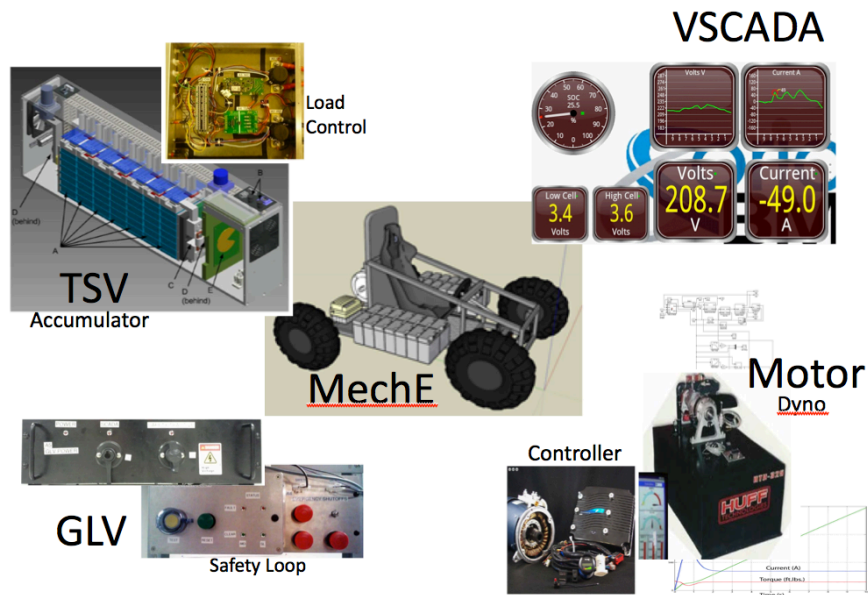


LFEV-Y5-2017

Lafayette Formula Electric Vehicle

Year 5

ECE492 – Spring 2017



Statement of Work

PRELIMINARY DRAFT

Lafayette College

Electrical and Computer Engineering Department

13 February 2017

Table of Contents

Scope.....	4
Deliverables	5
Hardware Purchasing Deadline (HPD).....	6
Final Delivery Date (FDD).....	7
D000: PDR Report and Presentation	8
D001: CDR Materials	9
D002: Users Manual	10
D003: Final Report and Maintenance Manual.....	10
D004: Acceptance Test Plan.....	10
D005: Acceptance Test Report	11
D007: Project Web Site	12
D008: Final Presentation and Delivery.....	12
D009: Conference Paper, Presentation, and Video.....	13
D010: Project Posters.....	13
D012: Software Maintainability Plan	13
D013: Purchasing Report.....	14
D014: Project Management and Status Letters.....	15
Management Requirements	17
Work Breakdown Structure	17
Labor Resources, Management, and Organization	17
Overhead Resources.....	18
Budget for Direct Costs	18
Non Budget Items	19
Acceptance Testing.....	19
System Integration	19
Technical Requirements.....	20
R000: General Rules and Requirements	20
R001: TSV Battery Pack Accumulator Requirements.....	21
R002: VSCADA	22
R003: Grounded Low Voltage (GLV).....	27

R004: System Cabling and Interfaces	28
R005: Tractive System Interface (TSI).....	29
R006: Dynamometer	30
R007: Cooling System Controller.....	30
General Project Requirements	32
Special Waivers and Restrictions.....	32
GPR001: Documentation	32
GPR003: EMI/EMC	34
GPR004: Hazmats.....	34
GPR005: Safety and Good Practice.....	34
GPR006: Reliability.....	37
GPR007: Maintainability	37
GPR008: Manufacturability.....	39
GPR011: Project Video and Final Demonstration.....	39
GPR012: Final Disposal of Projects	39
Acronym Glossary	41
Appendix – Template Documents	43
Individual Progress Report	44
Project Status Letter	45
Work Breakdown Structure Example	47

Scope

Lafayette College ECE Department is pleased to propose the design, fabrication, and testing of the electrical systems of an electric car suitable for entry into the SAE Formula Electric competition. Electrical car subsystems will be tested first in a Dynamometer System (Dyno) and then integrated into the actual car mechanical systems.

LFEV-Y5-2017 shall take the final steps toward a competition ready LFEV and will deliver an integrated set of subsystems that meet the following key requirements:

- **R001 TSV Accumulator** -- A competition ready, 96 Volt LiFePO4 accumulator (battery pack) for providing Tractive System Voltage (TSV) consisting of four, 7-cell packs..
- **R002 VSCADA** – Maintainable and reconfigurable, Vehicle SCADA software, built and tested, and fully interfaced to vehicle systems, dashboard, VCI, remote computers, and the dynamometer test stand. Software performs calibrated measurements, implements closed loop control of the throttle, and includes multiple interfaces that support multiple modes, including drive mode, demo mode, charge mode, shutdown mode, and maintenance mode. The maintainability of the SCADA system is of the highest priority.
- **R003 Grounded Low Voltage (GLV)** – electrical that runs on 120VAC mains power or an independent rechargeable battery system. GLV encompasses many functions and circuits relevant to its overall place in the system. These include SCADA hardware, Dashboard, Safety Loop, Interface Panels, BRBs, and GLV Power battery. GLV shall be professionally packaged, built, tested.
- **R004 Overall System Interfaces, Subsystem Integration, Cabling, and Packaging** – The top-level sub systems shall be fully integrated with professionally constructed cabling, enclosures, and panels suitable for the final integration of TSV, TSI, GLV, and motor/controller on both the Dynamometer and on a Formula car chassis. Cabling must be demonstrated and tested interfaced with the dynamometer test stand first before being transferred to the car. All systems are professionally constructed, labeled, and documented.
- **R005 Tractive System Interface (TSI)** – The integrated device that conducts the high voltage from the accumulator to the motor controller. The Tractive System Interface (TSI) includes the “pre-charge” relay, TSV voltage and current sensors, Insulation Monitor Device (IMD) and galvanic isolation hardware for CAN bus, throttle, and other motor controller interfaces. The TSI also contains brake and throttle plausibility circuits and other required interfaces relevant to its overall place in the system.
- **R006 Dynamometer** – A fully operational dynamometer motor test stand capable of measuring torque and RPM and applying a variable torque load to the motor. The dynamometer system shall be fully integrated with TSV, VSCADA, GLV, TSI and final system cabling and packaging.
- **R007 Cooling Controller** – A new cooling system with 24VDC power compatibility and CAN bus interface.

Detailed descriptions of the above requirements and associated deliverables are given below.

Deliverables

The description and due dates for deliverables are shown below.

Final delivery of all LFEV-Y5-2017 hardware and operational software shall be per GPR012.

All data items, reports, and forms shall be in compliance with and delivered per GPR001. Specifically delivery is required both to the web site *and* to the course instructors by email.

Successful delivery of an item requires that the faculty reviewer accept the item. **Posting and emailing a data item does not imply it is accepted.** Faculty requires reasonable time to review items. If a data item is rejected it must be re-submitted. After allowing faculty reasonable review time, students are encouraged to use *closed loop communication* to verify that data items have been accepted and to seek written confirmation from faculty. Deliverable acceptance should be documented in the ATR. Review delays, rejection, and resubmission is no excuse for a late deliverable.

No partial credit is given for unacceptable deliverables. Late deliverables are penalized 10% per day late for the first 4 days, then 10% per week.

Rejected deliverables lower your grade and cost the project valuable time, therefore students are encouraged to solicit other students and faculty instructors for an opinion on the completeness and correctness of draft deliverable prior to the due date.

DLV	Team Grade Weight	Description	Due Date
D000	5%	PDR Report, Presentation	ASAP
D001	15%	CDR Report, Presentation, Demos	HPD
D002*	5%	User Manuals	FDD
D003*	5%	Final Report and Maintenance Manuals	FDD
D004*	10%	Acceptance Test Plan	Outline at PDR. Must be approved prior to CDR
D005*	10%	Acceptance Test Report	One day after FDD.
D007	10%	Project Web Site	Must be updated weekly.
D008*	15%	Complete System, Final Presentation Demo/Delivery	Final disposition per GPR012 no later than FDD
D009*	5%	Conference Paper, Presentation, and Project Video	TBD (Typically 1 month prior to FDD)
D010*	5%	Project Posters	FDD
D012*	5%	Maintainability Plan	Outline at PDR. Final due 3 weeks after PDR.
D013*	5%	Purchasing Report	Weekly Updates, complete at FDD
D014	10%	Project Status Letters, Individual Progress Report, and Status Presentation.	Individual Progress Reports uploaded to Moodle by 5PM Friday every week beginning after PDR, including Spring Break and finals week. Project Status Letter due midnight Sunday. Status presentation during first class of every week.

**Drafts of D002, D003, D004, D005, D008, D009, D010, D012 and D013 must be provided to the course instructors for review at least 1 week prior to the final due date of these deliverables.*

Hardware Purchasing Deadline (HPD)

5 PM on the Thursday before 2017 Spring Break

All parts procurement, and part fabrication that relies on the Lafayette College machine shop or any outside vendor, including PC board and machined part fabrication, should be ordered by this deadline. Every subsystem BOM should be on order by this date. Purchases after this date, if allowed, will result in a team grade penalty.

Final Delivery Date (FDD)

**5PM on the final day of classes in the 2017
Spring Term.**

Unless otherwise noted, all deliverables must be provided by this date.

D000: PDR Report and Presentation

PDR Materials include the Overall **PDR Report**, a live presentation that summarizes the PDR Report, **slideshow file** from the live presentation, and **meeting minutes** and action items from the live PDR. The PDR Report includes a **hierarchical work breakdown structure**.

