SOFC Innovative Concepts and Core Technology Research Kick-off Meeting for DE-FE0026098

Advanced Materials and Manufacturing Processes for MW-scale SOFC Power Systems for Improved Stack Reliability, Durability and Cost

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Project Overview

- Background
- Project objective
- Technical approach
- Project structure
- Project schedule
- Project budget
- Project Management Plan (including Risk Management)

Background

- Certain high temperature metallic components in the LG Fuel Cell Systems (LGFCS) integrated block have been designed to meet the functional requirements of prototype systems; however, the reliability and cost of these components is judged to be unacceptable for a commercial product.
- Certain metallic components/subassemblies have been made using processes that are not conducive to cost-effective manufacture (e.g. extensive machining).
- The material currently used for many of the integrated block components has extremely good oxidation resistance; however, it has limited strength and resistance to grain growth embrittlement at the SOFC operating temperatures
- The material can be difficult to form and weld; thus, fabrication of components is inefficient and expensive

Project Objectives

Project Objective → qualify advanced materials and manufacturing processes for selected integrated block metallic components to significantly reduce cost, increased reliability, and improved endurance of the LGFCS cell and stack technology

- identify/validate advanced materials with foresight low-cost manufacture → ***advanced materials***
- validate advanced manufacturing processes for specific components that meet functional requirements and product cost targets
  - Additive Manufacturing (AM)
  - Hot Isostatic Pressing (HIP)
  - Powder Injection Molding (PIM)

  → ***advanced manufacturing net shape powder metal***
- increase the reliability of the metallic system hardware
- Increase the durability of the system/stack (e.g. minimize chrome release into cathode stream via use of alumina forming alloys)
- demonstrate that the new materials and components do not adversely impact stack performance → ***perform block test***

Project Objectives

General Objective → advance the body-of-knowledge and/or state-of-the-art in the implementation of advanced materials and design for advanced manufacture of metallic SOFC components.

- SOFC systems generally operate within similar temperature ranges and environments (reducing/oxidizing) → materials identified via this project will largely be relevant to most SOFC developers
- SOFC systems currently require low volume production (<100k) of certain complex and expensive components which may be amenable to the *Additive Manufacturing (AM)* process (e.g. ejectors)
- SOFC systems that require higher volume production (>100k) of certain small and intricate components that are not commercially available may be suited to the *Powder Injection Molding (PIM)* process (e.g. specialized coupling fittings)

Technical Approach

- Advanced materials selection will apply to the integrated block components including:
    - ejectors, pipework, coupling fittings, and flexible members
- LGFCS generated detailed material requirements for selected components including:
    - operating temperature
    - specific exposure to gas compositions
    - existing material of construction
    - specific qualitative material requirements parameters partly including: (*yield strength, creep rate, CTE, % elongation, grain growth embrittlement, oxidation resistance, chromium evaporation resistance, weldability, formability, and material cost*)
- Advanced manufacturing processes will be considered for the most complex/highest cost integrated block components including:
    - ejectors → applicable to Additive Manufacturing (AM)
    - coupling fittings → applicable to Metal Injection Molding (MIM)
    - other components may be identified

Technical Approach

EXAMPLE:

	Table 1 - Material Requirements Component #1		Component					
			A		B		C	
	parameter[1]	units	int.	ext.	int.	ext.	int.	ext.
Condition	gas composition[2]	type	IB A1	IB C2	IB A2	IB C2	IB A3	IB C2
	temperature, normal operation	°C	60		780		700	
	temperature, maximum	°C	80		810		730	
Structural	yield strength	MPa	◒		◒		◒	
	creep rate	%/1000 hr	◒		◒		◒	
	elastic modulus	GPa	◒		◒		◒	
	CTE	$10^{-6}/^{o}C$	◒		◒		◒	
	% elongation	%	○		○		●	
	grain growth embrittlement	---	◒		◒		◒	
Environment	oxidation resistance	$mg^2/cm^4/s$	○	◒	○	◒	○	◒
	corrosion resistance	---	○	○	○	○	○	○
	chrome evaporation resistance	$kg/m^2/s$	○	○	○	○	○	○
	carbon deposition resistance	---	●	○	●	○	●	○
	hydrogen embrittlement resistance	---	◒		◒		◒	
	carbon embrittlement resistance	---	---		---		---	
Process	weldability	---	◒		◒		●	
	formability	---	○		○		●	
	machinability	---	●		◒		◒	
	processing cost	---	◒		◒		○	
	3D printed	---	●		●		○	
Mat'l	existing material	---	440 SST		440 SST		440 SST	
	allowable material cost	---	◒		○		○	

