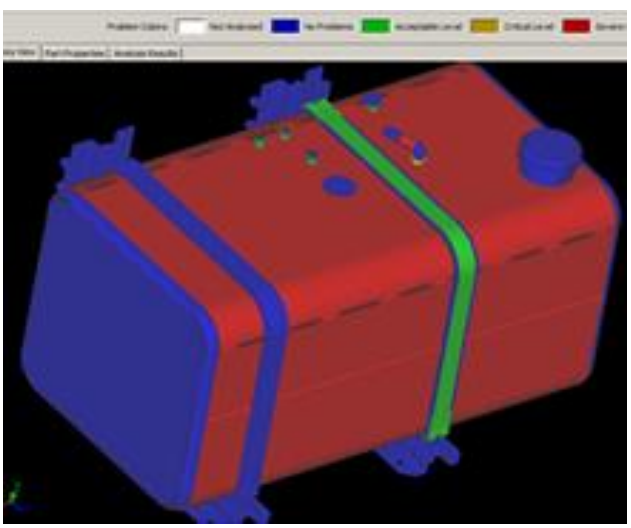


Figure 40: Fuel Tank - Galvanic Predictions at 15-years-Montreal

The aluminum fuel tank is predicted to have a "severe" probability of corrosion. This is due to a large number of minor galvanic interactions, and the resulting combination of all the individual probabilities.

The center fitting and fitting next to the tank also showed severe corrosion (see Figure 40). These two fitting are made from aluminum rather than brass. The center fitting is CARC while the Al fitting next to tank is Chromate-conversion coated. The severe corrosion failure of the center fitting is due to the interaction with the CARC (plus some contribution from the base material).

The initial uniform corrosion prediction results (only) of the fuel tank are shown in Figure 41.

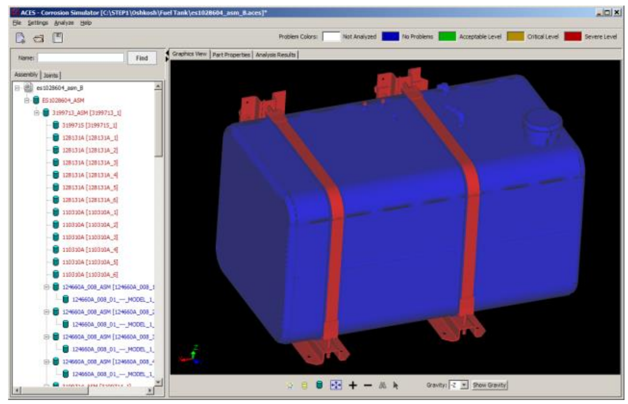


Figure 41: Fuel Tank - Uniform Corrosion Initial Results (with no coatings)

Since coatings were assigned to most parts (excepting brass fittings) in Figure 41, no uniform corrosion was predicted.

COATING BREAKDOWN ALGORITHMS

The ACES version used for the predictions in this paper does not have a time dependent coating breakdown algorithms. This enhancement is currently being developed under a subcontract award from PPG Industries Inc. provided by a prime contract from Army Research Labs. Details of this project are found in Reference 11.

Coating Deterioration was observed during the MTVR Accelerated Corrosion Deterioration Road Test (ACDRT), specifically to the:

- Truck Bed Frame (Figure 42),
- Air Tanks & Frame (Figure 43),
- Underbody Suspension (Figure 44), and
- Mounting Ladder (Figure 45).

Figure 42: Coating Deterioration on the MTVR Truck Bed Frame during ACDRT

Figure 43: MTVR Air Tanks and Frame Coating Deterioration during ACDRT

Figure 44: Underbody Suspension Coating Deterioration during ACDRT

Figure 45: MTVR Mounting Ladder Coating Deterioration during ACDRT

CONCLUSIONS AND RECOMMENDATIONS

The ACES Corrosion Simulator offers great potential as a future tool for predicting and controlling corrosion of wheeled vehicles and other assets. As currently implemented, ACES is an excellent prediction simulation code that can provide an engineering estimate of the corrosion resistance performance under various scenarios, and can forecast & display deterioration of vehicle system at specified points in time as well as perform “What-if?” trade-off studies with alternative designs, materials, etc.

The eventual simulation tool is envisioned to produce a continuous display of the deterioration of the full vehicle over time in a video presentation. It will be a tool for fast review of corrosion vulnerabilities in new designs & technology resulting in a shorten product development cycle time. It will be useful in specification/selection optimal design/materials during design/fabrication. It also can be used to define maintenance intervals/warranty based on expected performance. ACES should also provide an intelligent assistant in designing corrosion tests with reduction (or even possible elimination?) of full system corrosion testing (e.g., ACDRT).

The use of the product will produce higher corrosion resistant design construction that will result in more efficient utilization of maintenance personnel, subsequent reduction in the cost of repair/rebuild of components, and reduction in cost of corrosion and improved system reliability. An often-overlooked benefit is the development of an efficient knowledge base of lessons-learned and corrosion prevention-control policy and procedures. The result is an anticipated 10:1 Financial Return on Investment (ROI) over 10-years. Finally, a key benefit for the development of the simulator is the creation of AI assistant that never retires, resulting in the retention of expert knowledge. Rather ACES continues to get smarter using AI learning algorithms, which is part of a proposed future Knowledge Acquisition (KA) module.

The focus of the current work was to demonstrate the technical readiness level of the ACES system.. The effort identified several enhancements that are required to the product as follows:

- The development time-dependent coating breakdown algorithms. This enhancement is under development as described in Reference 11.
- The extension of the current time-dependent crevice corrosion algorithms to include fasteners, gaskets, spacers, moving joints, T-joint, sandwich, butt-joint, ell-Joint, as well as two other mating interfaces ("Fastening" and "Moving Joint").
- Extension of the galvanic corrosion algorithms to properly account for the effect of sacrificial cathodic coatings.
- The development of methods/logic for electrolyte entrapment/accumulation (i.e., poor drainage) to account for sustained time of wetness and poultice entrapment.
- Extension of the prediction algorithms to calculate the relative severity level of corrosion per ASTM D610 stages of corrosion [10], rather than the current likelihood of any corrosion. This would help in establishing a tie between ACDRT and field survey data and the ACES prediction output.
- The development of a Knowledge Acquisition facility within ACES that included learning algorithms, thereby allowing it to automatically grow as more knowledge is added to its knowledge base.

ACKNOWLEDGEMENTS

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DISCLAIMER

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