Given the limited time available for this project, it's important that a team hit the ground running. The first task to be tackled is preparing a preliminary design. The main tasks for this are the following:

1. Analyze the hard and soft requirements of project.
2. Analyze the existing design as documented in the web sites.

<http://sites.lafayette.edu/ece492-sp13/>

<http://sites.lafayette.edu/ece492-sp14/>

<http://sites.lafayette.edu/ece492-sp15/>

<http://sites.lafayette.edu/ece492-sp16/>

3. Analyze the resources available for this project, including the availability of time, money, and labor.
4. Decide what requirements teams will address and what team members will be personally responsible for each of these requirements.
5. Decide what requirements the teams will **NOT** address, and *have these omissions approved by faculty*.
6. Develop a preliminary system level design that meets the requirements. A system-design baseline includes a detailed and **complete hierarchical system block diagram** along with functional descriptions of these blocks and the interfaces between them.
7. Estimate the time, effort, and budgetary resources that will be required by the design and compare these estimates to the resources available.
8. Establish a hierarchical work breakdown (WBS) and schedule.
9. Allocate responsible individuals to determine individual responsibilities.
10. Do **cost analysis** and establish a detailed program budget that demonstrates compliance with financial constraints.
11. Develop a preliminary system **acceptance test strategy**. This should be a high level plan of how the team will prove that the final fabricated system meets all requirements.
12. Document all of this in a preliminary design report and slideshow, D000.
13. Submit the deliverable PDR Report and PDR Slideshow (both on the web site and by email).
14. Conduct a live Preliminary Design Review with faculty and reviewers, collecting comments and action items.
15. Deliver the meeting minutes.

All materials presented or referenced at PDR shall be on the project web site and delivered to course instructors 24 hours prior to the commencement of PDR. PDR meeting minutes are due with the next weekly status letter.

D001: CDR Materials

Deliverable CDR Materials include the CDR Report, a live presentation that summarizes the CDR Report, slideshow file from the live presentation, demonstration software from the required CDR demos, and meeting minutes and action items from the live CDR.

Deliverables due prior to CDR must be delivered and accepted prior to CDR in order for CDR to be undertaken. If any deliverables are missing, CDR must be cancelled and rescheduled (possibly with late penalties).

The CDR is a multi-disciplined technical and management review of the status of the project. All items that were presented at PDR (WBS, budget, ITCP, etc...) shall be updated, revised, or augmented as needed in CDR to communicate the current Plan of Record (PoR) for the project.

The printed WBS posted in room 400 shall be fully updated and re-printed for CDR.

Included in the CDR is a presentation of the system level Acceptance Test Plan (ATP), D004, that enumerates system level testing that will demonstrate compliance with all system level requirements.

The live CDR presentation must include a summary of all the topics in the CDR report. In addition the live CDR presentation must include

- **A live system state demonstration.** The team should conduct a system state demonstration using live hardware and software that shows all the system states and the events that cause transitions between states. Along with the demo, the CDR presentation must describe exactly where system state information will be maintained in hardware and/or software, what the state information consists of, and how the information required for state transitions is communicated among different locations.
- **User interface demonstrations** with live computer interactivity that implements as much as possible the final look, feel, and functionality of every user interface. It is desirable that the state demonstration be integrated with the UI demonstration.
- **Communication link demonstration** that proves operation of any wireless or wired communication links to every subsystem.

All materials presented or referenced at CDR shall be on the project web site and delivered to course instructors 24 hours prior to the commencement of CDR. CDR meeting minutes are due with the next weekly status letter.

D002: Users Manual

A users manual, per GPR001, shall be provided for each major subsystem and the system as a whole. This should be a high level document that contains an annotated drawing of the physical system, annotated screen shots of all user interface screens, annotated drawings of any physical control panels, indicator buttons, power switches, and other controls. The users manual must include a simplified block diagram, explains all operational procedures and techniques needed to operate the system in a safe and effective manner, including “getting started”, “FAQ”, detailed explanations of all functions and controls, and user level troubleshooting, calibration and maintenance.

D003: Final Report and Maintenance Manual

A professional quality soft-copy final report on DVD shall be provided. The Final Report shall be a single document of professional quality and suitable for printing that summarizes all high level aspects of the project and quotes or provides links and pointers to other documentation (e.g. sections in the Maintenance Manual, Users Manuals) giving full detail. The Maintenance Manual shall be a single document that unifies and indexes all low-level documentation (schematics, source code, test results, etc...) for the system. The DVD shall include a complete, static copy of the final project website indexed so as to be fully accessible on typical standalone PCs. The DVD must have an attractive cover and on-disk artwork. A ‘Sharpie’ written label is not acceptable.

The Maintenance Manual should be a low level document that explains the unique technical principles and details of system operation. The maintenance manual includes information on any advanced maintenance or calibration techniques that could be applied by an expert maintainer. A set of schematics, pinouts of all connectors, the signal assignments of all cables, the semantics of all interfaces (hardware and software), block diagrams, state diagrams, source code trees, and other low level information must be documented within this manual.

At least **Three Copies** of the DVD shall be produced and physically delivered individually to the chairman of the ECE department and to each of the course instructors. If necessary, the DVD can be supplemented by a thumb drives (also three copies) if more storage space is needed.

D004: Acceptance Test Plan

The Acceptance Test Plan (ATP) is a document that describes how the system as a whole will be tested and demonstrated so as to prove compliance with all requirements and specifications. The ATP should include forms that can be filled out by testers during execution. These filled out forms will be used to create the ATR.

Compliance must be **conclusively proved**.

Compliance can be proved in any of the following three ways:

- Analysis – detailed logical analysis can demonstrate compliance by reasoning from known facts (*a priori* or empirically) similar to the form of a mathematical proof. Analysis can be used cited research results in conjunction with the documented results of subsystem QA testing, along with generally accepted

technical principles to prove system level requirements are met. Analysis memos and relevant data are attached to the ATR.

- Test – an explicit test, experiment, or demonstration can be used to prove compliance with a certain requirement by acquiring new empirical facts and combining these with analysis as described above. The comprehensive results of any measurements conducted as part of an ATP test is included in the ATR, along with date and time of the test, the pass/fail criteria, uncertainty, statistical confidence, pass/fail result, witness name, and witness signature..
- Inspection –compliance is made evident by directly examining the system. Photographs with detailed annotations or other evidence gathered in an inspection is included in the ATR.

The ATP should be arranged to minimize the work involved in testing. If possible, multiple requirements should be demonstrated by each test. The ATP should include a compliance matrix making it obvious that all requirements have been addressed by the plan.

Numerical specifications shall be considered “passed” if the measured value is demonstrated by empirical statistical trials to meet the specification at a 90% confidence interval. Quantitative tests must be accompanied by an error analysis.

D005: Acceptance Test Report

The Acceptance Test Report (ATR) is a document that documents the results of the execution of the Acceptance Test Plan (ATP). The ATR should include measured test data, annotated inspection photographs, and analysis reports that demonstrate compliance with all specifications, and a list of deliverables with their successful delivery dates.

Each test should have the following items noted

- Date/Time
- Person Performing Test
- ECE Professor witnessing test. (optinal)
- Test Results
- Relevant Specs and Requirements
- Pass Fail Criteria
- Pass Fail Determination
- Error Analysis (uncertainty, confidence, etc...)

ECE faculty must be invited to witness testing, but is not obliged to witness any test. The testers and witnesses must have the option to physically sign individual tests and the overall document. Since the test reports will likely include such handwritten content, these portions need to be scanned and preserved in electronic form. The paper document must be handled per GPR001 and GPR012.

Although handwritten signatures are required, the ATR should use automation as appropriate to streamline work and improve accuracy. For example, it is often convenient to create the ATR in the form of a computer spreadsheet automating statistical calculations, pass/fail determinations, plots, etc...

For any requirement passed by inspection, photographs are required. The photos shall be annotated and incorporated into an inspection report that explains for each photo exactly what requirements are shown as satisfied.

Individual test results shall be accumulated on an ongoing basis as tests are conducted. Test results shall be delivered to the website within 24 hours of test completion. The ATR report gathers together all test results. The report comprises the accumulated results of subsystem and system testing per the test plans and other related data. It shall adhere to the documentation standards of GPR001. If the test reports include some handwritten content, they shall be scanned and preserved in electronic form. The original paper must be disposed of per GPR012.

For each subsystem type, the report should include a record of the testing of each instance of the subsystem, including the date and time of the testing along with a handwritten signature of the test technician. The testing record shall include the test procedure (or reference to applicable procedure documents) actual test results explicitly recorded compared against specification limits and pass/fail criteria with each result clearly marked as pass or fail.

D007: Project Web Site

A project web site is required per GPR001 and GPR012.

The content of this site shall be professionally presented and organized. Weekly updates of the site are required. The site must serve the real time needs of the project, but also must be left as a useful resource for reference in the years to come. Content on the site must remain available for at least 10 years. Content on the site must be visible over the Internet by the general public using a standard browser. The main content should be largely static, with portable formats (e.g. PDF, TXT, XML) used exclusively for presenting information so as to guarantee compatibility with future viewing software. In addition, all source code, original documents in native format (e.g. .docx, .xlsx, .c, .v, .m, etc...) shall be archived within the web site along with installation media for toolchains.

The use of supplemental “cloud storage” services (e.g. Google Drive, Dropbox, GitHub, etc...) are permitted only if the main website includes prominent, easy to find, index links to content on these services. Content not indexed by the web site effectively does not exist.

D008: Final Presentation and Delivery

LFEV-Y5-2017 must be fully integrated, tested, and actually working upon delivery. Demos, videos, lists, and spare procurement required by GPR006, GPR007, GPR008, and GPR011 must be completed. A final presentation shall be scheduled and conducted per GPR011. Engineering faculty and guests shall be invited to the final presentation.