(1)See Table 2 for complete list of parameter ratings.

(2)See Table 3 for complete list of gas composition types.

Technical Approach

EXAMPLE:

Table 2 - Description of Parameter Ratings

Structural	yield strength	○	low and/or not important (e.g. ferritic stainless steel)
		◒	medium and/or moderately important (e.g. austenitic stainless steel)
		●	high and/or critically important (e.g. Fe or Ni based superalloys)
	creep rate	○	not important
		◒	moderately important
		●	critically important
	elastic modulus	○	not important
		◒	moderately important
		●	critically important
	CTE	○	not important
		◒	moderately important (e.g. part will be welded to other part; CTE required to be 16.0 x 10^{-6}/ $^{\circ}$C ±20%)
		●	critically important - (e.g. CTE must to maintain seal integrity for conical coupling fittings)
	% elongation	○	not important
		◒	moderately important - minor cold forming or significant hot forming
		●	critically important - part will be formed and large % elongation required
	grain growth embrittlement	○	not important
		◒	moderately important
		●	critically important
Environment	oxidation resistance	○	not important
		◒	moderately important - stainless steels with chrome content > 18% acceptable
		●	critically important - Fe-base alumina formers or alumina forming austenitic stainless steels acceptable
	corrosion resistance	○	not important
		◒	moderately important
		●	critically important
	chromium evaporation resistance	○	not important - chromia formers acceptable
		◒	moderately important - alumina forming austenitic stainless steels acceptable
		●	critically important - Fe-base alumina formers or aluminized coating required
	carbon deposition resistance	○	not important
		◒	moderately important - carbon formation not desirable
		●	critically important - no carbon formation permitted; Fe-base alumina formers or aluminized coating req'd

Technical Approach

- LGFCS has teamed with Carpenter Technology Corp. to leverage their expertise in specialty alloys and powder metal processing
- Carpenter Technology Corp. is an international developer, manufacturer, and distributor of cast wrought and powder metallurgy specialty alloys
- Candidate materials will be selected from Carpenter Technology Corp.'s extensive alloy portfolio to meet the integrated block component requirements
- The feasibility of powder metallurgy processing of these candidate alloys will be evaluated and followed with material characterizations
- Carpenter Technology Corporation will offer tremendous insights regarding what process limitations exist for each of the identified advanced manufacturing processes under consideration including:
    - Additive Manufacturing (AM)
    - Hot Isostatic Pressing (HIP)
    - Powder Injection Molding (PIM)

Technical Approach

- Based on these trials, a material and manufacturing process will be chosen and LGFCS will procure prototype components to facilitate validation of the quality
- Newly manufactured components will be tested and qualified in a representative module of the LGFCS SOFC power system → this representative fuel cell module is the complete integrated block with full-size fuel cell stacks
- The integrated block will be tested while operating on natural gas for at least 1,000 hours
- The purpose of the test will be to validate the reliability and robustness of the newly manufactured components, and to confirm no deleterious impact on the performance of the fuel cell stacks.

