Hydrogen Fuel Cell on a Helicopter:

A System Engineering Approach

by

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ABSTRACT

Hydrogen fuel cells have been previously investigated as a viable replacement to traditional gas turbine auxiliary power unit onboard fixed wing commercial jets. However, so far no study has attempted to extend their applicability to rotary wing aircrafts. To aid in the advancement of such innovative technologies, a holistic technical approach is required to ensure risk reduction and cost effectiveness throughout the product lifecycle. This paper will evaluate the feasibility of replacing a gas turbine auxiliary power unit on a helicopter with a direct hydrogen, air breathing, proton exchange membrane fuel cell, all while emphasizing a system engineering approach that utilize a specialized set of tools and artifacts.

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INTRODUCTION

Hydrogen fuel cells have been gaining increasing attention from the technical and the industrial communities alike as a feasible alternative to internal combustion engines (ICE) for use as an auxiliary power unit (APU) onboard aircrafts. This interest is growing due to the fact that auxiliary power units do not require stringent performance and cost requirements that are normally associated with a propulsion system. Further, a fuel cell operates in an efficient and quiet fashion, which is becoming of increasing utility for both civilian and military applications.

While internal combustion engines are used as the main power plant on most transport vehicles, for smaller applications with low power profile, their efficiencies have been difficult to preserve mainly due to inherent features and characteristics such as, combustion quenching, high surface area to volume ratio of the combustion chamber and low reactant residence times [1]. As such, gas turbine APUs are typically used on aircraft during ground operations and while the main engines are not running, to provide most of the non-propulsion power required by the air vehicle. These are mostly engines with a single shaft and a single stage compressor [2] where the weight and size have been optimized at the expense of fuel efficiency, as shown in Table 1.

Table 1 Honeywell GTC36-155 Fuel Efficiency

Inlet Temp(^{0}C)[1]	Rated Output Power (KW)[2]	Fuel Flow(Kg/s)[3]	Fuel Efficiency[4]
-50	60.40	0.02694	5.24%
-40	60.40	0.02639	5.35%
-30	60.40	0.02556	5.52%
-20	60.40	0.02500	5.64%
-10	60.40	0.02444	5.77%
0	60.40	0.02361	5.98%
10	60.40	0.02278	6.20%
20	60.40	0.02222	6.35%
30	60.40	0.02167	6.51%
40	60.40	0.02111	6.68%
50	60.40	0.02056	6.87%

1 Compressor Inlet Temperature in Degrees Celsius
2 Rated Power in Kilowatt based on 81 Shaft Horse Power
3 Approximation from performance charts using fuel flow in Kg/hr
4 No load condition (idling)

The fuel efficiency calculations in the table were developed using Jet fuel (i.e. Kerosene) net calorific value of 42.8 MJ/kg, along with publicly available data from the Original Equipment Manufacturer (OEM) about rated power (kW) and fuel flow (kg/s) at various APU inlet temperatures (^{0}C). These low efficiency figures combined with other external factors, like stricter noise and emission standards imposed by airports and various authority having jurisdictions [3], triggered both the automotive and aviation industries to proactively search for alternatives to ICEs.

Although other technologies could very well be considered as viable options such as Lithium-Ion batteries APUs[4] , Hydrogen fuel cells (FC), due to their high energy content (i.e. kW-hr/Kg) [5] are considered more appropriate for applications where backup power is required over extended periods of time, which is mostly the case with APUs onboard aircraft and other heavy duty ground vehicles [6]. Further, given that FC technology is still at an early development stage on aircrafts in particular, introducing it to provide auxiliary power that does not relate to the propulsion of the air vehicle would allow incremental evolution of a full electric aircraft that builds on stable intermediate forms [7].

In light of this, the paper will explore a new usage for an existing technology, namely, a direct hydrogen Proton Exchange Membrane FC (PEMFC) APU on a helicopter. Rather than attempting to specify an optimal solution, the focus instead is placed on using model based system engineering (MBSE) to demonstrate an optimal *methodology* in capturing requirements, delineating structure, evaluating behavior and developing a parametric model to analyze unique configurations and assess innovative architectures.

CHAPTER 2

APPROACH

A *computable* use-case model was developed to define the existing aircraft auxiliary power architecture and derive a preliminary set of requirements for the new system using a FC. To accomplish this, the Object Management Group System Modeling Language, OMG SysML® (SysML) [8] hosted in the IBM Rational Rhapsody® [9] tool was used. Based on the Unified Modeling Language (UML), SysML is a graphical modeling language which includes simple yet powerful constructs to support the object-oriented paradigm, while providing a well-defined *ontology* with a set of representational primitives to describe a domain of knowledge. The SysML model that was created to support this effort consists of a graphical description of the gas turbine APU as it is generically used on the aircraft, including its operational context, the main functions that it is performing, along with the various external interfaces that are in place to achieve these functions. This became the baseline architecture to which all replacements to a gas turbine APU, including a FC, are derived from and compared to. Similarly, a graphical description was also developed for the proposed FC auxiliary power system [10] [11]. Given that the FC needs to address the same system level functions that the gas turbine APU is performing, the FC architecture was based on the use cases that have been defined previously for the gas turbine. Nonetheless, the resultant functional flow and the logical interfaces for the FC refine the original use cases to elaborate the differences between the two architectural concepts.

One important objective of a syntactically accurate descriptive model is to ensure that the legacy, as well as the proposed system is equally understood by all individuals. This results in clear communication and reduces the possibility of a different interpretation of the architecture among various stakeholders [7]. Also, an advantage of the object-oriented modeling approach is the ability to reuse model elements through “instances” of object classes [12] that retain the exact properties (i.e. attributes, ports, interfaces, constraints, etc…) of the parent class, thus ensuring precision and consistency across the entire model.

Next, an analytical model to verify the performance of the aforementioned descriptive model was developed. That is to say, given the physical and thermodynamic behavior of the FC, and that it is used in the same manner as described in the SysML model, the fuel cell performance is assessed primarily in regard to aircraft fuel efficiency and compared to that of a gas turbine APU. For that purpose, established physics-based equations of a PEMFC [13] along with actual aircraft mission data were captured and simulated using the model based design (MBD) tool MathWorks Simulink®.

The third focus of the study was to perform parametric analysis [12] in which key value properties of a FC including power rating, electric current density, catalyst content, fuel utilization and durability were *bound* to mathematical constraints which estimate operation and capital cost of a FC APU. Although various other powerful tools could be used to perform parametric analysis, most notably Boeing’s Design Sheet [14], however, to adhere to the original theme of the study (i.e. MBSE), SysML and MathWorks MATLAB® were again picked as the tools of choice. SysML Parametric Diagram was used to graphically describe constraints in the form of mathematical relations, with MATLAB’s Symbolic Math toolbox being used to solve the mathematical model.