Posters required by D010 shall be on display during the final presentation.

The Video required by D009 and GPR011 shall include clips from the development process that spans the duration of the project. For this reason, its necessary to work on capturing this video *throughout* the project. This video is shown as part of the final presentation.

The integrated hardware, software, and firmware constituting the LFEV-Y5-2017 system shall be installed in AEC rooms 400 and 401. Any additional parts, subsystems, paperwork, tooling, or other physical material associated with the system should be disposed of per GPR012. Soft copies of all deliverable data items shall be placed on the project web site per GPR012.

D009: Conference Paper, Presentation, and Video

The LFEV-Y5-2017 shall be documented in a suitable form and presented at an academic conference during the Spring 2016 term. One single student shall be elected by the teams to present a paper that highlights certain interesting aspects of the overall project. The conference paper shall be accompanied by a live conference presentation and an interesting, professionally produced video demo.

Since the conference paper is typically due a month before FDD, and may be limited to some small part of the overall project, the video presented at the conference generally cannot meet the requirements of GPR011 due at FDD. Nevertheless, the team is encouraged to produce the best video demo possible for the conference, and to further expand and improve this video to meet GPR011.

Most teams do not have a fully functioning system at the time of the conference. Nevertheless, a non-trivial live demo is preferred to a video. If such a live demo can be conducted, with permission of faculty it can replace the video in this deliverable requirement.

D010: Project Posters

Major subsystems of the LFEV-Y5-2017 shall be documented as attractive and interesting summary posters. These posters shall be delivered in electronic form per GPR001. In addition, the posters shall be physically printed in large, full color format and displayed in a poster session along with the final presentation (D008). The dimensions of the poster shall be compatible with available frames hung in the 4th floor AEC hallway, typically 47x35 inches. Images and text shall be clear and crisp when printed full size. The poster shall contain a web link to the project web site. Links shall be provided both as text and as QR code.

It's important that the poster quickly and effectively conveys the main aspects of the project. Review other ECE posters for formatting ideas. There are also some good online resources for poster design suggestions, such as

<http://colinpurrington.com/tips/poster-design>

D012: Software Maintainability Plan

Software maintainability is the most important software requirement. Unmaintainable software is completely and utterly worthless to a multi-year effort such as the LFEV

project, even if that software functions properly when demonstrated immediately after it was written.

The Software Maintainability Plan documents how the team plans to address the general maintainability requirements of the project, particularly those given in GPR007.

Any team that creates or substantially improves software for the project shall deliver a software-specific maintainability plan. Others must use the software written for this project over the 5-year life of the system. This deliverable documents how software maintainability will be achieved.

The software maintainability plan must be delivered in written form and accompanied by an oral presentation. The plan should describe the overall approach to software maintainability, and provide thorough answers to the following questions:

1. How will the software be installed on new hardware? What happens if the hardware goes obsolete?
2. How are errors and exceptions handled? How are logs viewed? How are exceptions configured and modified as requirements change?
3. How is backup performed? What is the restore procedure?
4. How is a fresh system deployed and validated on new hardware?
5. Are system logs and data files automatically trimmed? Or do they grow and require manual trimming or offloading? If so, how is this accomplished?
6. What is the design of the system API and how will this design support ongoing reliable operation, maintenance and expansion?
7. How is system configuration maintained? Will the system auto detect hardware configuration changes or will configuration maintenance be required? If the latter, what is the consequence of misconfiguration? How will the software function when only some of the system hardware is available? Are demo or simulation stubs available for major hardware?
8. How is system configuration checked? Are tools provided for generating valid configurations?
9. What tool chain will be used? Is the tool suite up-to-date and actively supported? Is the tool suite mature enough to have stable functionality? How is the tool chain installed in a new development system.
10. What third party software will be incorporated into the system? How will this be maintained, upgraded, or patched during the life of the system.
11. How are requirements in GPR007 met?

Evidence must be provided to support assertions.

D013: Purchasing Report

This report shall document every purchase by the project. Tables shall be provided that showing each purchase request, what items were purchased in that request, when the items were received, and any returns/refunds.

Summary tables shall be provided that give purchasing totals broken down by budget categories, by week, and by task group. Statistics shall be calculated for delivery elapsed time, delivery cost, sales tax, and other items of interest.

D014: Project Management and Status Letters

All students are required to work together and coordinate at an overall project level. Interfaces, functionality, schedule, and budget defined by individual teams must be checked and coordinated at an overall project level basis. Harmonized project level versions of these individual and team-level items shall be maintained. Project wide activities such as the project website, poster, and conference paper must be generated. A project wide management and system engineering effort must coordinate these project wide tasks. It is required that some form of system engineering/management team be created.

The system engineering team will have responsibility for project-wide deliverables such as the Project Status Letters and Acceptance Test Plan.

A single, weekly, project wide **Project Status Letter** (PSL) must be delivered per GPR001. An example is given in the appendix. This letter shall contain a summary of the individual progress reports. A single responsible individual shall be specified for each completed (or to-be completed) item.

Changes to the WBS can be proposed in the status letter. Typically new outcomes need to be added. Any changes shall be discussed at the status meeting.

The project status letter shall also include a cost summary that shows expenditures to date broken down by budget categories and compared with budgetary limits. Any over-budget items shall be identified, their consequences presented, and a mitigation plan given. A copy of every purchase request issued that week shall be attached to the status letter. A receiving report shall be included, identifying every item received, with delivery delay, and noting any ordered items not yet received.

Thirty minutes shall be allocated in the first scheduled class meeting of the week to an oral presentation of the status letter(s), if any.

In addition to the Project Status Letter, every student in the class is required to deliver their own **Individual Progress Report** (IPR). The IPR shall be delivered by upload to Moodle.

An example is given in the Appendix. This letter must identify schedule outcomes from the WBS that have been completed by that student in the previous week, and outcomes intended to be completed by them next week. Any overdue outcomes shall be identified, their consequences presented, and a mitigation plan given. Schedule items and action items must be specific and measurable outcomes. Task completion must be clearly defined and fixed. Only task outcome completion is to be considered. The ISL must not discuss “ongoing” or “in process” tasks. If nothing was completed in a given week, say clearly: “no work completed by me” and say why.

Status letters or progress reports are not accepted late.

Management Requirements

The LFEV-Y5-2017 shall be designed, developed, fabricated, tested, demonstrated, and documented by coordinated student teams during a challenging one-term (15 week) schedule. Each student team first conducts a Preliminary Design Review where that team presents a comprehensive system design and test plan to faculty reviewers and their peer teams. Based on feedback from the review and additional effort teams then refine this plan and conduct a Critical Design Review, followed by fabrication, development, and testing. Overall project management and inter-team coordination is also required.

Work Breakdown Structure

As part of PDR, a hierarchical task breakdown (Work Breakdown Structure, or WBS) shall be created in hierarchical tree form. An example WBS is shown in the appendix. This diagram focuses on the outcomes or milestones that must be accomplished to complete the overall project. The WBS should break down the overall project to identify specific, measurable outcomes that will be accomplished. The responsible individual and due date shall be noted on the WBS for each outcome. The WBS shall follow the 100% rule and comprise the entire project, including deliverables and management.

There must be at least one individual outcome work goal scheduled for every team member and due for completion each and every week of the project, including spring break week. The responsible individual for each work goal must be identified and noted in the WBS.

In addition to being presented at PDR, the WBS shall be printed in large format paper and posted in room AEC400. The WBS is reviewed weekly, updated as outcomes are completed, and expanded as new goals are discovered.

Labor Resources, Management, and Organization

Teams of Lafayette College students shall comprise the main engineering labor pool. The students involved in this project must establish processes for organizing, planning, and allocating work to individuals and teams. A reliable process for *closed loop* intra-team communication and management must be developed.

Design project teams are student led. The full responsibility for project management and production of deliverables lies with the individual student team. Nevertheless, engineering division professors are specifically allocated to support this effort as consultants throughout the term. On a time-available basis, additional Lafayette professors may consult with the team as required.

Testing of deliverables is defined by students and executed by students. Engineering faculty has the right to review, participate in, and direct testing activities, but these professors have no obligation to do so. Professors do not explicitly correct and grade your work as they do in other courses. When the team creates a text document, computer program, physical part, assembly, or other deliverable, the *team itself* is responsible for inspecting and documenting that the deliverable meets requirements.

How well students work together as a team correlates strongly with project success. Team members must communicate with each other, and ensure that all members contribute meaningfully to each meeting and to the project as a whole. Face-to-face meetings of the whole team are essential. Past experience has shown that excessive reliance on open-loop electronic communication (e.g. email, texting, google apps, etc...) can be counter-productive. The team must communicate closed-loop, physically meet, and actively inspect first-hand the work of all team members. When team members fail to meet goals, the team structure must adapt and other people must step up to do the work if the team is to be successful.

Overhead Resources

The student teams should not attempt to build everything from scratch. Some items should be purchased outright. Experienced technicians should fabricate other items. Students shall not do production mechanical fabrication.

The Lafayette College Engineering Division shops and labs shall be the primary technical resource for production fabrication. External contract fabrication facilities may be utilized when necessary, subject to the budget for direct costs. All fabricators must be located in the USA.

The team should be aware of the lead-time required by the machine shop and other resources, factoring this time into the project schedule.

Students may not submit un-reviewed “sketches” to the machine shop for fabrication. All drawings must be prepared according to GPR001 standards, archived on the web site in PDF format, and bear review signatures along with the name, email, and cell phone number of the responsible individual BEFORE being submitted to the machine shop.

Budget for Direct Costs

Direct costs, including shipping costs for the entire LFEV-Y5-2017 shall be limited to a total of \$3,000 US.