Technical Approach

- Upon completing the integrated block test, post-test analysis of the components manufactured via advanced processes, new materials, or both will be performed.
- Factors such as the extent of component material embrittlement, corrosion/oxidation, and the presence of component cracking or other types of component failures that would negatively impact overall system reliability will be evaluated.
- The components under evaluation will be compared to the similar component designs in the current IST system test when deemed appropriate.
- The overall performance of the identified block test will be compared to the performance of a recently tested block and the ongoing testing of the 200 kW class integrated block test system.

Project Structure

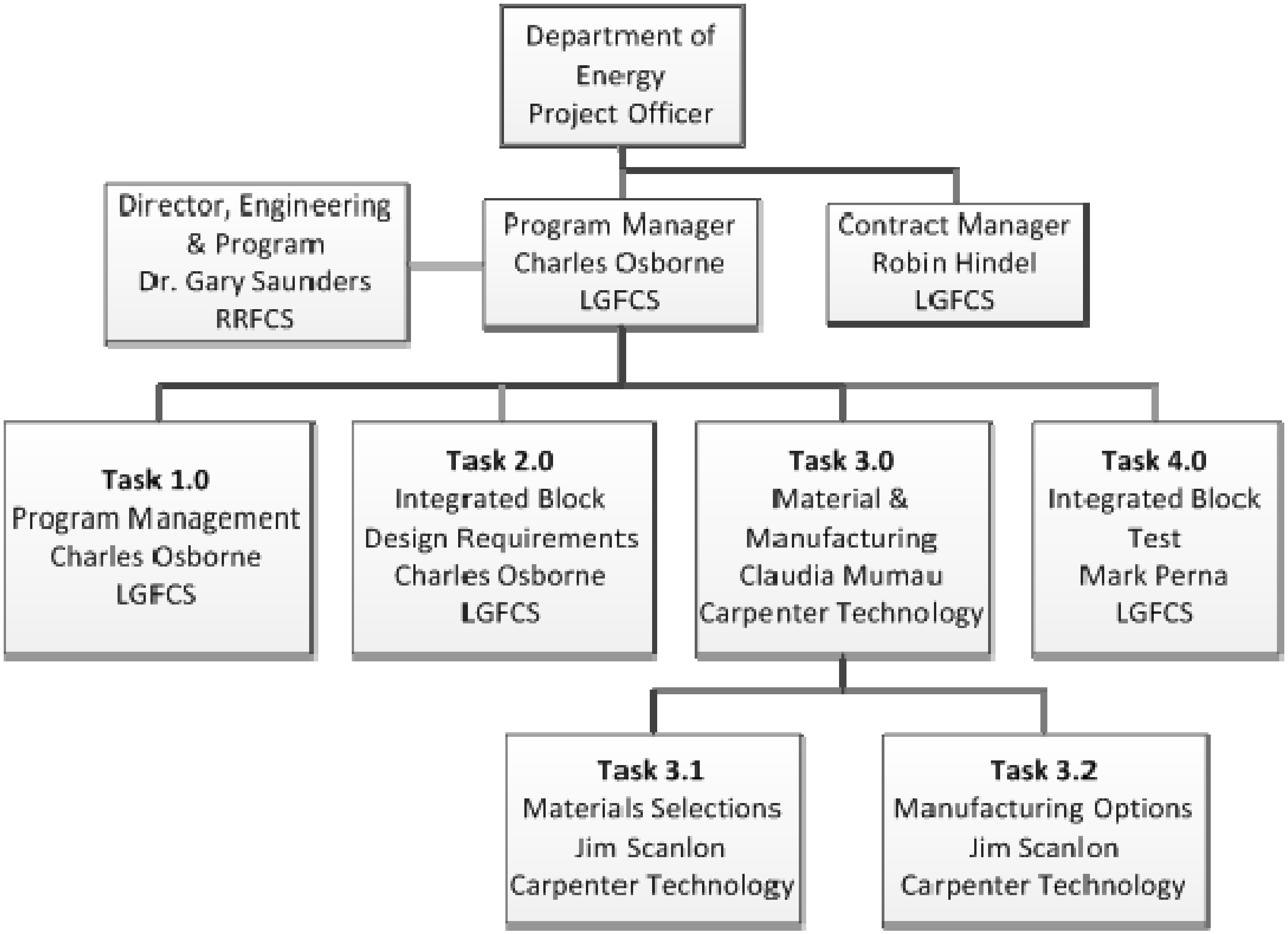

Figure 1 – Organizational Structure

Project Schedule

ID	Task Name	Start	Finish	Duration	Resource Names	Cost per Task ($)
1						
2	**1.0 Project Management**	**Thu 10/1/15**	**Fri 9/29/17**	**524 days**	**C. Osborne,LGFCS**	$281,450
3	Milestone 0: Project Authorization	Thu 10/1/15	Thu 10/1/15	0 days	COMPLETE	
4	Milestone 1: Submit Revised PMP	Fri 10/30/15	Fri 10/30/15	0 days	COMPLETE	
5	**2.0 Integrated Block Design Requirements**	**Fri 10/2/15**	**Fri 10/30/15**	**21 days**	**C. Osborne,RRFCS**	$123,154
6	Develop Material Requirements	Mon 10/5/15	Fri 10/30/15	20 days		
7	Milestone 2: Material Requirements Defined	Fri 10/30/15	Fri 10/30/15	0 days	COMPLETE	
8	Evaluate Candidate Components for Advanced Materials and Manufacturing Options	Fri 10/2/15	Tue 10/27/15	18 days		
9	Milestone 3: Candidate Components for Advanced Materials and Manufacturing Options Selected	Fri 10/30/15	Fri 10/30/15	0 days	COMPLETE	