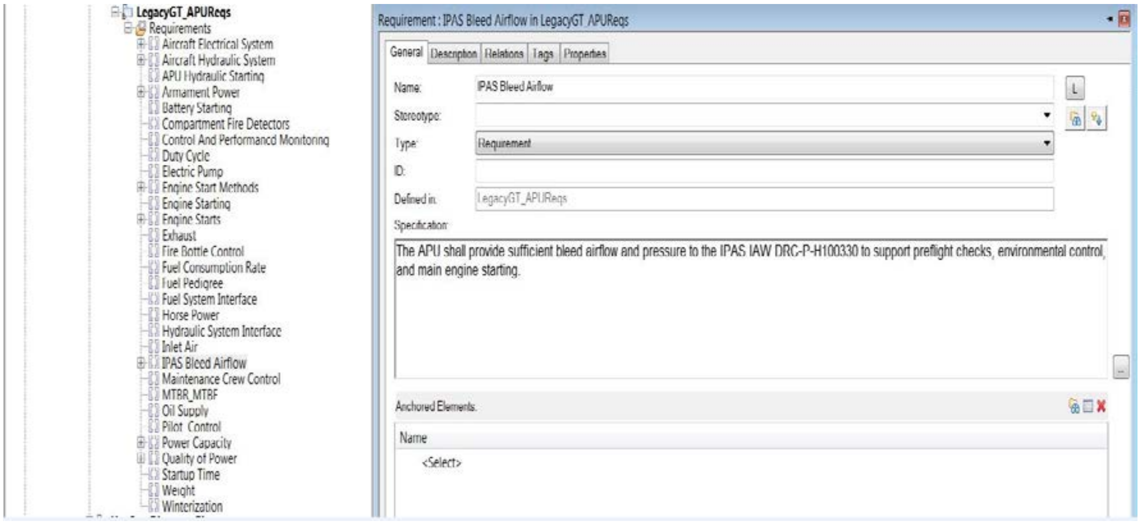
CHAPTER 3

GAS TURBINE APU LOGICAL ARCHITECTURE DESCRIPTION

3.1 System Context

The gas turbine APU that was considered as the baseline (i.e. legacy) system in this study is the Honeywell GTCP 36-155 rated at 81 Shaft Horse Power (shp) [2]. Besides key design requirements such as power capacity, weight, volume and response time, most of the requirements that were analyzed to describe the logical architecture of the gas turbine APU revolve around functional and suitability requirements.

Figure 1 “Legacy” APU functional requirements



- LegacyGT_APUReqs
  - Requirements
    - Aircraft Electrical System
    - Aircraft Hydraulic System
    - APU Hydraulic Starting
    - Armament Power
    - Battery Starting
    - Compartment Fire Detectors
    - Control And Performancd Monitoring
    - Duty Cycle
    - Electric Pump
    - Engine Start Methods
    - Engine Starting
    - Engine Starts
    - Exhaust
    - Fire Bottle Control
    - Fuel Consumption Rate
    - Fuel Pedigree
    - Fuel System Interface
    - Horse Power
    - Hydraulic System Interface
    - Inlet Air
    - IPAS Bleed Airflow
    - Maintenance Crew Control
    - MTBR_MTBF
    - Oil Supply
    - Pilot_Control
    - Power Capacity
    - Quality of Power
    - Startup Time
    - Weight
    - Winterization

Requirement : IPAS Bleed Airflow in LegacyGT_APUReqs

Name: IPAS Bleed Airflow
Stereotype:
Type: Requirement
ID:
Defined in: LegacyGT_APUReqs
Specification:
The APU shall provide sufficient bleed airflow and pressure to the IPAS IAW DRC-P-H100330 to support preflight checks, environmental control, and main engine starting.

Figure 1 illustrates the legacy APU requirements that were imported and captured in the model, which in turn constituted the corner stone for functional analysis of the system.

Figure 2 SysML BDD of the APU system context

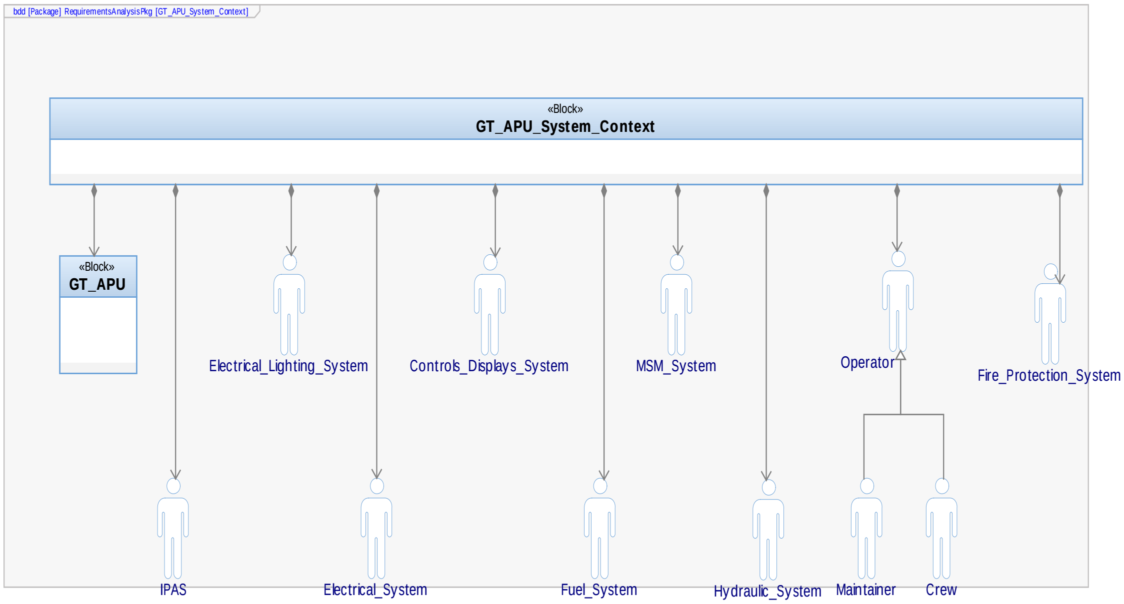
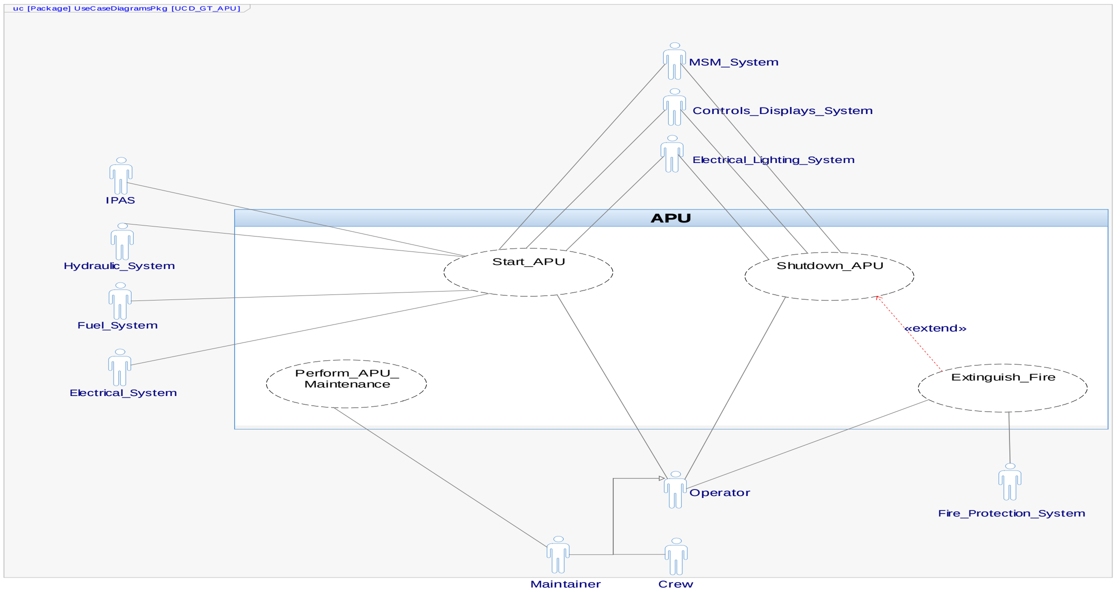