No expenditures will be approved till the project has developed a detailed budget. All purchases must fit within pre-established budget constraints.

Any direct item to be purchased must be requested on a Lafayette ECE Department Purchase Request form. An ECE professor must approve all requests. The team shall keep a binder or spreadsheet with all approved purchase request forms. These should be tracked by the team against orders and received material. It is recommended that a single individual be assigned for managing material procurement.

The ECE Department Secretary will *not* accept unapproved requests nor will the Secretary accept requests that are not on the standard form. Basis for approval will be the degree to which the expense fits with the project plan of record. *Overnight shipping will not be approved.*

Running totals of costs incurred should be updated daily or even in real time if necessary, especially near the purchasing deadline. Updated cost reports and budgets shall accompany requests for major purchases.

Received material without special safety considerations may be stored in the empty cabinets and shelves in room 412 and/or 400. It is the responsibility of the team to receive, inventory, and preserve the stock of received material.

Non Budget Items

In exceptional situations certain “big ticket” items must be purchased for the project with funds that are outside the general project budget.

Non-budget funding for such items may be sought from the Engineering Division subject to the approval of Engineering faculty. All such requests must be accompanied by written justification and must be submitted to faculty no later than CDR.

Acceptance Testing

The ultimate goal of the project is on-time acceptance of all deliverables. To this end, deliverable acceptance comprises the Acceptance Test Plan (ATP) and the Acceptance Test Report (ATR). All specified requirements must either be waived by written agreement prior to CDR, or demonstrated in the ATP/ATR by analysis, test, or inspection.

Everyone in the team gets the same project success portion in his or her grade as measured by the quality and timeliness of the ATP/ATR and its supporting deliverables. Thus, the importance of documenting ATP/ATR/QA/Analysis is paramount. All other activities in the project should serve the goals of on-time deliverables and successfully documenting acceptance testing.

At PDR and CDR a student team presents the plan for Acceptance Testing. For best chance of final success, **documented** QA, Analysis, and Acceptance Testing should be ongoing throughout the project. Test, demonstrate, and professionally document functions and deliverables early and often.

System Integration

Integrating independent subsystems into an overall working system is a critical and mandatory part of this project. It is easy to underestimate the amount of time and effort required for system engineering and system integration.

A team should conduct a vigorous **system engineering** effort from day-one and leave ample time at the end of the project for system integration, system debugging, and system acceptance testing.

Technical Requirements

The following requirements fully apply to the LFEV-Y5-2017 unless waived under written agreement with faculty. Compliance with these requirements must be established by analysis, demonstration, or inspection. Compliance results must be documented with the system, either in the ATR or in the QA Data Report. Based on results from these reports, the technical compliance grade is calculated with the following weighting

- **R000 General Rules and Requirements** – 12.5%
- **R001 TSV Accumulator** – 12.5%
- **R002 VSCADA** – 12.5%
- **R003 GLV** – 12.5%
- **R004 System Integration, Interfaces, Cabling, and Packaging** – 12.5%
- **R005 Tractive System Interface** – 12.5%
- **R006 Dynamometer** – 12.5%
- **R007 Cooling System** – 12.5%

The LFEV systems shall be developed in Acopian Engineering Center and shall reliably, safely, and maintainably operate over a 5-year service life.

R000: General Rules and Requirements

The deliverables of LFEV-Y5-2017 shall meet all the ECE project requirements given herein, including the “R” requirements: R000, R001, ... as well as the general project requirements GPR000, GPR001, To the largest extent reasonably possible that does not conflict with ECE requirements the LFEV-Y5-2017 shall meet all requirements given in both the Formula Electric and Formula Hybrid rules for 2017. These are available on the competition web sites.

<http://students.sae.org/cds/formulaseries/rules/>

<http://www.formula-hybrid.org/students/rules-and-deadlines/>

Requirements shall be demonstrated without requiring full integration and testing with the required wheeled vehicle chassis and mechanicals. The LFEV-Y5-2017 team shall design, test, and demonstrate electrical functions using the dynamometer test stand in such a way that the electrical functions can be easily integrated with the rest of the car at a later date.

Detailed analysis of the Formula Hybrid and EV rules was conducted during previous efforts. The 2017 team is encouraged to review and update these results. All rules should be met, if possible. Should the rules between Hybrid and EV be in conflict on some point, the LFEV should be designed to meet the rules associated with the specific competition targeted for this year.

Considerable progress was made in previous years, yet some software and hardware deliverables were never successfully integrated or failed to meet many LFEV requirements. The 2017 team may choose to re-use all or part of the previous work, or

completely discard it, as the team sees fit. This freedom to discard previous work notwithstanding, parts of the previous project that **do** adequately meet LFEV requirements may not be discarded and replaced with new parts that do not meet those requirements. The 2017 project should not “backslide”.

R001: TSV Battery Pack Accumulator Requirements

We believe the basic design of the TSV Accumulator in 2016 is acceptable for use in a competition car. Nevertheless, there are a few critical shortfalls. The team must analyze all requirements and provide a fully compliant accumulator system.

In particular, the following specific requirements must be explicitly addressed by the 2017 effort.

R001a: Integration – The TSV accumulator must be a complete assembly with professionally dressed and stabilized internal wiring arranged in safe, reliable, maintainable units that can be fully integrated with the rest of the system. **The delivery of at least four fully documented, fully integrated, fully updated, and fully tested TSV accumulators is required in 2017.**

R001b: Cell Balancing Algorithm – Firmware for the PacMan exists that can execute a basic “plug-and-forget” charging algorithm. This firmware shall be modified and extended to safely and efficiently manage all charging states and balance the charging of individual cells. Because the cell voltage varies as the pack’s current and temperature changes, it is not sufficient to base SOC estimates and charge termination conditions exclusively on crude cell voltage. A more sophisticated algorithm is required that includes consideration of pack current (coulomb counting) and the best available model of the cell. Similarly, discharge limits shall consider all relevant measurements and models, not only crude cell voltage. Comprehensive test data demonstrating charge/discharge management is required.

R001c: Data Acquisition – The PacMan shall communicate with the VSCADA system. VSCADA shall acquire data from all sensors and AMS boards in the pack (cell voltage, pack voltage, cell temperatures, pack internal temperatures, pack current) as well as acquiring SOC estimates and charge algorithm state. A Calibration and Error Analysis must be performed on the measurement process. This analysis shall calculate estimates of the uncertainties associated with all AMS measurands, especially SOC.

R001d: Displays and Indicators – The pack shall have a display managed by PacMan that shows pack voltage, current, SOC, cell balancing state, charging state, charging history, discharge history, cell temperatures, cell voltage, safety loop state, and other data of interest.

R001e: Pack controls – The pack shall have controls to allow interacting with the data display, to set any important modes or parameters for pack operation, and to reset PacMan and the AMS boards.

R001f: Low Current Output – A connector shall be provided that allows access to the full pack voltage with sustained current capacity of at least 10 amps. Fuses shall protect this connector output. It is acceptable but not required that this connector be the same as the charging port connector.

R001g Safety Shutdown – The packs must break the safety loop always while being charged, and should an unsafe condition exist at any time. Displays, indicators, and computer interfaces shall communicate the fault condition.

R002: VSCADA

LFEV-Y5-2017 shall develop a VSCADA (Vehicle Supervisory Control and Data Acquisition) system suite of application and system software that will provide comprehensive control and monitoring of the subsystems in the LFEV.

The VSCADA system runs on the GLV/SCADA internal computer and other devices. Hardware supporting VSCADA shall be present on the car as required (dashboard, VCI, AMS support, etc...) as well as off car (pit station, charger, monitoring and demo display, etc...) The VSCADA software shall run on this distributed hardware and perform all required functions. The delivered VSCADA software shall be fully documented with source code, design, and end-user documentation per GPR001.

Maintainability of the VSCADA is critical. This aspect shall be reviewed in D012 and must be demonstrated in acceptance testing.

The VSCADA system shall be integrated with the Dynamometer in a way that mimics, as accurately as possible, the operations of an actual car. The developed VSCADA should be useable on the car without recompiling.

VSCADA addresses several EV competition requirements including:

- Shutting Down of Tractive System gracefully for ‘configurable’ error
- Ready To Drive Sound
- Control of Tractive System/Extra Action for Ready To Drive

VSCADA acts as the “brains” of the overall vehicle system. It takes input from system’s sensors and controls the system state. VSCADA displays limited information to the driver and extensive information to developers for diagnostics. The logging and data analyzing functions support vehicle science activities. As such, logs and data must be readily accessible.

VSCADA is also critical for testing the car in the MCS dyno test stand. For this reason, VSCADA shall have the ability to control the throttle and dyno torque load, as well as acquire torque measurements and dyno RPM through the USB interface to the Huff dynamometer DAQ box.

In addition to the Huff USB interface VSCADA should use JGB boards on the CAN bus to acquire additional dyno sensor data including

- oil temperature
- coolant temperature before and after the Curtis
- coolant flow rate

VSCADA computer hardware shall be provided as required to handle the VSCADA user interface and processing requirements. This includes on-car and off-car functions.

VSCADA software shall be a suite of programs, clients and servers, built with a unified design with shared data formats, protocols, look and feel. To the greatest extent possible, the same core system must run on various hardware platforms in and around the LFEV components.

The VSCADA software must start automatically, reaching a sane, operational state without human interaction. Performing a sudden, unexpected shutdown of the VSCADA software shall not cause failure or significant data corruption. All VSCADA software should automatically initialize when car GLV is powered up. It should not be necessary to manually run various programs and edit files to get the system going after a reboot or power outage.

Several different physical user interfaces and displays are required.

