Summary: Final Report for Valeo Engine Cooling for External Corrosion Protection for Copper/Brass Heat Exchangers Using Electrochemical Deposition Coating (EDC)

SUMMARY: Using 112 copper brass radiators in this study, this report presents the corrosion, heat transfer, and durability test results on 5 different radiator designs. The report clearly shows the advantages of Electrochemical Deposition Coating (EDC) to substantially increase the life of copper brass radiators with negligible reduction in heat transfer performance. In addition, special tests were performed on gaskets, plastic tanks and solders in order to determine any detrimental effects occurring as a result of the required curing temperatures, between 360º F and 400º F.

I. INTRODUCTION: Extreme increases in the use of salt for snow and ice removal on roads and increased atmospheric pollution from both automobiles and other sources have created a much more severe corrosion environment for automotive radiators. As a result, corrosion problems in copper brass radiators, which previously occurred primarily in severe marine environments, are occurring in increasing ranges of geographical areas, There has been little information available on the use of coatings to reduce copper brass radiator corrosion. Growing evidence exists that radiator corrosion, and fin corrosion in particular, are occurring more frequently as a result of an increasing presence of acidic gases in the air, some of which come from catalytic converter systems. There is evidence that solder and brass corrosion may occur in a neutral environment containing salt, while fin corrosion becomes more severe if other factors such as acidity and sulfur compounds are present.

The cause of corrosion is the contact of materials with different electrochemical potentials in the presence of a corrosive environment. For instance, the electrochemical potentials of the main components of copper brass radiators are:

Tin =	-0.136 V/SHE
Lead =	-0.122 V/SHE
Iron =	-0.045 V/SHE
Copper =	+0.344 V/SHE

V/SHE = Volts/Standard Hydrogen Electrode

There is a significant difference between the electrochemical potential values between these metals. The corrosion resistance requirements, as per Customers Engineering Standards, call for exposure to Neutral Salt Spray Fog, ASTM B117-85. Normally, there are two criteria, the functional, where some customers require only 240 hours with no leaks. (Other customers require 1,680 hours with no leaks.) The other criteria is aesthetic, which normally consists of 96 hours with less than 20% visible corrosion.

There are three methods for corrosion protection:

1) To isolate the materials from the environment (surface coatings).

2) To reduce the corrosion potential difference between the metals in contact (tin/lead rich fins).

3) To contact the metal to be protected with another having a lower corrosion potential (zinc rich fins).

Usually the least expensive type of coating to make the radiator look black was considered satisfactory. In some cases low-cost coatings tend to hold contaminants in place and provide areas for corrosive materials to accumulate, so they actually make the corrosion problem more severe.

Techniques for corrosion prevention have been advancing rapidly. Radiator designs have been developed that utilize tin-lead (Valeo Zaragoza) or zinc rich fins (Outokumpu patent) and different conversion coatings applied by spraying or immersion (Brugal process by Valeo Italy), and Electrochemical Deposition Coating (EDC). These corrosion protection technologies have made inroads into the copper brass radiator industry. However, it has been recognized that the ideal corrosion protection system meets the following criteria:

1) Extend the life of copper brass radiators, especially in severe environments, to a 10-year life,

2) Achieve the best durability for the least cost,

3) Be processed using currently available technology,

4) Present minimal environmental, health, and safety problems, both in application, and during repair of the units,

5) Have a minimal impact on the rate of heat transfer, and
6) Be processed at temperatures that do not adversely affect solder, gaskets, and plastic tanks. (Because of the wide variety of materials used in solders, gaskets and plastic tanks, individual determinations must be made based upon the following process temperatures for EDC: Temperatures fluctuate between 360º F and 400º F for approximately 25 minutes.)
Within the currently available technologies, EDC meets all the aforementioned criteria.

II. ELECTROCHEMICAL DEPOSITION COATING (EDC): EDC is a process where black epoxy is applied electrically inside a dip tank. Epoxy particles are charged positively and are attracted to the negatively charged radiator. Under an applied electrical field, the positively charged particles migrate to the negatively charged surfaces on the radiator, forming a coherent film with excellent mechanical adhesion (Cross Hatch Adhesion: 4B to 5B by ASTM D3359-93). As the film builds to a thickness of between 0.8 mils and 1.2 mils, the radiator becomes insulated and restricts further deposition. EDC thickness varies no greater than 0.4 mils, or less than 0.0005".