Figure 2 shows a SysML Block Definition Diagram (BDD) of the gas turbine APU *system context*, with the APU modeled as a *Block* to distinguish it as the System under Consideration (SuC) from the other “actors”, that is, other entities external to the SuC that exchange “services” with it to accomplish a specific *use case* (i.e. system goal). These include the Mission Systems Management (MSM), Electrical System, Integrated Pressurized Air System (IPAS), Hydraulic System, Controls and Displays System, in addition to others. More importantly, the gas turbine APU and all the actors have a *Composite Relationship* with the top level system context, also shown as a block, thus, describing the system context as that environment incorporating the APU and the actors, with any subsequent functional analysis to be performed, including *flow modeling* and the associated logical architecture, only to address the interfaces between these entities that are part of the system context.

The main underlying benefit of using a holistic, top-down system modeling approach is to ensure accuracy and consistency at early development stage of the system. For instance, the model constrains users from adding interfaces between the APU and any new *emergent* actors downstream in the modeling process, without first requiring a revisit to the system context to explicitly add those new actors in and perform a full revaluation of the model, hence, providing a method that lends itself well to the recursive and reiterative nature of the system engineering process.

The system requirements and context were further *refined* by a SysML use case diagram, which consists of a graphical depiction of the “associations“ between the SuC use cases and the actors, as shown in Figure 3.

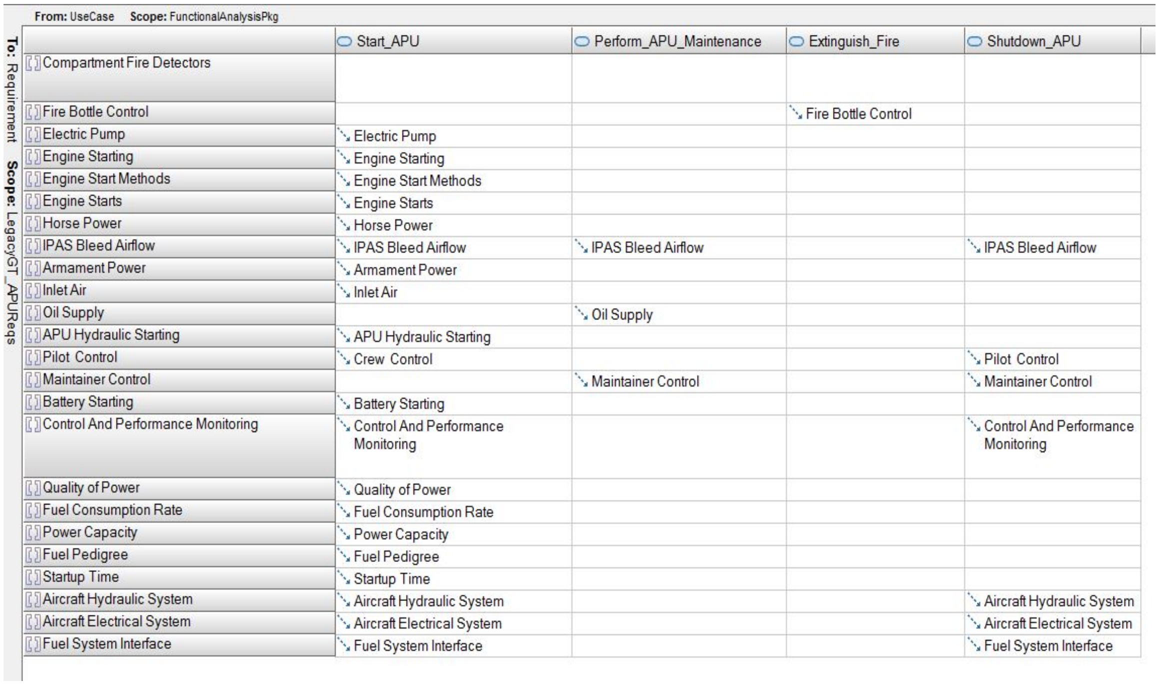
Figure 3 Gas Turbine APU Use-Case Description



A point to note about the use case diagram is the associations that the aircraft mainatiners and crew (Pilot and Co-Pilot) have in relation to the APU. To highlight this difference, a *generalization* relationship between the Maintainer and the Crew actors on one side and an Operator actor on the other side actor was created. In SysML, this particular syntax implies general, common roles defined in Operator that apply to both the Crew and the Maintainer, but also allows to *redefine* these general roles with more specialized ones for each of the two actors. Explicitly speaking, any operator whether a crew or a mainainter can use the APU, either by starting it *(*Start_APU) or shutting it down (Shutdown_APU), as well as in the *exceptional* use case Extingish_Fire, which *extends* Shutdown_APU by initiating an emergency shutdown. On the other hand, it is only a specialized operator, that is the maintainer, who can use the APU to perform maintenance (Perform_APU_Maintenance).

In addition to describing the system architecture, requirements traceability was done in this study to assure that all functional and performance requirments are covered by the use cases, as shown in Table 2.