Required Physical Interfaces

- **R002a:** Car Dashboard Display (Speedometer, odometer, accumulator voltage and current, SOC fuel gauge, temperatures, “check engine light”, log messages. Control functions should include “soft throttle” with cruise control). When integrated with the dynamometer the dashboard should also include display of torque, motor RPM, and allow calibrated control of torque load.
- **R002b:** Safety System (controls, indicators, and electrical interfaces as required by safety).
- **R002c:** Remote Computer Interface (Complete dashboard display and control, plus full diagnostic display of all car and dyno data and full maintenance mode control of car and dyno parameters.)
- **R002d:** Remote Cell Phone App Interface (Data-only summary similar to car dashboard. No control functions.).

These interfaces must support different operational states of the overall car. Depending on the interface, the car state will have differing impact. Operational modes are broad associations of related states. To the maximum extent reasonably possible, VSCADA hardware and software are required to support operating in and switching between all modes and states independently at all interfaces, and displays. Full functionality shall be available at all of the above interfaces in every mode.

A software controlled throttle interface to the Curtis Motor Controller that integrates with a manual, foot-controlled throttle and is programmable over CAN bus shall be provided. This overall throttle system shall comply with Formula EV rules and allow both automated and manual testing of the throttle. This software throttle shall be provided in addition to the throttle control available through the Huff DAQ system under USB control.

A wireless link shall be provided for communication between the car VSCADA and the off-car interfaces (Cell phone, remote PC).

On appropriate interfaces, plots of measurands versus time shall be generated.

Required Functional Modes

The following functional modes are required. They are not mutually exclusive.

R002e: In the *Maintenance mode*, all measurands can be acquired and displayed, both in calibrated and uncalibrated form. All control functions (e.g. throttle) can be explicitly set. VSCADA shall allow trained human technicians to easily control, alter, and monitor all the processes, parameters, and internal workings of the car systems at the lowest possible level. When operating in this mode, it shall be possible to alter, enable, or disable the various safety checks and interlocks that constrain functionality and state transitions in other modes. Security and safety features must be provided to protect this mode from accidental access.

R002f: In *Drive mode* a minimal display and interaction with extensive automation and safety checking per Formula EV rules is provided to the driver to support and optimize his or her operation of the vehicle in all its operational states, without undue distraction. Note that *drive mode* applies both to the dynamometer configuration and the vehicle configuration.

R002g: A *Drive mode demo* shall be provided (selectable and parameterized from maintenance mode) that allows all functions of driver mode to be realistically and safely exercised, tested, and demonstrated, including motor operation, vehicle sensors and AMS interaction without modification of VSCADA, even if some or all of these other subsystems are not available. The drive mode demo display must be identical to the normal drive mode display except that a clear indication on the display must mark any simulated data and distinguish this demo mode from actual drive mode.

R002h: *Charging mode* of the accumulator and/or GLV power must be possible with an appropriate display and data acquisition through SCADA. At a minimum overall pack and individual cell data must be acquired and visualized for every charge cycle. Charging mode is mutually exclusive with drive mode.

R002i: A long term *shutdown mode* shall be supported. This mode shall configure all hardware in a safe, quiescent state to permit long-term storage without draining batteries.

R002j: Except during shutdown, or as modified by maintenance mode, at all times ***monitoring and data acquisition*** by VSCADA continuously collects data or real-time and forensic analysis. Access to this data must be possible at all interfaces. It shall be possible to transfer data easily from VSCADA to other computers either by removable media or network file transfer.

Simultaneous operational modes shall be supported to the largest extent possible. At a minimum the dashboard must provide a driver mode display at the same time as VSCADA performs monitoring and data acquisition along with possible maintenance and experimentation through the PC or cell phone interface. Charging the battery in plug and forget mode shall be possible simultaneous with maintenance, monitoring and data acquisition. Except when overridden in maintenance mode, safety rules and limits shall prevent conflicting or unsafe operation.

Data Acquisition

R002k: VSCADA shall acquire data from the many vehicle sensors, converting this raw data to calibrated measurands. VSCADA shall include inherent support for acquiring, logging, storing, and updating calibration data for every measurand. Calibration shall not be “hard-coded”.

All recorded data and logs shall be readily available for review and visualization either in numerical or graphical form.

The LFEV system shall use a commercial Curtis motor controller and Huff DAQ system with computer interfaces already installed. VSCADA shall use these interfaces to access, record, and display all available motor controller and dyno data in a form that is integrated with the overall LFEV data display.

Along with sensor data, the VSCADA system shall log any events, exceptions, faults, or changes in operational state of the LFEV, including safety interface events.

The VSCADA system shall be expandable to allow the incorporation of additional sensors, measurands, and control functions. Expansion shall be accomplished in a way that does not require recompiling software to make configuration changes. Auto-detecting hardware, rather than static configuration, is encouraged. It is critical that the system adapt easily and safely to different numbers of cells and packs.

At a minimum, the following measurands shall be monitored and stored by the VSCADA.

- Overall TSI voltage, current, and power delivered to the motor controller.
- Individual cell voltages, aggregate pack voltages and current.
- Sensor outputs required to assist diagnosis of failure in the pack fuse or the AIRs.
- State of charge of the aggregate accumulator, separate packs, and individual cells.

- Temperatures of ambient, all subsystems, individual cells in the accumulator, and significant fuses or other devices that may heat up normally or as a result of an anticipated fault.
- Data available from the motor controller.
- Vehicle Speed and distance travelled
- Safety loop system state
- Temperatures of all major systems
- Insulation monitor data
- Data available from a GPS or INS located on-car.
- Data available from the Huff Dyno Test Stand, including torque, oil and coolant temp, coolant flow rate, and RPM measured by the dyno tach.

Uncertainty of these measurands shall be analyzed and specified.

It shall be possible to measure individual parameters up to 60 times a minute or at slower rates. All parameters shall have their values logged electronically along with a time stamp at some minimum rate. Sampling rates shall be individually programmable for each measurand as a function of overall system state and set to reasonable defaults for each state.

The VSCADA data storage shall have sufficient capacity for retaining data records over the lifetime of the system. Data storage shall be accumulated in a portable, non-proprietary format readily useable by commonly available data analysis tools.

A backup system and re-installation recovery strategy must be developed to allow the VSCADA system to be promptly repaired after a hardware failure (e.g. bad hard disk, accidental disk formatting, broken CPU, etc...) in less time than the MTTR given in GPR007.

SCADA Automation

R002l: VSCADA shall be capable of closed loop control and “scripting” of Motor Controller System (MCS) Test Stand operation. Specifically, it shall be possible to set motor RPM and torque through closed loop control to a constant or as a function of time. “Cruise control” shall be available at the dashboard interface. Various dynamic scenarios such as trapezoidal profiles simulating actual car dynamics on the competition racecourse shall be programmable.

R002m: The capability to set alarms and shutdown rules shall be provided. At a minimum it shall be possible to have the VSCADA system automatically log an event, enable an alarm, or declare a fault to shutdown the LFEV should a monitored parameter cross some predefined threshold or leave some range. It shall be possible to add and alter alarm rules without recompiling the system. Rule definitions shall be flexibly programmable.

R003: Grounded Low Voltage (GLV)

According to Formula EV rules, the positive and negative terminals of the accumulator TSV output must be totally isolated from car chassis ground. All circuits that are part of TSV, including TSV negative are considered “high voltage” and must be galvanically isolated from the Grounded Low Voltage circuits in the system. All designs must maintain GLV and TSV isolation.

R003a – GLV Power

TSV can only be used to power the tractive system. All other electrical systems on the car (safety loop, SCADA, dashboard, RTD, etc...) are powered by the Grounded Low Voltage (GLV) system.

Specifically, the GLV power system shall

- Provide 24 VDC supply voltage with sufficient current to supply all the power needs of all the GLV systems. If a subsystem requires a lower voltage (e.g. 12V or 5V) regulators or DC-DC conversion shall be provided by that subsystem.
- GLV negative is connected to car chassis ground at only 1 point in the system.
- Contain a rechargeable battery of sufficient capacity to run the car GLV systems for at least three hours.
- Be rechargeable by means of a UL listed charging device that plugs into the 120 VAC mains. The charging system shall be capable of powering the GLV system indefinitely as it simultaneously charges the GLV battery with *plug and forget* functionality in a manner similar to typical laptop computers or cell phones.
- The GLV battery shall be protected from full discharge, overcharge, overcurrent, and overvoltage.
- Power management software and hardware should allow the GLV system to safely sit idle without fear of over-discharge and damage.
- It shall be possible to charge a fully discharged GLV battery without disassembly or special actions.
- GLV voltage, current, temperature, and SOC shall be displayed with a visible indicator or meter and measured by VSCADA over CAN bus.

The use of a commercial battery and charger to meet these requirements is acceptable.

R003b – GLV Safety Loop

The design of one or more nested safety loops and controllers shall be reviewed by the LFEV-Y5-2017 team and revised as needed to improve electrical and mechanical performance, reliability, and maintainability.

The main function of the Safety Loop is to drive the coils of the 24VDC Accumulator Isolation Relays (AIRs) in the accumulator.

The safety loop system shall be packaged so as to be fully compliant with all Formula EV rules, including shock, vibration, temperature, and humidity (including rain).

The safety loop system shall be packaged so it is straightforward to integrate with the car.

The cabling requirements for car installation shall be analyzed and a set of safety cables suitable for use on the car and/or the dyno MCS test stand shall be designed, fabricated, and tested.

A safety loop analysis document shall be generated. This document shall justify the design of the safety loop system. Possible faults and risks shall be analyzed. Discussion and justification of the system in the context of the formula EV rules is required

The safety loop system shall be interfaced with VSCADA so that the state of the loop(s) can be logged by VSCADA and so that VSCADA can trip the safety loop(s) should there be a fatal VSCADA error. Other than in these two limited ways, the GLV Safety Loop is a system that is totally separate from VSCADA and does not rely on VSCADA for its main operation.