II.A. ADVANTAGES OF EDC: The process is automated. The EDC has very good physical and chemical resistance properties, and it possesses excellent appearance. It has exceptional capacity to reach hidden areas and cover 99.5+% of all surface area. Any metal can be treated using the same EDC solution, and only conductive areas are coated. (Plastic tanks, gaskets, etc. are not coated.) EDC is water borne, and therefore considered an environmentally green process. EDC has received a military specification number and is approved for used by the National Science Foundation (NSF). Of all the processes investigated, EDC provides the best relationship between durability and cost.

III. TESTING PROCEDURE: One hundred and twelve radiators were used. Table 1 shows radiator designs, sample size, and test procedure. Sixty (60) samples were coated using EDC, and the remaining samples were tested as reference for evaluation against the EDC units.

III.A. CORROSION: The goal of these tests is to provide additional information on corrosion testing results from those previously reported (REP Road Environment Pollutant Solution. Accelerated corrosion test), and compare test results with a base line. Salt Spray, Compound Cycle and SWAAT (Sea Water Acetic Acid Test) tests were performed. See Table 2 and Table 3.

These are the reference tests currently applied in USA and Europe. The tests are:

i) S.S.: Neutral Salt Spray ASTM B 117 - 85 to failure.

ii) Compound Cycle: Honda Specification. Cycle: 5.5 Hours of Na Cl (5 %) solution spray at 35ºC (95ºF), 0. 1 Hour ramp time to 24ºC (75ºF), 1.3 Hour of 24ºC (75ºF) forced air circulation, 0.1 Hour ramp time to 50ºC (122ºF), 14.5 Hours of 50ºC (122ºF) 95 % humidity, 2 Hours of 50ºC (122ºF) air drying, 0.5 Hour ramp time to 35ºC (95ºF), Total: 24 Hours = 1 Cycle.

iii) SWAAT: Acidified Synthetic Sea Water (Fog) Testing, ASTM G-85-85 A3 to failure.

III.B. HEAT TRANSFER & AIR PRESSURE DROP: According to Chrysler standard PF-7435/8733. Two points air velocity: 10 and 20 miles/hor (16.1 and 32.2 Km/hour). See Table 4.

III.C. DURABILITY TESTS: Pressure and thermal cycling, along with cold aging, were performed in order to determine detrimental effects of curing temperatures on gaskets, plastic tanks, and solders. See Tables 5, 6, and 7.

III.C.1. PRESSURE CYCLE. THERMAL CYCLE. COLD AGING.

PRESSURE CYCLE:

Test Conditions:	0-20 lb/in^2 g (0- 1388 KPa), 4 cycles/min.
Solution:	100 % Ethylene Glycol
Temperature:	121ºC (250ºF)
No. Cycles:	36,500
Test Criteria:	No leaks air under water at 20 lb/in^2 g (138 KPa).

THERMAL CYCLE

Test Conditions:	4 - 6 lb/in^2 g (28 - 41 KPa), 12 cycles/hour.
Solution:	City water
Temperature:	13º - 91ºC (55ºF - 195ºF)
No. of Cycles:	12,400
Test Criteria:	No leaks air under water at 20 lb/in^2 g

COLD AGING

Test Conditions:	20 lb/in^2 g, constant
Solution:	50/50 glycol/water mixture
Temperature:	-29ºC (-30ºF) for 15 hours
Cycle:	Ramp to 118ºC (245ºF) over 1.5 hrs
	118ºC (245ºF) for 6 hrs
	Ramp to -29ºC (-30º F) over 1.5 hrs

Length: 21 days

Results: No leaks air under water at 20lb/in^2 g (138 KPa)

III.C.2. Physical and Mechanical tests on Gaskets, and Plastic Tanks: Test matrix and results are given in Tables 5 and 6.

III.C.3. Tensile Test on Solders: Test matrix and results are given in Table 7.

III.C.4. Tensile Strength Test Results on Tube/Header Joint Samples: Test results are given in Table 8.

Table 1. Test Matrix of Radiator Units Used in Test.