Table 2 Requirments to Use-Cases Traceability



From: UseCase **Scope:** FunctionalAnalysisPkg

To: Requirement **Scope:** LegacyGT_APUReqs

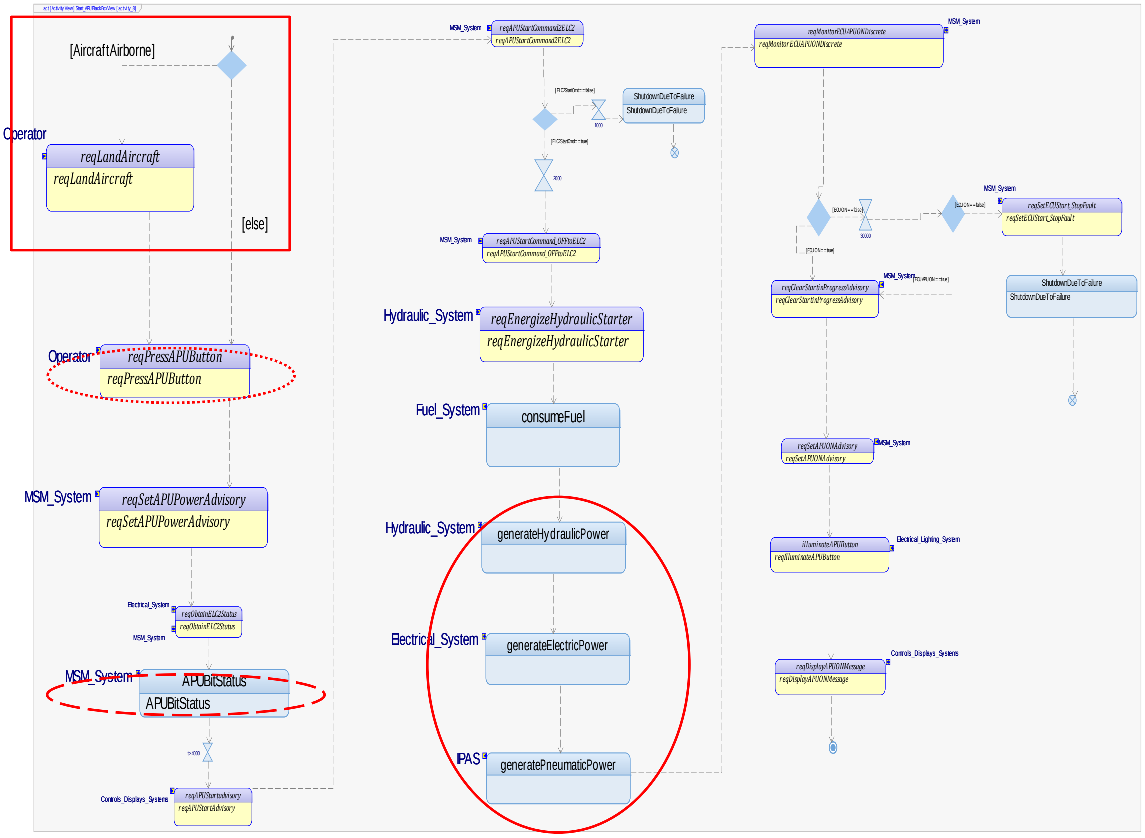
	Start_APU	Perform_APU_Maintenance	Extinguish_Fire	Shutdown_APU
Compartment Fire Detectors				
Fire Bottle Control			↘ Fire Bottle Control	
Electric Pump	↘ Electric Pump			
Engine Starting	↘ Engine Starting			
Engine Start Methods	↘ Engine Start Methods			
Engine Starts	↘ Engine Starts			
Horse Power	↘ Horse Power			
IPAS Bleed Airflow	↘ IPAS Bleed Airflow	↘ IPAS Bleed Airflow		↘ IPAS Bleed Airflow
Armament Power	↘ Armament Power			
Inlet Air	↘ Inlet Air			
Oil Supply		↘ Oil Supply		
APU Hydraulic Starting	↘ APU Hydraulic Starting			
Pilot Control	↘ Crew Control			↘ Pilot Control
Maintainer Control		↘ Maintainer Control		↘ Maintainer Control
Battery Starting	↘ Battery Starting			
Control And Performance Monitoring	↘ Control And Performance Monitoring			↘ Control And Performance Monitoring
Quality of Power	↘ Quality of Power			
Fuel Consumption Rate	↘ Fuel Consumption Rate			
Power Capacity	↘ Power Capacity			
Fuel Pedigree	↘ Fuel Pedigree			
Startup Time	↘ Startup Time			
Aircraft Hydraulic System	↘ Aircraft Hydraulic System			↘ Aircraft Hydraulic System
Aircraft Electrical System	↘ Aircraft Electrical System			↘ Aircraft Electrical System
Fuel System Interface	↘ Fuel System Interface			↘ Fuel System Interface

The table arrangement shows APU system requirements in the left hand column and the use cases in the top row, with SysML *trace* relationships between the two. For example, the use case “Perform_APU_Maintenance” traces to a requirement with title “Oil Supply” (actual requirement not shown) in the far left column, indicating that the APU maintenance use case will address the oil supply requirement. Note that Model traceability can be performed at various levels of abstraction, where each function and attribute that results from the process of functional analysis could also be traced to system requirements. This is not within the scope of this study and was not captured in the SysML model.

3.2 Functional Analysis

Successful models are those that refrain from simultaneously consider all the complexity of the real system and instead, drive down to the bottom on only few “functional threads” or paths, while showing slivers of the whole system along the way [15]. As such, elaboration of the GT APU base use case Start_APU was carried out with SysML Activity Diagrams, as shown in Figure 4.

Figure 4 Activity Diagram for the GT APU Start-Up Sequence



The activity diagram above combines traditional system engineering functional flow constructs [16] which describe the logic of starting and operating the GT APU, with the service request modeling approach [9]. Although SysML sequence diagrams have been conventionally used to model service request architectures and other message-based behavior of systems [8], however, to streamline the model and make it easier to understand, SysML “action pins” were used to describe the “interactions” that take place between the SuC (i.e. APU) and the actors. For instance, to initiate the GT APU startup sequence on the aircraft, an operator must press the APU start button located in the crew station (i.e. Cockpit). To describe this interaction, an *asynchronous message* (i.e.

reqPressAPUButton) representing a service request from the SuC to the Operator actor is created, as shown by the name and direction (i.e. output) of the action pin inside the dotted-line circle. Similarly, an actor could also request a service from the SuC, in which case the APU would be providing that service. An example of that is where the MSM requests Built-in Test (BIT) Status from the APU, circled in the diagram by a dashed-line around the action APUBitStatus with an input pin from the MSM.

Another sequence that is captured by the activity diagram describes the *Guards* or conditions under which the GT APU could be operated. Operators can only startup the GT APU while the aircraft is on the ground and it is recommended that it remains turned off otherwise (i.e. in flight). In the diagram, this is described by the group of action messages shown inside the square box in the upper left corner of the diagram. In addition, the model captures three key actions (i.e. services), shown inside the solid line circle, that the SuC provides to other systems onboard the aircraft; these are:

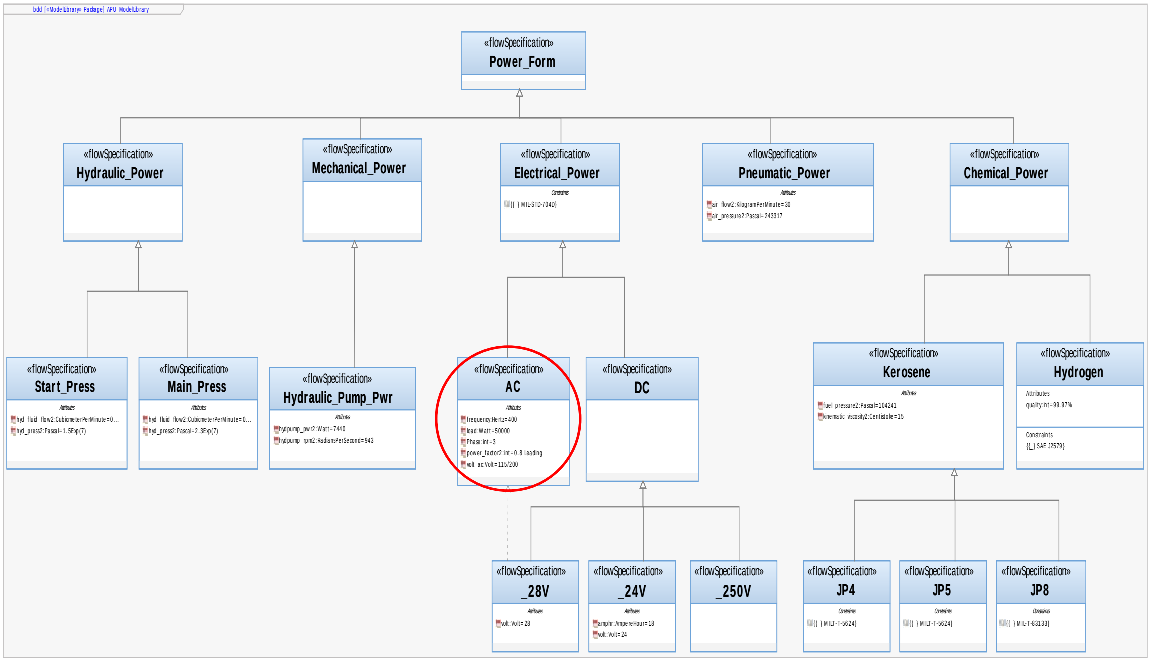
- generate hydraulic power
- generate electric power
- generate pneumatic power

While *decomposing* these functions into a more detailed sequence of actions is possible, nonetheless, keeping the model at this level of abstraction facilitates comparison of the proposed FC architecture with the gas turbine APU during early stages of system analysis. Consequently, further description of the logical architecture was based on these main functions.