R003c – Vehicle User Interface Panels

Numerous controls, indicators, switches, displays, and Big Red Buttons (BRB's) are required for vehicle operation, testing, and safe operation. These include interfaces on the dashboard, side panels, Accumulator packs, and the Vehicle Computer Interface. A thorough review or requirements shall be made and the vehicle user interface panel design must meet all relevant requirements. It is critical that the interface panels have a professional appearance, with quality labeling, wiring, and packaging.

All vehicle interfaces shall be compatible with car installation. Before use in the car, they shall be demonstrated on the dynamometer test stand. A 19" rack cabinet shall be used to hold all these interfaces in lieu of a car chassis.

R003d – Vehicle Computer Interface Hardware

GLV shall incorporate hardware allows SCADA to provide a full diagnostic display of all car and dyno data and full maintenance mode control of car and dyno parameters. Suitable CPU(s) and user interface hardware (e.g. Graphics display, touch screen, keypad, buttons, lights, etc...) shall be provided along with embedded computer hardware, storage media access, and ports in support of SCADA requirements.

R004: System Cabling and Interfaces

The top-level sub systems shall be fully integrated with professionally constructed cabling, enclosures, and panels suitable for the final integration of TSV, TSI, GLV, and motor/controller on both the Dynamometer and on a Formula car chassis. Cabling must be demonstrated and tested interfaced with the dynamometer test stand first before being transferred to the car. All systems are professionally constructed, labeled, and documented.

R004a – Cabling suitable for the integration of TSV, GLV, and motor/controller on a Formula car chassis and meeting GPR005 shall be demonstrated and tested interfaced with vehicle subsystems and the dynamometer test stand. To every extent reasonably possible, cables shall be suitable for use both with the dyno and with the car. Cables shall be standardized. The following functions must use standard cables and connectors that are used exclusively for these functions:

- CAN Bus
- GLV Power
- Safety Loop

The connectors and pinouts chosen for these three functions must be consistent throughout the system.

R004b – A system wide **System Diagram** and accompanying **Interface Control Document** shall provide detailed documentation of every cable in the system, including length, pinout, wire colors, gauges, connector specification, assembly instructions and discussion of the signals transmitted including source, destination, and purpose.

R005: Tractive System Interface (TSI)

A system called the Tractive System Interface (TSI) allows tractive (TSV) power to flow between the accumulator packs and the Curtis motor controller. The TSI is controlled by the GLV safety loop and VSCADA. In earlier documents, the TSI is called a “load controller”.

R005a – Tractive System Interface

The TSI must meet requirements from the Curtis motor controller (e.g. precharge relay), and formula EV rules (e.g. the TSMP interface is part of the TSI, etc...). A thorough review or requirements shall be made and the TSI design must meet all relevant requirements.

The TSI system shall be packaged so as to be fully compliant with all Formula EV rules, including shock, vibration, temperature, and humidity (including rain).

The TSI system shall be packaged so it is straightforward to integrate with the car.

The cabling requirements for TSI shall be analyzed and a set of GLV and TSV suitable for use on the car or MCS dyno test stand shall be designed, fabricated, and tested.

The TSI is interfaced with SCADA using the CAN bus. Through this interface, the TSI state can be controlled, the tractive system voltage and current measured, and the state of the insulation monitor recorded.

R005b – Throttle and Brake

The TSI contains the brake and accelerator plausibility circuits and other items relevant to its location in the system and required by the FEV rules.

The TSI contains a galvanically isolated throttle interface circuit that integrates with a manual, foot-controlled throttle and interfaces to both the motor controller and to VSCADA. This overall throttle system shall comply with Formula EV rules enforcing throttle and brake plausibility and allow both software controlled or manual throttle with optional cruise control.

R005c – Galvanic Isolation

The TSI contains the TSV/GLV ground insulation monitor device required by FEV rules. The TSI interacts with the safety loop based on the state of the insulation monitor. The resistance measured by the insulation monitor shall be displayed.

Most of the CAN bus in the system is grounded low voltage. The CAN into the motor controller is at high voltage (TSV). The TSI must include a CAN bus isolator segmenting the CAN bus into TSV and HV segments.

The TSI contains galvanic isolation and other circuitry to support the control interfaces to the motor controller, including throttle, forward/reverse, and pre-charge relay control.

R005d – Controls

An OFF/AUTO locking key-switch shall be provided by the TSI. In the OFF position, this switch forces an open pre-charge relay coil circuit to completely disable the pre-charge relay. In the AUTO position the pre-charge relay coil circuit is restored allowing the relay to be controlled by the motor controller “main contactor” drive signal. At least two keys shall be delivered for this switch.

A FWD/NEUT/REV switch shall be provided by the TSI. In the FWD position, the motor controller shall be configured for CW rotation of the motor. In the REV position, the motor shall rotate CCW. The NEUT position is the same as FWD except that the safety loop circuit is opened. This switch shall have a cover to prevent accidental activation.

The TSI also contains indicators or interfaces for indicators required by the FEV rules, including the “ready to drive” sound and the Tractive System Active light.

R006: Dynamometer

The 2017 team must deliver a complete and fully operational dynamometer motor test stand in room AEC 401. The dynamometer shall be capable of measuring torque and RPM and applying a variable torque load to the motor. The dynamometer system shall be fully integrated with TSV, VSCADA, GLV, TSI and final system cabling and packaging. The source of TSV shall be either the four battery packs or the 25 kW power supply installed in room 401. The Huff system for torque measurement and load control shall be interfaced to the overall system.

R007: Cooling System Controller

A functional cooling system for the motor controller already exists on the Dyno in room 401. The system is based on commercial components purchased from Koolance (<http://koolance.com/>). Although the existing system could be used as-is, there are several improvements required.

R007a: Operating Voltage – For improved compatibility with GLV, the cooling system shall operate entirely on 24 VDC power.

R007b: Safety Loop Interface – The cooling controller must interface with the LFEV safety loop. A fail safe design shall be developed that will open the safety loop when fluid flow is too low, or when fluid temperature is too high.

R007c: CAN Bus Interface – The cooling controller must interface with the CAN bus.

R007d: Data Acquisition – Measurements of inlet and outlet fluid temperature, and fluid flow rate shall be acquired and this data shall be accessible over the CAN bus.

R007e: Fan and Pump Control – Fan and pump speed shall be automatically controlled based on fluid temperature. Parameters for the control algorithm, as well as manual override, shall be possible over the CAN bus.

R007f: Compatibility – The cooling system shall use 13x19mm PVC tubing, Koolance QD4 disconnects, and to the largest extent possible use components purchased from Koolance that are identical to or compatible with the existing cooling system.

R007g: Independence – The existing cooling system on the Dyno must remain intact and functional at all times. Removing parts from or otherwise altering the existing cooling system is not permitted. The new cooling system must be a complete and independent replacement.

General Project Requirements

The following requirements fully apply to the LFEV-Y5-2017 unless waived or superseded herein by specific requirements of this project. Compliance with these requirements must be established by analysis, demonstration, or inspection. Compliance results must be documented with the system ATR.

Special Waivers and Restrictions

Should a requirement from the Formula Hybrid EV competition rules not agree with another requirement given or referenced herein, as a general principle, both requirements shall be met, if reasonable to do so. If it is not possible or reasonable to meet both of the conflicting requirements, the team shall work with Lafayette engineering professors, possibly in conjunction with the Formula Hybrid organization authorities and Lafayette Security and Safety, to resolve the conflict.

Analysis can be used to show the system is compliant to GPR003; no formal EMI/EMC certification testing or empirical data is required.

Surface temperatures, supply current drains per GPR005 must be analytically predicted at CDR and physically spot-checked to verify as compliant during ATP. If non-contact IR thermometers are used, the measurements must be corrected for emissivity and an error analysis provided.

The existing project safety plan from the 2015 must be reviewed in 2017 and updated if required. All student participants must read, understand, and agree to the updated plan.

The 50% power supply-overrating requirement does not apply to the accumulator subsystem as a whole.

GPR001: Documentation

Complete and accurate documentation must be provided with all projects. These documents shall include documents for mechanical and electrical fabrication, test results, software development kits, maintenance manual, user manual, and specification compliance matrices, and technical papers. All documentation shall be accumulated in electronic form, centralized in a project web site, and thoroughly indexed.

Data items shall be delivered both to the course instructors and to the project web site. In the case of moderate sized PDF documents, the document should be emailed to course instructors and posted on the course web site. For larger deliverables, email notice may be sent to course instructors along with a URL of the deliverable as placed on the web site.

Text documents shall be typewritten in a professional style commensurate with quality standards established by Lafayette College ECE writing courses (e.g. ES225 and ECE211).

All drawings shall be complete in accordance with the standards established in ME210 and ECE491. In addition drawings must

- Be legible and neat – freehand sketches are unacceptable
- Exactly and unambiguously describe the most recent version of the part or assembly, including any bug fixes or improvements
- Give all critical dimensions with units
- Specify all materials
- Have a Lafayette or project specific border with completed title block that includes correct names, dates, part name, number, etc...
- Include the name of a specific individual requesting the part, with their full name, email, and phone number.

Parts must have a unique part number. Assembly drawings and BOMs should use these part numbers consistently.

A part drawing should show the part number somewhere in the title block, the part number should be included in the drawing file name, and the part number should be marked on the part itself at some inconspicuous location using an indelible marker, metal stamp, or other permanent marking system.

Any drawing submitted to the Lafayette Engineering Machine Shop for fabrication must be approved and signed by the designer, the team project engineer, and relevant faculty. “Rough” sketches without approval signatures may not be submitted to the shop.