10	**3.0 Identification, Analysis, and Testing of Material Sets and Manufacturing Options**	**Sun 11/1/15**	**Tue 1/24/17**	**323 days**	**Carpenter Tech.,C. Osborne,RRFCS**	$1,683,598
11	Evaluate Design Options for Selected Components to Suite Advanced Manufacturing - LGFCS/RRFCS	Sun 11/1/15	Tue 3/1/16	88 days	STARTED	
12	Perform Preliminary Cost Analysis for Design Options of Selected Components - LGFCS/RRFCS	Sun 11/1/15	Tue 3/1/16	88 days	STARTED	
13	Milestone 4: Preliminary Design and Cost Analysis for Selected Components Finalized - LGFCS/RRFCS	Tue 3/1/16	Tue 3/1/16	0 days	PLAN – YTD	
14	Finalize Detailed Design and Analysis of Selected Components to Accommodate Advanced Manufacturing - LGFCS/RRFCS	Wed 3/2/16	Tue 11/29/16	195 days		
15	Initiate Final Analyses for Projected Cost at Production Volume - LGFCS/RRFCS	Wed 3/2/16	Tue 11/29/16	195 days		
16	Milestone 5: Issue Released for Manufacture Drawings for Selected Components - LGFCS/RRFCS	Tue 11/29/16	Tue 11/29/16	0 days	PLAN – YTD	
17	**3.1 Identification and Qualification of Material Sets**	**Sun 11/1/15**	**Thu 4/21/16**	**125 days**		
18	Identify Candidate Alloys	Sun 11/1/15	Thu 12/3/15	25 days		
19	Milestone 6: Candidate Alloys Identified based on Task 2.0	Thu 12/3/15	Thu 12/3/15	0 days	COMPLETE	
20	Alloy Powder Production - Feasibility Testing of Candidate Alloys for Powered Metal Processing (+10 HOLIDAY)	Fri 12/4/15	Thu 1/28/16	40 days		
21	Milestone 7: Production of Alloy Powders Complete	Thu 1/28/16	Thu 1/28/16	0 days	PLAN – YTD	
22	Material Characterization Testing of Top 3-5 Candidate Powders (chemical analysis, particle size distribution, flow and shape)	Fri 1/29/16	Thu 4/21/16	60 days		
23	Milestone 8: Top ranked alloys selected for consolidated shape testing	Thu 4/21/16	Thu 4/21/16	0 days	PLAN – YTD	