3.3 Power Form Classification

Item flows across system parts are often modeled in terms of signal (I/O), however, given the main functions that the APU performs onboard the aircraft, which are to generate hydraulic, electric and pneumatic power, we chose to describe item flows in term of power flows. Figure 5 shows SysML *Flow Specification* blocks used to specify the characteristics of the different power forms used in the model and their *classification*.

Figure 5 Power Form Classifications

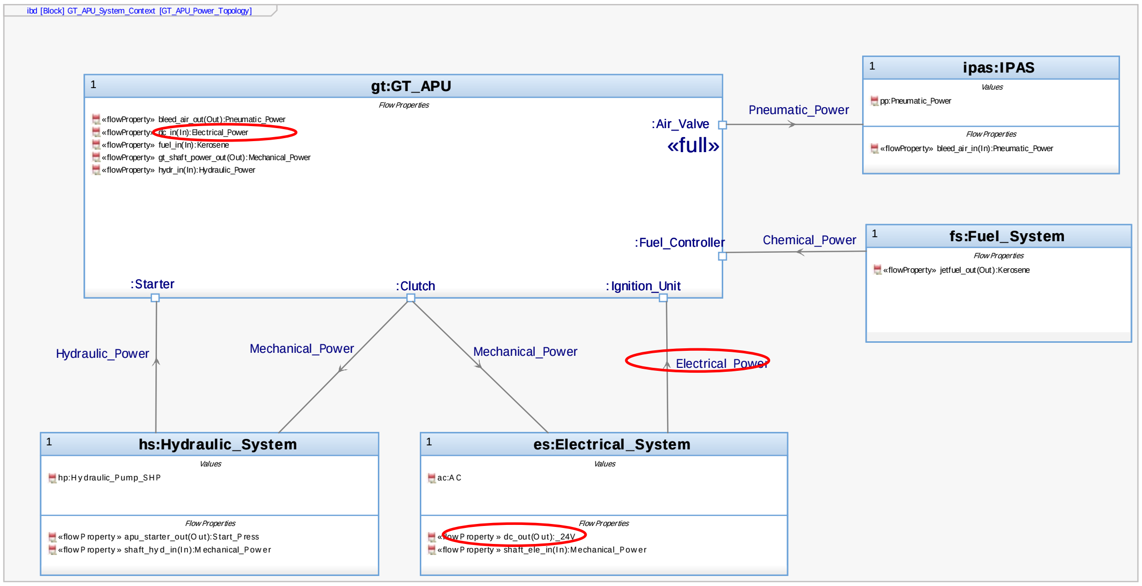


Note that generalization relationships were again used here to delineate the hierarchy and specialization of the various forms. To illustrate, consider the AC power block circled in the diagram. The flow specification for AC power contains "attributes" that specify the features of that power form as being a 3ø(phase) with an amplitude of 115/200 Volts, frequency of 400 Hertz, power factor of 0.8 leading. Besides, AC power form *inherits* the attributes of the more general, Electrical_Power form which in turn has its own, additional set of attributes and constraints including compliance with MIL-STD-704D [17]. Also note the *dependency* relationship between the _28V power and AC power, which implicitly emphasizes that the aircrafts 28Volt DC power source is dependent on the availability of AC power. Using this definition, any reference to or usage of AC power throughout the model is only in relation to these properties, resulting in enhanced clarity and reduced ambiguity of the system description.

3.4 Gas Turbine APU Use Case Realization

Gas Turbine APU Logical architecture, in terms of power flows was then defined using SysML Internal Block Diagram (IBD), as shown in Figure 6. Of special importance to MBSE and as one of its main enablers is the concept of block instantiation. By creating instances that retain the features of existing model blocks, system engineers can leverage the flexibility of "reusing" these blocks across different sections of the model, depending on the level of abstraction or aspect of the system that is being modeled [18].

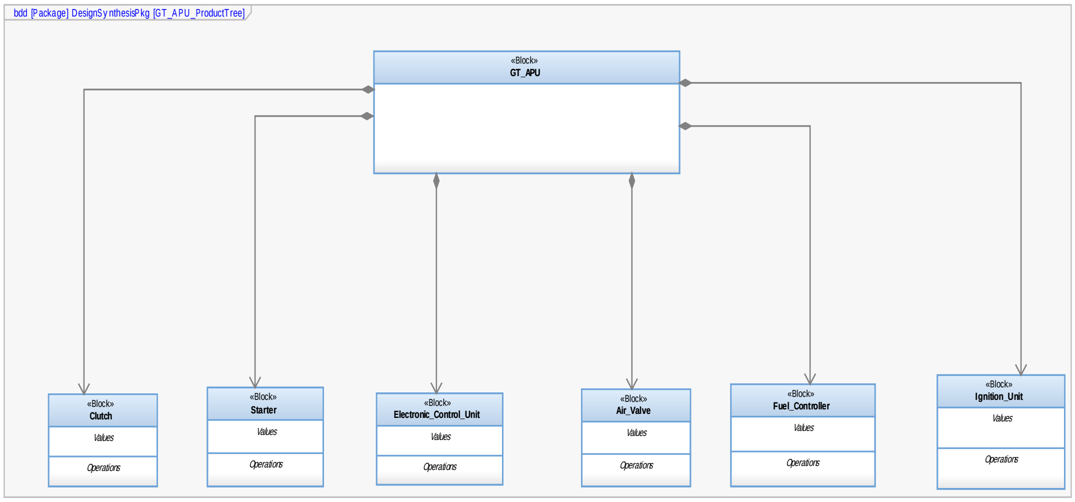
Figure 6 Gas Turbine APU Use Case Realization



The objects shown in the diagram (gt:GT_APU, ipas:IPAS, es:Electrical_System, etc. …) are instances of blocks that were previously defined in the model. SysML uses the notation Instance name: Block name to refer to these instances. In the diagram, the gt:GT_APU object for example , indicates that gt is an instance of the block GT_APU, with any change to the structure (product tree) or behavior (operations) done to GT_APU being automatically reflected on all of its instances across the entire model, and vice versa.

SysML offers two different methods to represent *access points* on the boundary of a block, *proxy ports* and *full ports*. Depending on whether the modeler is only attempting to *expose* certain features of a block, in which case a proxy port would be used, or to have the port fully "handle" the block interface. As seen on the logical architecture IBD of Figure 6, the ports that are specified on the GT_APU object, including air valve, fuel controller, ignition unit, clutch and starter represent functional parts on the gas turbine "product tree", shown in Figure 7. These ports can essentially modify incoming and outgoing flows of the APU and therefore, full ports shown with stereotype <<*full*>> were used to model these objects. For diagram clarity, the stereotype notation is displayed for the air valve port only.