Radiator Type	Surface Condition	Size Sample	Corrosion S. S. SWAAT	Heat Transfer Air Pressure Drop	Pressure Cycle	Thermal Cycle	Cold Aging
28.6"w x 18..5"h	Unpainted		4	2	2	2	4
1 Row, 20 fpi	Standard Paint		4	2	2	2	4
Plastic Tanks	EDC		16	3	3	10	6
24.1"w x 21.5"h	Unpainted		4	2	2	2	4
2 Row, 21 fpi.	Standard Paint		4	2	2	2	4
Brass Tanks	EDC		16	3	3	10	6
18.0"w x 24.0"h	Unpainted		10	2	2	2	6
2 Row, 12 fpi	Standard Paint		10	2	2	6	6
Brass Tanks	EDC		14	3	6	4	6
19-5"w x 36.5"h	Unpainted		0	0	0	0	0
3 Row, 13 fpi	Standard Paint		7	2	2	3	2
Plastic Tanks	EDC		10	2	3	2	2
26.1"w x 29.9"h	Unpainted		0				
3 Row, 15 fpi	Standard Paint		1	1			
Brass Tanks	EDC		1	1			

Table 2. Corrosion Test Results: Test Days to Failure, Using 3 Test Methods: Salt Spray, Compound Cycle, and SWAAT

Radiator Type	Surface Condition	Sample Size	>>Corrosion Test: Days To Failure<<		
			Salt Spray	Compound Cycle	SWAAT
Core Size:	Unpainted	6	4 days	7 days	6 days
18.0"w x 24.0"h	Unpainted	6	4 days	8 days	7 days
2 Row					
12 fpi	Std Painted	6	4 days	6 days	4 days
Brass Tanks		6	4 days	7 days	4 days
	EDC	11	21days	47 days	15 days
			37 days	131 days	9 days
			131 days	131 days	5 days
			101 days		
			101 days		
Core Size:	Std Painted	2	4 days		
19.5"w x 36.5"h			6 days		
3 Row					
13 fpi	EDC	4	35 days		48 days
Plastic Tanks			55 days		48 days
Core Size:	Treated with	4	26 days		24 days
16.5"w x 23.0"h	Brugal, then		26 days		36 days
1 Row	Painted				
24 fpi					
Plastic Tanks					
Core Size:	EDC	1	141 days		
26.0"w x 29.8"h					
3 Row, 15 fpi, Brass Tanks					
Core Size:	Unpainted	4	9 days		12 days
28.6"w x 18.5"h			12 days		15 days
1 Row					
20 fpi	Std Painted	4	6 days		11 days
Plastic Tanks			7 days		11 days
	EDC	6	188 days		34 days
			188 days		45 days
			161 days		52 days
Core Size:	Unpainted	4	6 days		5 days
24.1"w x 21.5"h			6 days		10 days
2 Row	Std Painted	4	3 days		10 days
21 fpi			6 days		12 days
Brass Tanks	EDC	6	159 days		30 days
			145 days		32 days
			102 days		44 days

Table 3. Corrosion Test Results: Hours to Failure, Using 3 Test Methods: Salt Spray, Compound Cycle, and SWAAT

Radiator Type	Surface Condition	>>Corrosion Test: Hours to Failure<< S.S.	Compound Cycle	SWAAT
18"w x 24"h	Unpainted	96 hrs	180 hrs	156 hrs
2 Row, 12 fpi	Std Painted	96 hrs	156 hrs	96 hrs
Brass Tanks	EDC	2904 hrs	2472 hrs	360 hrs
19.5" x 36.5"h	Unpainted			
3 Row, 15 fpi	Std Painted	120 hrs		144 hrs
Plastic Tanks	EDC	1080 hrs		1152 hrs
16.5"w x 23"h	Treated with			
1 Row, 24 fpi	Brugal and	624 hrs		720 hrs
Plastic Tanks	Painted			
26"w x 29.8"h	Unpainted			
3 Row, 15 fpi	Std Painted	120 hrs		
Brass Tanks	EDC	3384 hrs		
28.6"w x 18.5"	Unpainted	252 hrs		324 hrs
1 Row, 20 fpi	Std Painted	156 hrs		264 hrs
Plastic Tanks	EDC	4296 hrs		1048 hrs
24.1"w x 21.5"	Unpainted	144 hrs		420 hrs
2 Rows, 21 fpi	Std Painted	108 hrs		264 hrs
Brass Tanks	EDC	3248 hrs		848 hrs

According to the results in Tables 2 and 3, we can expect an increase in radiator life by a factor of between 9 and 30 in Salt Spray, and 3 to 8 times the life in SWAAT.

