FARADAY
TECHNOLOGY, INC.

Pulse Reverse Alloy Plating for Increased Lifetimes for Biocombustors

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DOE Focus Program on Low Cost Coatings

Problem:

- Biomass combustion reactors are subjected to various corrosive attacks due to the wide range of potential materials that will be burned in them, including:
 - Gasoline, grass and other carbon based waste
- These give off mixtures of:
 - Alkali halides (fly ash particulate)
 - Halogen Acids
 - Water
 - Sulfur and Nitrogen Oxides

Potential Solutions:

1. Replace the composition of the internal materials used within bio-combustors.
 - Corrosion resistant SS, Ni Alloys, or Co alloys (*THESE ARE COST PROHIBITIVE*)
2. Apply a high value coating to existing bio-combustors or lower cost steels.
 - Coating could consist of corrosion resistant alloys like Stellite 21 or Inconel 740

Objective of Program

- Develop a *cost effective*, *scalable*, and *flexible* electrodeposition based coating process that can be applied to the corrosion sensitive regions of existing and next generation bio-combustors
 - **Ni** and **Co** based alloys have been shown to possess excellent *alkali/halide attack* resistance
 - **Co** based alloys have been shown to possess *sulfidation* resistance
 - Mo additions into the metal alloys also seem to improve corrosion resistance and *high temperature* stability.
 - **Cr** improves temperature stability and corrosion resistance in *high temperature* systems

Alloy	Co	Ni	Cr	Fe	Mo	W
Inconel [®] 740	20	(base)	25		0.5	–
Inconel [®] 718	-	(base)	19	25	3	-
Haynes [®] 25	(base)	10	20		–	15
Stellite [®] 21	(base)	3	29		6	–

Experimental Plan Outline

- **Substrate:**
 - **Low cost ferritic or austenitic steels**
 - 304 SS, 410 SS, 441 SS; 1" x 4" dual sided
- **Coating compositions**
 - [Co/Ni] – Cr – [Mo/Fe] (composition variance)
- **Testing Parameters:**
 - **CTE** (quick CTE test at Faraday within muffle furnace)
 - Coating composition
 - **XRF**
 - **High temperature corrosion test at 700°C in Air**
 - 1000 hr Salt Spray (Remove after every 100 hr for weight and reapplication)
 - High salt loading (3 mg/cm²) and low salt loading (1 mg/cm²)
 - **Cross-sectional SEM analysis of oxidation**

Experimental Setup

- Using the electrolyte designed within the Hull Cell study and approximate applicable current densities we transitioned to coupon studies
- **Cell**
 - 3: 1" x 4" samples prepared simultaneously
 - 29 L cell Volume
 - FARADAYIC® Flow Assembly*
- **Samples prepared**
 - Pure Ni (Wood's bath)
 - Varying Thickness
 - Pure Cr (1411 and 1318)
 - Varying Thickness
 - NiCr, CoCr, NiCoCr (1411 and 1318)
 - Varying Ni Concentration
 - Varying Co Concentration

*Gebhart, L.E., and Taylor, E.J., U.S. Patent 8,329,006, December 11, 2012.

1" x 4" Samples Prepared for Accelerated Corrosion Trials

Coupon Numbers	Substrate, 441	Thickness, μm	Composition, wt%		
			Cr	Co	Ni
87	441	70	100		
98	441	95	94	5	
100	441	90	95	5	
99	441	80	92	8	
96	441	80	70	30	
133	441	70	55	45	
94	441	60	60	39	
122	441	60	47	50	
153	441	130	45	40	15
152	441	120	45	40	10
102	441	65	80	14	6
109	441	65	64	25	10
103	441	60	71	18	10
101	441	60	66	25	8
112	441	60	53	31	14
110	441	60	46	36	15
111	441	60	40	40	18
151	441	60	20	55	25
104	441	50	55	30	13
126	441	50	35	30	35
105	441	40	51	32	14
107	441	40	44	39	15
108	441	40	41	39	16
106	441	40	38	39	15

Coupon Numbers	Substrate, 410	Thickness, μm	Composition, wt%		
			Cr	Co	Ni
119	410	160	100		
129	410	130	100		
131	410	110	100		
120	410	100	100		
93	410	100	99	1	
132	410	100	60	40	
95	410	50	60	39	
121	410	50	40	60	
134	410	100	65	25	10
150	410	80	20	60	20
136	410	70	85	11	4
137	410	60	85	11	4
148	410	60	70	10	10
139	410	50	65	22	12
149	410	45	25	60	15

Alloy	Co	Ni	Cr	Fe	Mo	W
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Stellite® 21	(base)	3	29		6	—

Accelerated High Temperature Corrosion Studies

- 100 h salted oxidation [1 mg/cm^2 – salt loading: sea salt applied to surface from 3.5 w/w% solution prior to corrosion test]
- Ten consecutive 100 h salted oxidation
- Thermal Cycle
 - Ramping from room temperature to 100°C at 10°C/min
 - Dwelling at 100°C for 30 minutes
 - Ramping from 100°C to 450°C at $1\text{-}2^\circ\text{C/min}$
 - Dwelling at 450°C for 60 min
 - Ramping from 450°C to 700°C at 10°C/min
 - Dwelling at 700°C for 100 hours
 - Ramping from 700°C to room temperature at 10°C/min