Figure 7 GT APU Product Tree



In addition to item flows, which represent what is flowing between the APU and the actors, SysML *Flow Proportites* were used in the gas turbine APU logical architecture IBD to specify what can flow thru each block and in what direction, whether into or out of the block. Unlike item flows, which are shown using arrows between blocks, flow properties are displayed within designated structural compartments inside the block. Note that both item flows and flow properties are instances of the various power forms classification blocks that were defined earlier, which is used by the tool (i.e. Rational Rhapsody) to confirm compatibility of flows between blocks. For example, adding an item flow between two blocks that is outside the classification hierarchy of the flow properties defined within the two blocks causes the tool to flag that flow as being incompatible.

A common approach to model flows is that the type of the item flow is the same as or more general than the source flow property, and that the type of the target flow property is the same as or more general than that of the item flow [15]. For example, the aircraft’s electrical system (the source) provides 24 volt dc power to the gas turbine APU (the target) to generate the high energy, electrical spark to ignite the fuel-air mixture in the gas turbine. To model this, a flow property ”dc_out”, which is an instance of the power form “_24V”, with direction “Out”, is specified for the electrical system. Also, an item flow between the gas turbine APU and the electrical system was created and given the type “Electrical_Power”, which according to the power form classification is more general than “_24V”. At the gas turbine APU end, a flow property “dc_in”, which is an instance of “Electrical_Power” and have an “In” direction was then created within the gt object. All of these model elements are circled in the logical architecture IBD diagram of Figure 6.

Beside item flows and flow properties, some actors shown in the IBD have attributes which are also instances of the power form classification. These refer to critical characteristics of that actor, which the candidate FC system must address to be considered as a viable alternative to the gas turbine APU. Specifically, the Hydraulic System contains an attribute named “hp”, which is an instance of “Hydraulic_Pump_ Pwr”. According to the definition of that power type (see Figure 4), it is a form of mechanical power with properties of 7440 Watt (W) and 943 Radians Per Second (rad/s), referring to the actual power required to run the hydraulic pumps and pressurize the hydraulic system. Currently, this is being achieved by the APU using a set of mechanical gears and a shaft interfacing the APU with the hydraulic pumps on the aircraft. Furthermore, the IPAS system, which mainly supports environmental control functions onboard the aircraft, requires a stream of pressurized air at 243317 Pascal (Pa) and a pressure of 30 Kilogram Per Minute (kg/min), depending on the operational conditions.

These values are captured in the model in the form of an attribute of the IPAS system (i.e. pp:Pneumatic_Power). Therefore, besides providing electrical power, if we to consider a FC to replace a gas turbine APU, it must be able through additional ancillary parts to provide the aircraft with the required amounts of hydraulic and pneumatic flow, a point which will be emphasized in the following section of this paper.

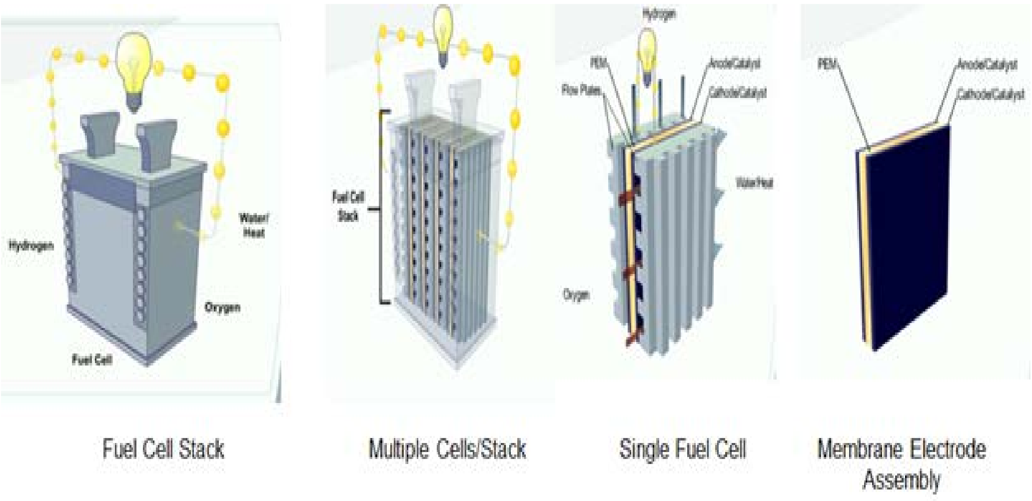
CHAPTER 4

PEMFC LOGICAL ARCHITECTURE DESCRIPTION

PEMFC is an electrochemical conversion device where the main reactants, Hydrogen and Oxygen (or Air), in the presence of a catalyst, spontaneously react to produce a direct current (DC). The *electrochemical combustion* reaction that takes place within a FC is similar to the chemical, galvanic reaction that takes place in traditional batteries. Yet, from a thermodynamic standpoint, the main difference between a FC and a Battery is that mass flux does take place across the boundary of the FC, referring to the fact that Hydrogen and Oxygen can be continuously supplied, which allows continuous operation of the FC. Whereas, no mass flux is permitted across the boundary of a battery, therefore, always requiring the time consuming process of recharging and replenishing its main reactants.

At the core of the PEMFC is a solid polymer electrolyte membrane, which due to its unique chemical and physical characteristics, allows only protons (i.e. positive hydrogen ions) to pass from the positive electrode (i.e. anode) of the cell to the negative electrode (i.e. cathode), and hence the name of the device. The PEM and the two electrodes are conventionally combined into one component which is often referred to as the membrane-electrode assembly (MEA). To be used as an electrical source and provide the required output voltage, several fuel cells are usually connected either in series or parallel to form the Stack. The physical interconnection between neighboring individual cells in the stack is achieved through the means of Bipolar Plates (or flow plates), which also function as current collectors, conducting electrons from the anode of one cell to the cathode of the adjacent cell in the stack, or to the external circuit. In addition, the Bipolar Plates contain flow channels through which Hydrogen and Oxygen flow, which then diffuse to the anode and cathode of the cell, respectively. Figure 8 below shows the main components making up the fuel cell stack[22].