Final drawings of fabricated parts must be indexed and archived on the project web site in PDF form. It should be possible to click on a drawing and open it directly without needing to download and unzip an archive.

All original paper documents should be scanned and stored electronically. The original should be disposed of per GPR012.

Test reports for hardware and software must show the date/time of testing, name and signature of the tester, and name/signature of any witnesses.

For all electronic PCB designs the following fabrication documents are required: dated, and numbered schematics or mechanical drawings on Lafayette College drawing format, circuit net-lists, bills of materials, artwork, assembly drawings, and all other files and instructions necessary for CAM or manual manufacturing. The source files for fabricating PCBs and editing linked schematics shall be clearly identified and preserved.

Documentation must be provided both for original designs and for any subcontracted designs. For purchased vendor components within the design, all vendor manuals and documentation shall be retained with the system. Proper mechanical drawings are required for fabricated mechanical parts. Manufacturers data sheets and interface drawings are required for all purchased components.

For software and firmware designs: Source code, and executable binaries for all applications; Verilog, constraints and configuration bitstreams for FPGAs; and ROM image files in commonly accepted JED or HEX formats for all PLDs.

Videos shall be produced in compression formats that play reliably on most PC, Mac, and Linux computers. Both a full resolution (640x480) and a compact (320x240) version shall be created.

All documentation must be provided and delivered in electronic form. Emailing a description of a document along with a URL into the project web site is an acceptable and desirable form of delivery. The use of standard and portable document formats (*e.g.* PDF, TXT), must be used so that the documentation can be viewed on any computer without the need for proprietary applications. Nevertheless, along with a viewable PDF version of every document, the original source format of the document (.docx, .vsd, etc...) must be archived on the site. The documentation must be arranged in an organized and professional manner on the project web site.

To promote the College in general and the ECE Department in particular, documentation, hardware, and software shall be marked with the name of the college (using the official logo) along with the words “Electrical and Computer Engineering” in a similar sized font. All circuit boards, major assemblies, enclosures, racks, and any significant hardware subsystem, as well as all software modules, files, “About” screens, “splash screens” shall be so marked. In addition, the names of project team members may be added in a professional and tasteful way to titling on documentation, hardware, and software.

GPR003: EMI/EMC

Unintentional electromagnetic radiation radiated or conducted from designs must meet US CFR Title 47 Part 15 subpart B regulations for Class A digital equipment. Intentional radiators must meet subpart C regulations. Exemptions from 15.103 are not allowed.

GPR004: Hazmats

Hazardous materials should be avoided in designs. If use of a hazardous material is essential to the function of the design and there is no non-hazardous alternative, the use of the hazardous material must comply with the Lafayette College Chemical Hygiene Plan.

All materials used in electronic circuit fabrication must meet 2002/95/EC RoHS directives. NiCd or Lead-Acid batteries may not be used in new designs.

Any portion of the design or prototype that is discarded must be discarded according to the Lafayette College Chemical Hygiene plan. Also, projects should discard the collected electronic waste in an ecological-friendly manner as per the 2002/96/EC WEEE directive, either by ecological disposal or by reuse/refurbishment of the collected waste.

GPR005: Safety and Good Practice

All work shall comply with good industry practice that enhances reliability and maintainability. These practices include such items as

- Color coded wiring in accordance with applicable industry standard color codes (*e.g.* NFPA 79 or UL508 for power wiring, EIA/TIA 568 for network wiring, etc...)
- Clear labeling of all controls and indicators.
- An obvious and clearly labeled system-wide power shutdown switch.
- Silkscreen on PCBs that includes reference designators, noted power supply voltages and other critical signals. Silkscreen must show a Lafayette College logo,

leopard paw icon, the words “Made in USA”, the words “Electrical and Computer Engineering”, assembly number and revision, and designated locations for serial numbers to be attached or written. PCB bottom copper should have text indicating the board part number and rev.

- Fuses shall be mounted in UL listed sockets or holders and at least 5 spares must be included with system delivery; breakers shall be resettable. All are readily accessible per maintainability requirements.
- Service loops on all cable harnesses.
- Access panels on enclosures.

Software/firmware developed must adhere to the principles and practice established in Lafayette College course CS205. Source code must be maintained under configuration control.

FPGA Logic shall be defined in HDL according to the rules and guidelines established in Lafayette College course ECE491.

Embedded computer processors shall have reset buttons. These buttons must be readily acceptable for maintenance, but not so easy to hit that they degrade reliability.

Major, visible enclosures shall have pilot lights, indicators, meters, displays, and other features that allow observers to be able to tell what is “going on” within the box without need for extra equipment.

Power LEDs shall be green. Red LEDs shall be reserved for error or exception conditions.

Wiring connections shall be insulated with heat shrink tubing or other rugged material. Electrical tape may not be used for insulating wire connections.

Circuits must be enclosed either by fully grounded metal enclosures, or fully insulated non-metal enclosures. PCBs may not be mounted directly to the outer walls of enclosures. Every enclosure must be labeled both externally and internally. All cables and wiring harnesses must be labeled. Labeling must be consistent with the ICD.

Every cable between assemblies shall have at least one dedicated ground return within that cable.

Current drain analysis must be provided for all power supplies. Each supply voltage must have a current rating with a 50% safety factor over the anticipated peak current.

All resistors or other parts dissipating more than 25 milliwatts shall be identified and analysis shall be provided that shows all such parts are properly rated for peak and average power dissipation and have a proper heat sink and fan, if necessary, that provides adequate cooling over the ambient temperature range.

Fans should be protected with grilles and filters. EMI analysis must consider the fan opening and specify EMI tight grillework if necessary.

Components must be cooled such that the surface temperature is no greater than 40 degrees C above ambient.

Power dissipation rating of parts shall be 50% overrated over the required temperature range.

Working voltage of capacitors shall be 25% overrated above the peak voltage anticipated, including all expected glitches, spikes, and tolerance limits.

Project activities must adhere to the general Lafayette College safety policy, possibly augmented by any ECE Department or ECE Laboratory safety rules. Applicable rules are those in effect on the date of ATP.

Any project that develops AC RMS or DC potential differences greater than 30 Volts between any two points within the design (other than at the unmodified mains input side of a UL listed commercial power supply) must develop and implement an electrical safety plan before any circuits are powered. The safety plan must document the processes, design constraints, and equipment that will be used to ensure the safety of all participants.

The safety plan must include a “sealing” process for enclosures that contain voltages >30 Volts. Enclosures must be sealed with a label signed by a Qualified Individual (not a student) before being energized and tested by students.

The ECE Director of Laboratories must approve the electrical safety plan.

A project team member must be designated project safety officer. It shall be the project safety officer’s responsibility to insure that all activities adhere to the project safety plan.

All equipment developed must comply with applicable national standards. Specifically, all electric supply, communications lines, and equipment must be designed, constructed, operated, and maintained in accordance to The National Electrical Safety Code (NESC) – ANSI C-2. Installations of electric conductors and equipment that connect to a building main supply of electricity must be designed, constructed, operated and maintained in accordance to The National Electric Code (NEC) ANSI/NFPA 70.

Any interconnection with the Lafayette College power grid is subject to the approval of Plant Operations. Any interconnection with the Lafayette College campus computer network is subject to the approval of the Information Technology Services department.

Use and design of lasers shall be in accordance with American National Standards Institute (ANSI) Z136.1-2000, "American National Standard for Safe Use of Lasers". Only low power Class I, II and Class IIIa (<5 mW) lasers should be used. If project requirements necessitate higher power, the project must develop and implement a laser safety plan before any laser work begins. The safety plan must document the processes, design constraints, and equipment that will be used to ensure the safety of all participants.

All projects that involve RF power of any level must be designed to ensure that participants are not exposed to RF in excess of the recommended exposure limits adopted by the FCC (most recently in 1996, but note the proposed rule change in 2003). If project requirements necessitate radiated RF power in excess of 100 mW, the project must develop and implement an RF exposure safety plan before any high power RF work begins. The safety plan must document the processes, design constraints, and equipment that will be used to ensure the safety of all participants.

Projects that contain recognized hazards must develop a project safety plan. Such hazards include but are not limited to high altitude, operation at sea, on lakes, or in rivers or

mines, exposure to electrical, chemical, biological, radiological, or psychological hazards.

All projects that involve machinery that create hazards such as those created by point of operation, ingoing nip points, rotating parts, flying chips and sparks, etc..., must develop and implement a machinery safety plan before any machinery work begins. At a minimum the plan must address US Title 29 CFR Part 1910 Occupational Safety and Health Standards, Sub Part O, Machinery and Machine Guarding.

All applicable Lafayette College safety rules shall apply to this project, including posted rules in labs and shops used by team members.

GPR006: Reliability

The system wide Mean Time Between Failures (MTBF) must be greater than 1000 hours over the system lifetime.

Reliability requirements must be demonstrated in the ATP both by analysis and by Inspection. The use of MIL-HDBK-217, Bellcore TR-332, or other equivalent techniques are encouraged for the analysis. Every part and subsystem in the full BOM must be explicitly considered in the MTBF analysis.

Parts with power dissipation over 25 milliwatts shall be identified and the reliability analysis shall include reliability derating of these components based on the expected dissipation.

In addition to the analysis, a reliability inspection shall be conducted during ATP where the system is shown to operate for 24 hours without any obvious failure.

Failures are defined as anything that causes system requirements to be missed. Failures include, but are not limited to computer software lock-ups, shutdowns caused by overheating, automatic operations stalled by exceptions or requests for human intervention, as well as random component failure.

GPR007: Maintainability

Software Maintainability

Software must be developed according to an explicit Software Maintainability Plan.