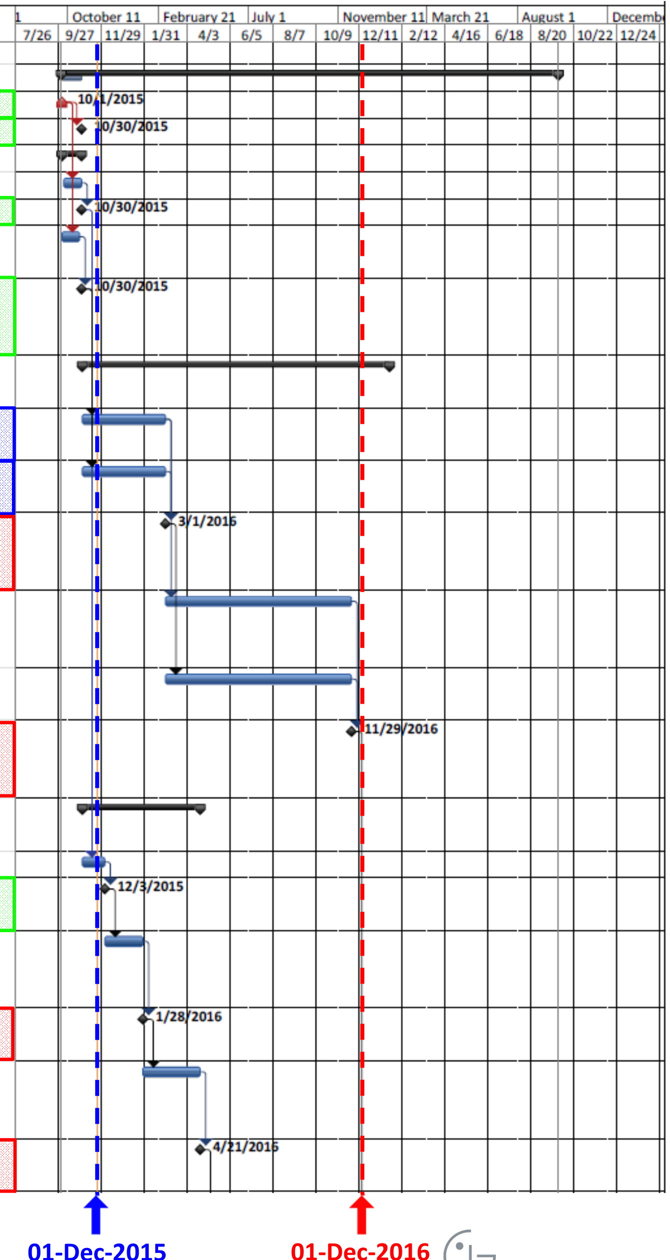

Figure 2 – Project Schedule

Project Schedule

	Task	Start	Finish	Duration	Resource	Cost
24	**3.2 Manufacturing Options for Selected Components**	**Fri 4/22/16**	**Tue 1/24/17**	**198 days**		
25	Produce Consolidated Shapes for Coupon Testing of Selected Powders	Fri 4/22/16	Thu 6/2/16	30 days		
26	Machine test samples	Fri 6/3/16	Thu 7/7/16	25 days		
27	Trials for Candidate Materials with test samples	Fri 7/8/16	Thu 9/15/16	50 days		
28	Metallographic Examination (Microstructure, Failure Mechanisms)	Fri 9/16/16	Thu 11/10/16	40 days		
29	Milestone 9: Select Final Alloy(s) for Component Evaluations	Thu 11/10/16	Thu 11/10/16	0 days	PLAN – YTD	
30	Finalize Analyses for Projected Cost at Production Volume (Carpenter Tech. and LGFCS)	Fri 11/11/16	Thu 11/24/16	10 days		
31	Milestone 10: Technical and Financial Review	Thu 11/24/16	Thu 11/24/16	0 days	PLAN – YTD	
32	Finalize Selection of Vendor(s) for Selected Components	Fri 11/11/16	Thu 11/17/16	5 days		
33	Milestone 11: Initiate Procurement of Prototype Components with Advanced Materials and Manufacturing Processes	Tue 11/29/16	Tue 11/29/16	0 days	PLAN – YTD	
34	Vendor to Demonstrate Powder Metal Component Quality and Reproducibility	Wed 11/30/16	Tue 1/24/17	40 days		
35	Milestone 12: Vendor Qualified - Initiate Procurement of Components Req'd for Task 4.0	Tue 1/24/17	Tue 1/24/17	0 days		