Figure 8 PEMFC Stack Main Components



Fuel Cell Stack

Multiple Cells/Stack

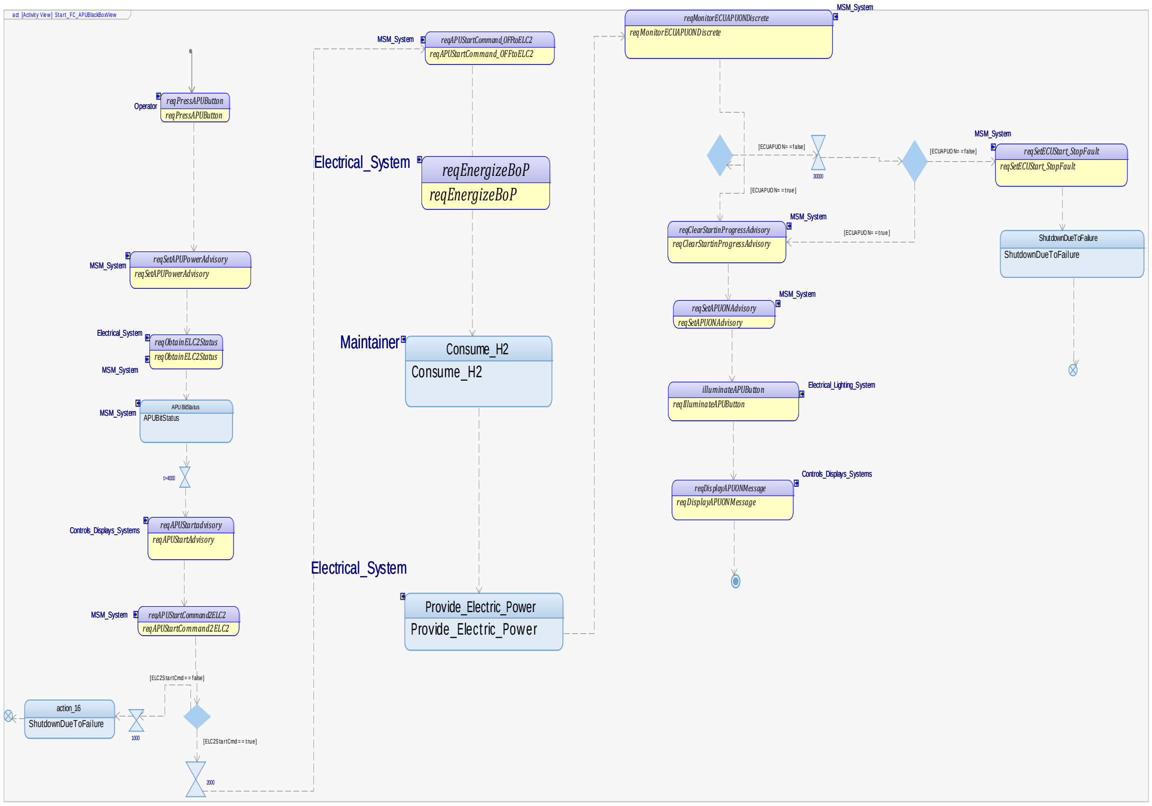
Single Fuel Cell

Membrane Electrode Assembly

4.1 PEMFC APU Functional Analysis

Based on the gas turbine APU use case model, a descriptive functional flow for the proposed FC APU system was developed as shown in the SysML activity diagram of Figure 9.

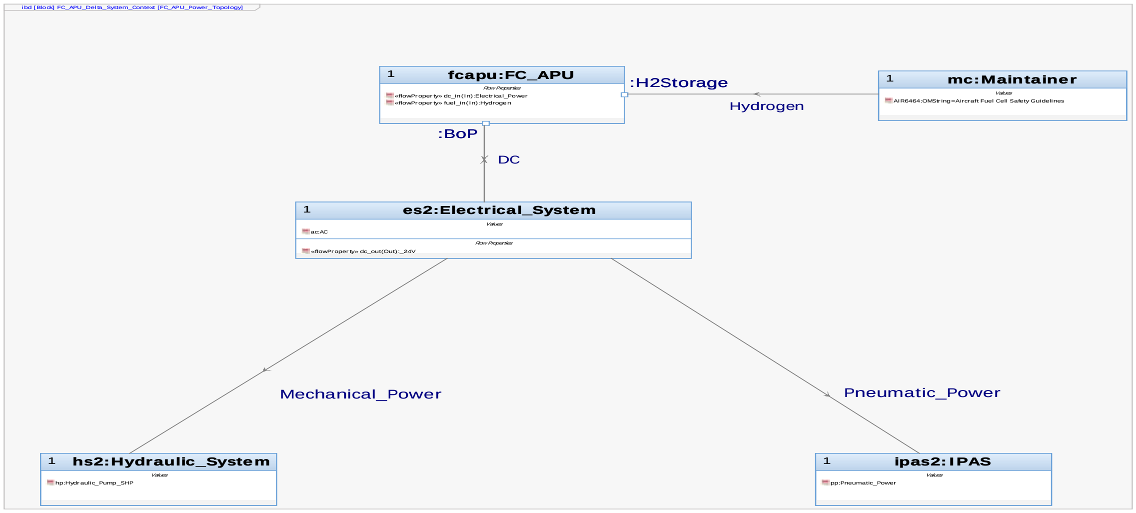
Figure 9 PEMFC APU Start-Up Sequence “Theoretical”



There are several points to notice about the actions and messages in the activity diagram. First, PEMFC have a much lower operating temperature than the gas turbine, ranging between 122-212 ^{o}F [6], which should, in theory, allow operators to use the FC during ground operations as well as during flight. The diagram reflects this difference by omitting the logic which required that the aircraft be on ground when operating the APU. Besides, recalling that one of the first functions when starting the gas turbine APU involved energizing a hydraulic starter by means of hydraulic pressure. On the other hand, a FC would normally require a start-up electric power to energize its pumps, fuel controller, air valves, and other supporting equipment which are referred to as Balance of Plant (BoP). These would mainly allow and control the flow of the main reactants, Hydrogen and Air (i.e. O2) through the flow channels within the stack and trigger the electrochemical reaction to take place. Also, since the FC is an electrical power source, it is mainly the aircraft electrical system that would directly interface with the FC APU to achieve the main functions discussed previously, as shown in the activity diagram.

4.2 PEMFC APU Use Case Realization

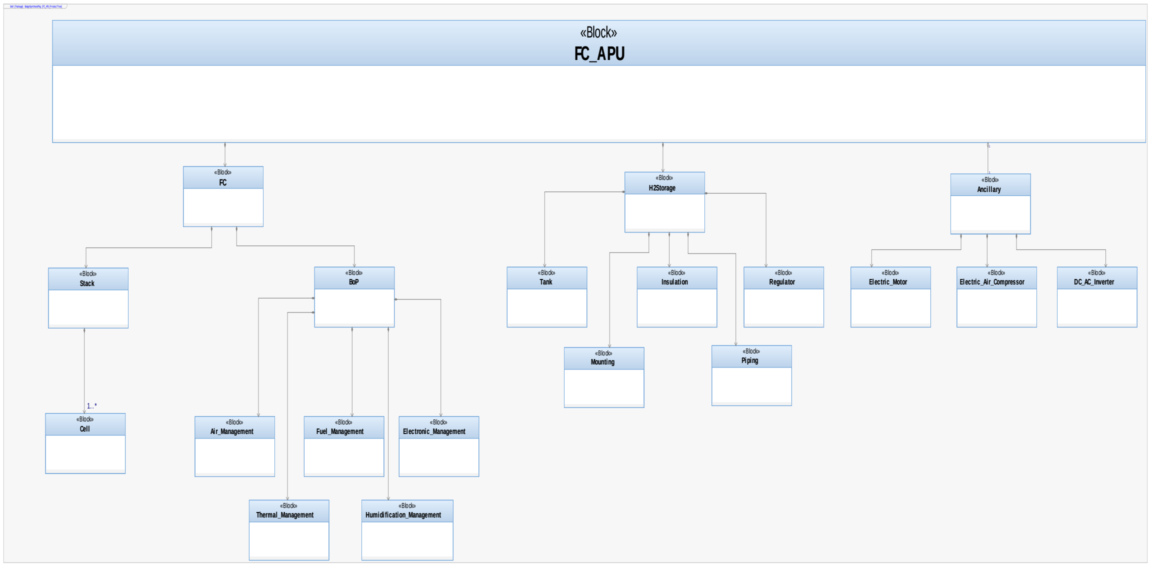
Figure 10 PEMFC APU Use Case Realization



The FC APU logical architecture of figure 10 shows the power forms that are exchanged between the FC APU and other systems across the aircraft, with flow properties and attributes defined for each block. The various blocks including es2, hs2, ipas2 and mc are instances of the same actors that were created previously in the model to define the gas turbine APU logical architecture. Note the bidirectional “DC” item flow that is being exchanged between the FC APU and the electrical system, indicating that the FC requires dc power to energize its BoP, after which it starts providing DC power to the rest of the aircraft. The diagram also shows an attribute of the aircraft maintainer (i.e.