IV. Table 4 shows the results on the heat transfer performance and air pressure drop, comparing unpainted and painted radiators to EDC radiators. Maximum deviations were about 1.4 % lower in relation to unpainted samples. The EDC radiators performed better than the standard painted radiators.

Table 4. Heat Transfer and Air Pressure Drop

Table 4. Heat Transfer Results. Hn = Heat Transfer in BTU/min/of, dP = Air Pressure drop in inches of water. CL6 = Heat Transfer divided by the sixth root of the pressure drop. Air Velocity = 20 and l0 miles/hour.

Radiator Type	Surface Condition	Sample Size	Hn20	Hn10	dP20 P20	dP10 DPIO	CL6:20	CL6:10
28.6 x 18.5	Unpainted	4	22.54	15.87	0.872	0.324	23.06	19.16
1 Row, 20 fpi	Painted	4	22.44	15.90	0.878	0.327	22.94	19.16
Plastic Tanks.	EDC	10	22.52	16.12	0.937	0.347	22.77	19.24
Comparison	vs. Unpainted		-0.09	1.58	7.45	7.10	-1.26	0.42
% Difference	vs. Painted		0.36	1.38	6.72	6.12	-0.74	0.42
24.1 x 21.5	Unpainted	4	36.05	22.89	1.899	0.733	32.4	24.09
2 Row, 21 fpi	Painted	4	36.19	22.95	1.943	0.727	32.4	24.17
Brass Tanks	EDC	10	36.28	23.03	2.016	0.766	32.28	24.08
Comparison	vs. Unpainted		0.64	0.6l	6.16	4.50	-0.37	-0.04
% Difference	vs. Painted		0.25	0.35	3.76	5.36	-0.37	-0.37
18.0 x 24.0	Unpainted	6	21.03	14.62	0.824	0.284	21.72	18.02
2 Row, 12 fpi	Painted	6	20.03	13.55	0.845	0.271	20.6	16.85
Brass Tanks	EDC	6	20.76	14.43	0.841	0.287	21.37	17.77
Comparison	vs. Unpainted		-1.28	- 1.30	2.06	1.06	-1.61	-1.39
% Difference	vs. Painted		3.64	6.49	-0.47	5.90	3.74	5.46
19.5 x 36.5	Unpainted	3	36.49	23.19	1.949	0.696	32.65	24.64
3 Rows, 13 fpi								
Plastic Tanks	EDC	3	36.24	22.98	1.988	0.716	32.32	24.29
% Difference			-0.69	-0.91	2.00	2.87	-1.01	-1.42

IV.A. As to all durability tests, pressure cycling, thermal cycling, and cold aging, all test samples of gaskets, plastic tanks, and solder met the specified requirements. No samples were found to leak at 21 lb/in^2 g air under water. See Tables 5, 6, and 7.

Table 5. Durability Tests for EPDM Gaskets Before and After EDC Process

TEST	Sample Size	>>**Condition**<< **Before/After/After 7 Cure/Cure/Days***			Chrysler MS-BF54 Specification	>>**Average Results**<< **Before/After/After 7 Cure/Cure/Days****		
Hardness, ASTM D2240-86. Shore A, Pts.	6	6 pts/6 pts/10 pts			53 - 85	62	62	61
Tensile, ASTM D412-87	24	6	6	6	10 MPa, Min 1,450 lbf/in^2	1,479 lbf/in^2	1,464 lbf/in^2	1,452 lbf/in^2
Elongation	24	6	6	6	275 % Min	320%	296%	278%
Compression Set ASTM 395-89, 70 Hours @ 125ºC (257ºF) Method B	12	3	3	3	25 % Max	0.102" 18.9%	0.083" 10.8%	0.091"
Fluid Aging, 55% Distilled Water 45% Ethylene Glycol 168 hours at 125ºC (257ºF) and 137.8 KPa at 20 psi. ASTM D471	24	6	6	6	Durometer Max Loss: 7 pts Tensile and Elongation Max Loss: 10%	H: 64 T:1,396 lbf/in^2 E:294%	H: 64 T:1,367 lbf/in^2 E:284%	H: 66 T:1,356 lbf/in^2 E:290%