36	**4.0 Integrated Stack Block Test**	**Fri 12/2/16**	**Fri 9/29/17**	**217 days**	M. Perna,LGFCS	$1,036,948
37	Develop Test Plan for Stack Block Test	Fri 12/2/16	Thu 2/2/17	45 days		
38	Milestone 13: Submit Test Plan for Stack Block Test	Fri 2/3/17	Fri 2/3/17	0 days		
39	Procure New IB Components with Advanced Materials and Maunfacturing Processes	Fri 2/3/17	Thu 3/30/17	40 days		
40	Milestone 14: Receive Newly Manufactured Components for Task 4 Test	Thu 3/30/17	Thu 3/30/17	0 days		
41	Build/install Integrated Block into OPV and perform pre-test checks	Fri 3/31/17	Wed 5/17/17	35 days		
42	Commission test facility (check instrumentation & safety system proof test)	Thu 5/18/17	Wed 5/24/17	5 days		
43	Start-up for Block test & load stacks	Thu 5/25/17	Mon 5/29/17	3 days		
44	Milestone 15: Initiate Full-load Block Test	Mon 5/29/17	Mon 5/29/17	0 days		
45	Initiate Full load Block Testing - 1000 hrs - including one (1) system restart	Tue 5/30/17	Fri 7/28/17	44 days		
46	Milestone 16: Full-load Block Test - COMPLETE	Fri 7/28/17	Fri 7/28/17	0 days		
47	Finalize Preliminary Report for 1000 hour System Test	Mon 7/31/17	Fri 8/18/17	15 days		
48	Milestone 17: Preliminary Report for 1000 hour System Test - COMPLETE	Fri 8/18/17	Fri 8/18/17	0 days		
49	Execute Post-test Inspection of Components	Mon 7/31/17	Fri 8/25/17	20 days		
50	Finalize DOE Test Report	Mon 8/28/17	Fri 9/29/17	25 days		
51	Milestone 18: Submit Final Test Report	Fri 9/29/17	Fri 9/29/17	0 days		