All software source code must be maintained under configuration control. Release snapshots must be archived on the project website.

The system must start from cold power-up and boot to full operational status without requiring user interaction beyond enabling power and safety procedures.

Any PC software must be packaged for installation with a SETUP.EXE, RPM, “make install” or equivalent installer allowing it to be installed easily on any compatible computer.

Configuration parameters, calibration factors, preferences, and options shall not be hard-coded within the software source code. It shall be possible to alter these various factors without recompiling software or physically disassembling hardware. Altered configuration parameters must be persistent through power cycling and reboots. The

system must have a function to initialize itself with sane (factory default) configuration content if requested.

All data and configuration files must be in a generally supported format (e.g. XML) or the format required by a mature and well supported application (e.g. MySQL database files, Berkeley db, etc...). The use of custom formatted ASCII or binary files for configuration or data storage is not permitted. Files shall be accessible either through removable media or network file transfer or both.

Log files, data files, and any other files that grow over time shall be automatically trimmed by system software.

A scheme for automatic system backup of data storage shall be provided.

To the largest extent possible, the use of passwords shall be avoided. If the use of a password is unavoidable for serious security reasons, the password must be archived in a clearly documented location, and the maintainability plan shall explicitly provide a scheme for password recovery.

The use of removable media (thumb drives, flash media cards) is permitted for configuration parameters, offline storage, access, and backup. If removable storage is used for configuration, the system must have the inherent capability to operate without media, and to initialize blank media with sane configuration content.

Enumerated devices, such as USB, must be automatically discovered by the system and assigned correct port designations such that the system operates correctly after re-enumeration without any interaction or re-programming by the user. Port designations may not be “hard coded” in the software or firmware.

Any cell phone software must be packaged and available from an online “App store” for easy installation on any compatible phone without requiring special alterations of the phone such as SDK installation or jailbreaking.

Hardware Maintainability

Maintainability requirements for hardware must be demonstrated in the ATP both by analysis and by Inspection. The use of MIL-HDBK-472 (N1) and MIL-STD-470B, ISO/IEC 25000:2005, or other equivalent techniques are encouraged for the analysis.

In the hardware maintainability analysis you should assume a stock of recommended spare parts. The list of these spare parts should be included in the ATP. The Users Manual should include a section giving simple troubleshooting procedures. The Maintenance Manual should have more elaborate diagnosis and troubleshooting resources.

Should there be a failure, the system wide Mean Time To Repair (MTTR) must be less than 1 week over the system lifetime. MTTR applies to both hardware and software.

In addition, a maintainability inspection shall be conducted during ATP where a novice using procedures included in the User Manual demonstrates the diagnosis and repair of a likely failure, and an expert using resources included in the Maintenance Manual demonstrates the diagnosis and repair of an UN-likely failure.

GPR008: Manufacturability

All designs must be built from components and subassemblies that have a sustainable source of supply over the system lifetime. To demonstrate that this requirement is met in hardware, it must be shown that each item in the Bill of Materials (BOM) for the design is available from a minimum of two independent suppliers or justification must be given for sole source procurement. In addition, industry trends shall be considered when selecting implementation options. Designs should choose options most aligned with future industry trends.

The tolerances of components shall be considered in the design. Any component with a value that determines a critical voltage, time constant, frequency, or other parameter shall have a tolerance such that system requirements are met with 99% yield in manufacturing. An analysis shall be provided that identifies any tolerance critical components and proves that the tolerances are adequate to meet system requirements at that yield.

GPR011: Project Video and Final Demonstration

A video summary of the entire project must be produced.

The video should include a project introduction and summary, a collage of clips from the development process, a high level demonstration of the capabilities of the system, and a brief conclusion. It should be engaging, memorable, and professionally produced with titles, tasteful effects, and music. The video should be approximately 5 minutes in length.

In addition to the video, completed projects must be demonstrated live for review by ECE faculty. This live demonstration should include a brief oral presentation with slideshow describing the key technical achievements of the project. A screening of the project video shall follow, along with a live demo of the actual system in operation.

The entire design, or some major functional subsystem of the design, must be suitable for continuous, unattended display as a self-contained, active demonstration that would excite the interest of students, faculty, and other ECE Department visitors.

Such demonstrations must fit in a compact public area (possibly replacing an old, obsolete demo) and operate safely and without unreasonable disturbance of its neighbors.

In demo mode, computer screens must periodically display the Lafayette ECE logo, list of team members, and a team photo to the extent permitted by the graphics capabilities of the screen, and functional realizability.

If powered by building mains, the demonstration shall automatically restart after a power outage. User interaction with the demo is encouraged, but if activated by some passer-by, the demonstration must deactivate automatically after a short delay. The MTTR and MTBF of the demonstration must meet or exceed the project-level Maintainability and Reliability requirements given herein.

GPR012: Final Disposal of Projects

Projects may be stored for future work, placed on display, or discarded. Time must be included in project schedules for final disposal.

If a project is to be stored, all its materials must be collected together in a single location. If possible, these materials should be enclosed in a sealed container, locked cabinet, or secure room that contains only these materials from one project and no other. If certain parts are impractical to store with the bulk of the project materials, these separate parts must be clearly labeled so their association with the stored project is obvious.

Projects placed on display may have portions not on display. The undisplayed portions shall be either stored or discarded as described herein.

Portions of projects or complete projects that are discarded must be discarded in accordance with Hazmat procedures described herein.

Test equipment moved from labs shall be replaced in its original location.

Trash, loose wires, scattered components, and other detritus resulting from frenzied development and testing shall be cleaned up.

Paper documents that have been scanned per GPR001 shall be placed in a paper recycling bin.

The project web site must be updated constantly with the most recent versions of all documents. The documents on the final web site must match the delivered system. Obsolete documents on the web site shall be removed.

Acronym Glossary

AC	Alternating Current
AEC	Acopian Engineering Center
AIR	Accumulator Isolation Relay
AMS	Accumulator Management System
API	Applications Programming Interface
ATP	Acceptance Test Plan
ATR	Acceptance Test Report
BOB	Break out Board
BOM	Bill Of Materials
BMS	Battery Management System
BRB	Big Red Button
CAM	Computer Aided Manufacturing
CFE	Customer Furnished Equipment
CFR	Code of Federal Regulations
CDR	Critical Design Review
COC	Certificate Of Compliance
DC	Direct Current
EC	European Community
ECE	Electrical and Computer Engineering
EMI	Electro Magnetic Interference
EMC	Electro Magnetic Compatibility
ETC	Estimate To Complete
FAQ	Frequently Asked Questions
FCC	Federal Communications Commission
FDD	Final Delivery Date
GLV	Grounded Low Voltage
HV	High Voltage
HVD	High Voltage Disconnect
ICD	Interface Control Document
IMD	Insulation Monitoring Device
IPR	Individual Progress Report
ITCP	Individual Technical Contribution Proposal
JGB	John Gehrig Board (CAN bus DAQ board)
LFEV	Lafayette Formula Electric Vehicle
MCS	Motor Controller System
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NEC	National Electric Code
NESC	National Electrical Safety Code
OBPC	One Board Per Cell
OBPP	One Board Per Pack

PacMan	Pack Manager
PDR	Preliminary Design Review
PM	Program Management
POR	Plan Of Record
PSL	Project Status Letter
QA	Quality Assurance
RH	Relative Humidity
RMS	Root Mean Square
ROM	Read Only Memory
RTDS	Ready To Drive Sound
SCADA	Supervisory Control and Data Acquisition
SDK	System Development Kit
SOC	State of Charge
SOW	Statement of Work
TSAL	Tractive System Active Light
TSI	Tractive System Interface
TSMP	Tractive System Measuring Point
TSMS	Tractive System Master Switch
TSV	Tractive System Voltage
UI	User Interface
UL	Underwriters Laboratories
VCI	Vehicle Computer Interface
VSCADA	Vehicle Supervisory Control and Data Acquisition
VSRD	Vehicle Systems Requirements Document
WBS	Work Breakdown Structure

Appendix – Template Documents

Individual Progress Report

IPR Number [serial number]

Covering period from [Start Date] to [End Date]

Prepared by: [Student Name (s)]

Tasks I completed in the previous week:

[List specific, clear definition of completion that can be checked. Make special note of deliverables accepted or requirements demonstrated successfully.]

Task Completed 1: WBS Item Number, description

Task Completed 2: WBS Item Number, description

D00X Delivered: WBS Item Number, description

...

Tasks I plan to complete next week.

[List specific, measurable planned task outcomes along with the responsible individual for each goal.]

Due 1: WBS Item Number, description

Due 2: WBS Item Number, description

...

Proposed Changes

[Propose new goals or sub-goals to be incorporated into the WBS.]

Overdue WBS Items

[Give consequences and a mitigation plan]

Project Status Letter

PSL Number [serial number]

Covering period from [Start Date] to [End Date]

Prepared by: [Student Name (s)]

Tasks Summary from the previous week:

[Summarize the data from the Individual Status letters, giving special emphasis to overdue tasks that require mitigation, backup-behavior, or redesign]

Plan for next week:

[Summarize the plan for next week, giving special emphasis to tasks due that appear to be at risk]

Proposed Changes

[Propose new goals or sub-goals to be incorporated into the WBS.]

Cost Summary

[example]

Budget Category	New This Period	Total To Date	Budget
Food	\$10	\$225	\$200
Lodging	\$0	\$200	\$200
Transportation	\$20	\$125	\$300

[List over-budget items. Give consequences and a mitigation plan]

Receiving Report

[List every item received, with delivery delay]

[List any ordered items not yet received]

[List overdue items. Give consequences and a mitigation plan.]

Purchase Requests

[attach all new purchase requests as appendix]

Work Breakdown Structure Example