* Immersed in EDC liquid

** Immersed in EDC liquid

Table 6. Durability Tests for Thermoplastic Nylon 6/6, Glass Fiber Reinforced Plastic Tanks Before and After EDC Process

TEST	Sample Size	>>**Condition**<< **Before Cure**	**After Cure**	**After 7 Days Exposed To EDC Liquid**	Chrysler MS-BF54 Specification	>>**Average Results**<< **Before Cure**	**After Cure**	**After 7 Days Exposed To EDC Liquid**
Tensile Strength ASTM D638	18	6	6	6	25,960 Min lbf/in^2	26,789 lbf/in^2	26,005 lbf/in^2	25.965 lbf/in^2
Elongation & Break ASTM D638	18	6	6	6	3 % Min	3.8%	4.7%	3.5%
Tensile Strength 7 Days Conditioning Tensile Bars in 50/50 Solution of Ethylene Glycol/ Water at 132ºC (270ºF)	18	6	6	6	40 % Min Retention Of the Original Tensile Value	14,475 lbf/in^2	14,400 lbf/in^2	14,200 lbf/in^2

According to the results in Table 5 and 6, all tested rubber gaskets and plastic tank sample sections met the Chrysler specification requirements. These requirements were met even under extreme conditions, i.e., leaving the samples immersed in the EDC liquid for 7 days.

Table 7 shows the most common composition of the solders used for current production, and their respective melting temperatures.

Table 7. Melting Temperature of Solders Most Commonly Used In Radiator Production

Joint	Solder Composition Tin/Lead Wt %	Melting Temperature
Fin/Tube	5/95	320ºC (608ºF)
Tube/Header	50/50	210ºC (410ºF)

The solder composition presenting the lowest melting point (eutectic) is 61.9 % Tin/38.1 % Lead, it melts to 183ºC (362ºF). Since the melting point of the solder composition 5 % Tin/95 % Lead is far enough from the curing temperature of EDC at 177ºC (360ºF), no tensile tests were performed on these radiator sections.

Tensile tests were performed on tube/header sections from two different radiators designs. A Tinius Olsen constant deformation speed LC-B 10,000 Lb capacity tensile tester was used for this purpose. The tensile rate was 0.3 in/min (7.5 mm/min). Refer to Table 8.

Table 8. Tensile Strength Test Results on Tube/Header Joint Samples

Tube Dimensions	Sample Size	U.T.S.* in psi Before	After
Thickness = 0.009" Width = 0.708"	12	53,641	50,863
% Reduction		**5.2%**	
Thickness = 0.0063" Width = 0.63"	12	49,570	46,957
% Reduction		**5.27%**	

- U.T.S. = Ultimate Tensile Strength
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According to the test results in Table 8, none of the samples failed in the soldered joint which means that, even after the EDC process, the soldered joints remain stronger than the tube material. The tube material suffered only a slight reduction in its mechanical properties.

V. Conclusions:

1) The corrosion tests on the EDC samples showed significant improvement in corrosion resistance of copper brass radiators. (More than 3,000 hours functionality and 1,000 hours aesthetics.)

2) The EDC process offers significant advantages over other corrosion protection techniques for the best relationship between durability/cost.

3) The heat transfer performance and air pressure drop were slightly diminished after the EDC process; however, test results show these losses in heat transfer and air pressure drop were not as significant as the losses encountered using standard paint samples.

4) The durability tests performed on these radiators, and the special tests performed on gaskets, plastic tanks, and solders, showed no detrimental effects on these parts after submitting radiators to EDC curing temperatures of 177ºC (360ºF) for 25 minutes. Even under extreme conditions (that would not be found in the EDC process, i.e., soaking parts for 7 days in the EDC liquid), no significant, detrimental effects could be observed or measured.

5) According to the above presented results, the EDC process can extend the life of a copper brass radiator significantly beyond the life achieved with current coatings, with a 10-year life sought by automotive manufacturers as the ultimate goal.