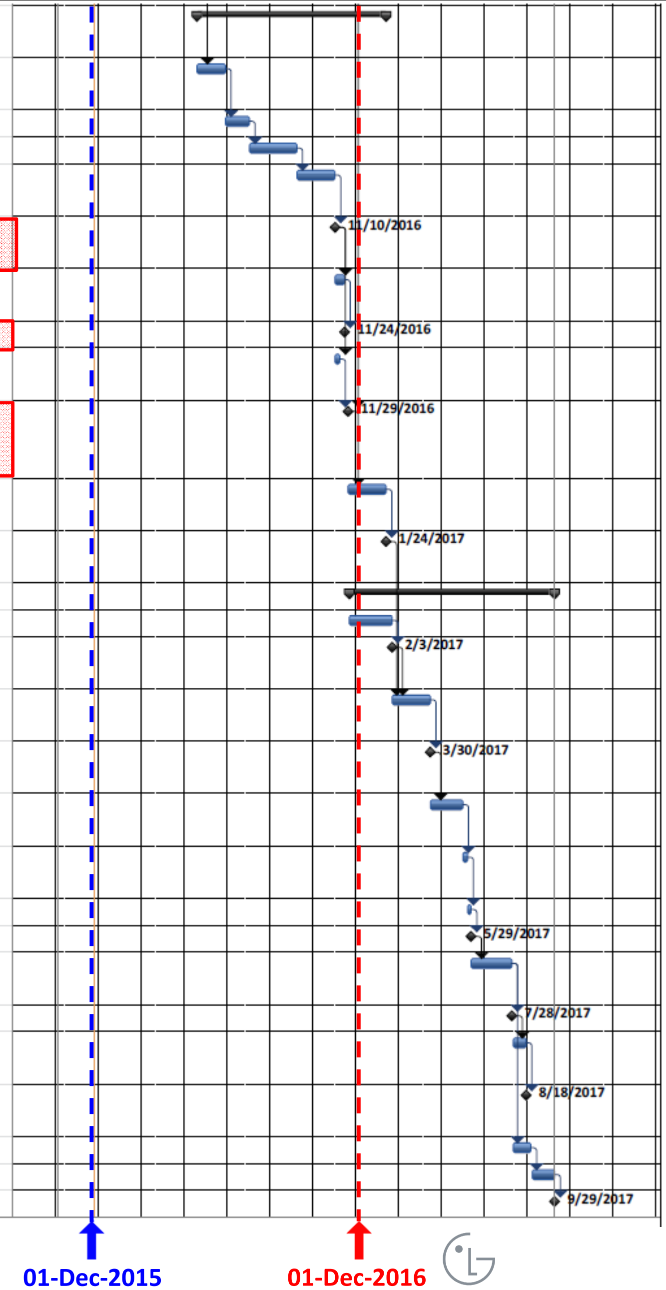

Figure 3 – Project Schedule

Project Budget

Baseline Reporting Quarter	Budget Period 1 (10/1/15-9/30/17)								
	10/1/15 – 12/31/15	1/1/16 – 3/31/16	4/1/16 – 6/30/16	7/1/16 – 9/30/16	10/1/16 - 12/31/16	1/1/17 – 3/31/17	4/1/16 – 6/30/17	7/1/17 – 9/30/17	Total Budget Period 1
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	
Baseline Cost Plan									
Federal Share	$ 233,818	$ 262,120	$ 237,429	$ 236,803	$ 237,929	$ 502,793	$ 393,010	$ 396,097	$ 2,500,000
Non-Federal Share	$ 53,477	$ 63,302	$ 54,133	$ 54,101	$ 54,159	$ 121,093	$ 104,627	$ 120,257	$ 625,150
Total Planned	$ 287,294	$ 325,422	$ 291,562	$ 290,904	$ 292,088	$ 623,887	$ 497,637	$ 516,355	$ 3,125,150

Table 3 – Quarterly Project Costing Profile

Budget Period	**Fiscal Year** (year in which the cost will be incurred, not appropriated)	Performing Organization	Planned Costs	
			Federal Share	Non-Federal Share
1	FY16	Applicant (LGFCS)	$379,323	$120,254
1	FY17	Applicant (LGFCS)	$1,000,485	$295,377
1	FY16	Sub-Recipient (RRFCS)	$172,004	$0
1	FY17	Sub-Recipient (RRFCS)	$110,502	$0
1	FY16	Sub-Recipient (Carpenter)	$418,843	$104,759
1	FY17	Sub-Recipient (Carpenter)	$418,843	$104,760
		Total	$2,500,000	$625,150