Accelerated High Temperature Corrosion Study Effects Analysis

500 h

1000 h

SS441

SS410

- High Cr concentration is important for extended corrosion resistance.
- The presence of Co, Ni, or Co and Ni in low concentrations <50% seems to improve the performance
- **410 SS seems to have a better CTE match to a high Cr concentration coating when compared to 441SS substrates**

Baseline Substrates Performance after 1000 h Accelerated High Temperature Corrosion Study

Preliminary 1000 h Accelerated High Temperature Corrosion Study

Cross-section of Sample 58

Thermal Cycle Test (ORNL)

One Cycle: 45 minutes soak at 700°C in air, with a 15 minutes cooling period followed by reheating

Thermal Cycle

11-153 after 200 cycles thermal shock tests

It is hypothesized that the coating acts as a **Thermal or Diffusion Barrier Coating** so even though it has a Porous Microstructure it is **adherent** and provides **excellent corrosion protection**

Colorado State Cookstove Corrosion Test

Coupons in holder
Stove Off

Coupons in holder
Stove On

Coupons in holder
Stove On – Temp
Measurements

Temperature Profile

Coupon	Starting Mass (g)	Cululative Mass Change (mg/cm ²) after 640 hr exposure
FeCrAl	19.02	4.2/4.5
410	20.48	3.5/-3.6
11-148	23.57	4.4/-2.4
11-163	23.57	6.0/-5.8

Scale to Component

Patent Application#

PCT/US2013/068809

Baseline Economic Analysis for Exemplar Component

- Estimate using Cookstove Design from Literature

ENVIROFIT® Bulk Wrought Material Pricing

Patent Application#

PCT/US2013/068809

**0.61 ft² internal area
exposed to biocombustor
hot zone**

	\$/lb	Density (lb/in ³)	Cost per Volume of Material (\$/in ³)	Cost per Area Assume 1/8" Thick Material (\$/ft ²)	Cost of 0.61 ft ² exemplar component (Fig Right)
718 IN	\$ 17.75	0.297	\$ 5.27	\$ 94.86	\$ 57.86
625 IN	\$ 16.51	0.305	\$ 5.03	\$ 90.54	\$ 55.23
Hastelloy X	\$ 16.79	0.297	\$ 4.99	\$ 89.82	\$ 54.79
Haynes 25	\$ 50.67	0.330	\$ 16.72	\$ 300.96	\$ 183.58
316L SS	\$ 2.74	0.285	\$ 0.78	\$ 14.04	\$ 8.56
304 SS	\$ 1.73	0.285	\$ 0.49	\$ 8.82	\$ 5.38
410 SS	\$ 3.01	0.282	\$ 0.85	\$ 15.3	\$ 9.33
441 SS	\$ 1.85	0.278	\$ 0.51	\$ 9.18	\$ 5.60
FeCrAlY*	\$ 4.50	0.261	\$ 1.17	\$ 21.06	\$ 12.85
FeCrSi*	\$ 3.50	0.242	\$ 0.85	\$ 15.30	\$ 9.33
Stellite® 21	\$ 54.75	0.301	\$ 16.48	\$ 296.64	\$ 180.95
Stellite® 6	\$ 54.03	0.305	\$ 16.48	\$ 296.64	\$ 180.95

Initial Electrodeposition Based Economic Analysis

- Base material cost: \$9.33

Coating Cost Estimate

Patent Application#

PCT/US2013/068809

Line No.	Plant Parameters	10,000 Units	100,000 Units	1,000,000 Units
1	Cylinder Size	0.61 ft2	0.61 ft2	0.61 ft2
2	Run Time (sec)	7200	7200	7200
3	Total Units/Hr	2	16	128
4	Total Hours worked per day	24	24	24
5	Units/Day (24 hr.)	48	384	3072
6	Days worked per year	348	348	348
7	Units/Yr. (348 days)	16,704	133,632	1,069,056
8	Plating Line Cost (\$/unit)	\$0.48	\$0.119	\$0.06
9	Material Cost (\$/unit)	\$48.40	\$12.10	\$5.97
10	Labor Cost (\$/unit)	\$12.50	\$1.56	\$0.39
11	Total Cost (\$/unit)	\$62.08	\$15.00	\$6.82

Overall Conclusions

- Demonstrated a wide range of [Co/Ni] – Cr – [Mo/Fe] alloy coating compositions can produced
- Demonstrated process scalability from a Hull Cell to flat coupons
- Demonstrated the potential of specific coatings to surpass 1000 h accelerate high temperature corrosion, 200 1h thermal shock trials, and 640 h simulated cookstove burning trials at 700°C
 - *SS 410 is a better base substrate for developing biocombustor components in comparison to SS 304 and SS 441*
 - *>70 w/w% Cr alloy w/ Ni or Co improves lifetime performance by at least 5 fold when compared to SS 410 alone*
- Demonstrated that the process maybe an economically viable approach for improve cook stove biocombustor lifetimes
 - Cost estimate for 90 w/w% NiCr coating is \$19.41/ in³ or \$6.82 per 4 mil coating on a 0.61 ft² component produced at 1,000,000 units per year
 - 92% of cost is in the current estimate for consumables.
 - *This would realize a 70% cost reduction compared to base IN625 materials*

Special thanks to all our team members for their support

THANK YOU FOR YOUR ATTENTION!
QUESTIONS?

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