Table 4 – Budget Period/Fiscal Year Project Costing Profile

Project Management Plan

- Success Criteria at Decision Points

Decision Point	Date	Success Criteria
Candidate Components for Advanced Materials and Manufacturing Options Selected	30-Oct-15	Highest cost components selected; potential for significant design simplifications; improvement in system reliability anticipated
Preliminary Design and Cost Analysis for Selected Components Finalized	1-Mar-15	Preliminary design demonstrates significant potential for improved cost, functionality, and manufacturability
Select Final Alloy(s) for Component Evaluations	10-Nov-16	Alloy(s) meets or exceeds all product requirements, facilitates lower-cost advanced processing options for mass production
Issue Released for Manufacture Drawings for Selected Components	29-Nov-16	Finalized design offers significant cost savings; expected cost benefit from advanced manufacturing processes is consistent with projected business production volume
Vendor Qualified - Initiate Procurement of Components Req'd for Task 4.0	24-Jan-17	Quality and reproducibility of making new parts has been demonstrated
Execute Post-test Inspection of Components	31-Jul-17	Post-test inspection reveals no indication of component failures, excessive oxidation, carbon deposition, or any other aspect that may compromise component function/system reliability

Table 5 – Success Criteria at Decision Points

Project Management Plan

- Project Risks and Mitigation Strategies

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management Mitigation and Response Strategies
Technical Risks:			
The most desirable alloys fall below required life due to oxidation resistance or fuel corrosion	Moderate	Low	Some components may need modified to include appropriate coatings
The most desirable alloys are not suitable for powder metal processing	Low	Moderate	Use less than optimal material. Alternatively, use alternative advanced or conventional manufacturing processes
System testing shows fuel cell contamination (due to chrome) is greater than required for stack life	Moderate	Low	This risk is only on the cathode air side components. If system testing shows a negative impact on cell performance due to this component, a coating on cathode air side materials will be considered.
Resource Risks:			
Short staffing to support block tests	Low	Moderate	Shared resoures between UK and US; use of Contractors when/if required
Block test stand in Canton unavailable at the time needed for Integrated Stack Block Test (Task 4)	Low	Low	Utilize one of similar test stands in Derby to conduct this test
Management Risks:			
Delivery of newly manufactured components delayed such that Integrated Stack Block Test is delayed	Low	Moderate	Alternative means for testing new components with full-size cells could be considered that would allow for later delivery of new parts

Table 6 – Project Risks and Mitigation Strategies

BACK-UP

Project Management Plan

- Milestone Log

Milestone Number	Task or Subtask Number	Milestone Title/Description	Planned Completion Date	Verification Method	Milestone Number	Task or Subtask Number	Milestone Title/Description	Planned Completion Date	Verification Method
1	1.0	Submit Revised PMP	30-Oct-15	document transmittal	10	3.2	Technical and Financial Review	24-Nov-16	written record
2	2.0	Material Requirements Defined	30-Oct-15	written record	11	3.2	Initiate Procurement of Prototype Components with Advanced Materials and Manufacturing Processes	29-Nov-16	written record
3	2.0	Candidate Components for Advanced Materials and Manufacturing Options Selected	30-Oct-15	written record	12	3.2	Vendor Qualified - Initiate Procurement of Components Req'd for Task 4.0	24-Jan-17	written record
4	3.0	Preliminary Design and Cost Analysis for Selected Components Finalized	1-Mar-15	written record	13	4.0	Submit Test Plan for Stack Block Test	3-Feb-17	document transmittal
5	3.0	Issue Released for Manufacture Drawings for Selected Components	29-Nov-16	written record	14	4.0	Receive Newly Manufactured Components for Task 4.0 Test	30-Mar-17	written record
6	3.1	Candidate Alloys Identified based on Task 2.0	3-Dec-15	written record	15	4.0	Initiate Full-load Block Test	29-May-17	written record
7	3.1	Production of Alloy Powders Complete	28-Jan-16	written record	16	4.0	Full-load Block Test - COMPLETE	28-Jul-17	written record
8	3.1	Top ranked alloys selected for consolidated shape testing	21-Apr-16	written record	17	4.0	Preliminary Report for 1000 hour System Test - COMPLETE	18-Aug-17	written record
9	3.2	Select Final Alloy(s) for Component Evaluations	10-Nov-16	written record	18	4.0	Submit Final Test Report	29-Sep-17	document transmittal

Table 7 – Milestone Log