AIR6464 – Aircraft Fuel Cell Safety Guidelines) [19], which specifies the main guidelines and required operator competencies for the installation of fuel cells on-board aircraft for the purposes of supplying auxiliary power, including safe handling of the hydrogen fuel.

Figure 11 PEMFC APU Product Tree



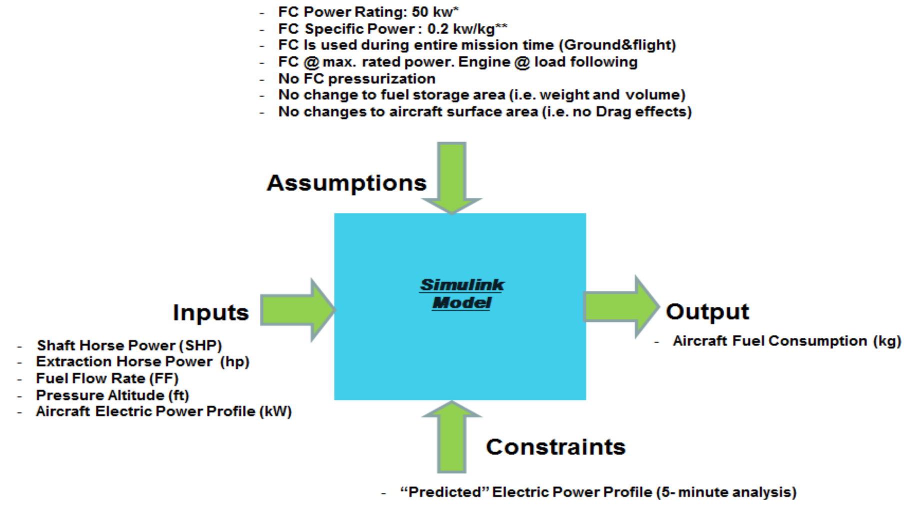
The BDD in figure 11 describes the FC APU product tree which is made up of the FC and the Hydrogen storage (i.e. H2Storage), shown in the diagram using part relationship arrows connected to the top level block. The FC is decomposed into the Stack and the BoP, with the stack shown as having multiple cells using SysML *multiplicity* notation [1..*]. The BoP is also shown as consisting of various parts including Air, Thermal, Fuel, Electronic and Humidification Management components. On the other hand, the Ancillary System is associated with the FC APU using the *reference* relationship arrow circled in the diagram, which according to SysML syntax specifies any ancillary components (i.e. Electric Motors, Electric Air Compressor, DC/AC Converter) as external to the FC APU system, but will be required to satisfy the system use cases. Therefore, any reference to the system only include these components that are part of the FC APU, namely the stack, the BoP and the hydrogen storage tanks.

CHAPTER 5

SYSTEM PERFORMANCE

Total fuel consumption and efficiency simulations to show the feasibility of removing the GT APU and adding a FC on a helicopter were performed using MATLAB Simulink. Central to the simulation approach is assessing not only the benefit of the FC in generating electricity, but also the performance penalty the new system may impose due to its added weight on the aircraft. The model is based on inputs from actual aircraft flight data, aircraft electric power profile, along with a set of assumptions and constraints that are discussed in the following sections.

Figure 12 Simulink Model Black Box Representation



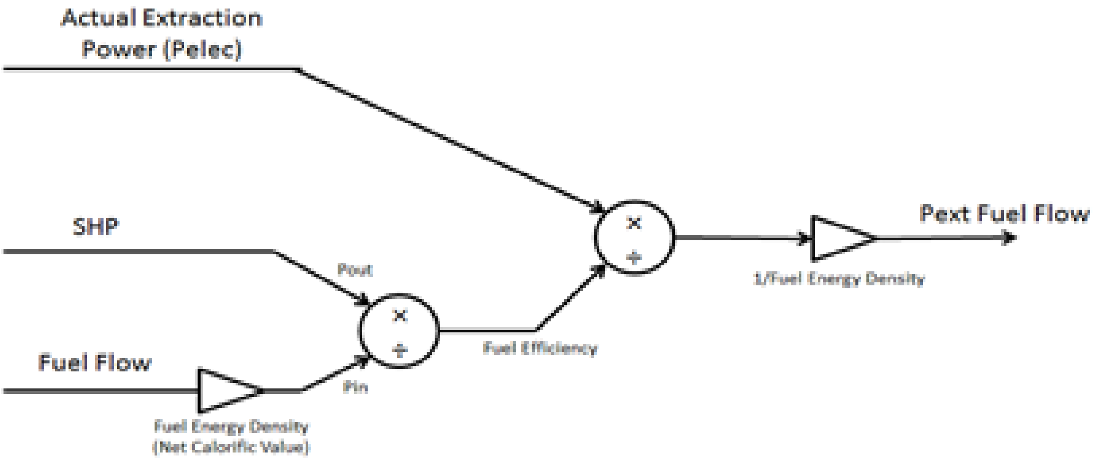
*Required FC rating determined according to aircraft Electric Load and Power Source Capacity Study

**FC power densities up to 0.4 kw/kg have been demonstrated. However, we assumed 0.2 kw/kg in the simulation to account for any unforeseen weight additions

5.1 Model Development

Full explanation of model development is provided in [20]. However, to extend its applicability to rotary wing platforms, modifications to the original model were made in this study to account for a helicopter’s gas turbine main engine fuel consumption and efficiency, rather than using a jet engine from a commercial airplane. Specifically, to calculate the fuel efficiency of a helicopter’s main engine and the amount of fuel it consumes when sharing load with the FC (i.e. Pext Fuel Flow), the model was modified to use the helicopter’s main engine shp instead of the thrust power produced by a jet engine, as illustrated in the figure below. Otherwise, the rest of the model remained mostly unchanged.

Figure 13 Simulink Model Modifications



5.2 Input Data Collection and Pre-Processing

Required input data to the simulation include engine Shaft Horse Power (shp), Fuel Flow rate (FF) measured in pound per hour (lb./hr), Extraction Horse Power (hp) and aircraft pressure altitude in feet. To calculate fuel consumption rates, both during

APU ground operations and during flight, the same set of data inputs (i.e. shp, FF, hp) were required for both the APU and the aircraft's main engine [21]. In addition, an electric power profile for the aircraft in Kilowatts (KW) was also required as a model input.

To obtain SHP and FF values, "raw data" as collected from the Maintenance Data Recorder (MDR) onboard the aircraft during a 3.8 hours mission of combined ground and flight operations was used. The recorded data included parameters such as pressure altitude, engine torque, engine power turbine angular speed, along with discrete values indicating when the APU was being operated. Using these parameters in conjunction with first principles equation relating mechanical power to force, power input values were calculated as follows:

$$\text{Power (P)} = \text{Torque (F)} \times \text{Angular Velocity (V)} \qquad (1)$$

Where:

(P) is in watts,

(F) is in newton meter,

(V) is in radians per second.

The Simulink model requires the power input in terms of shaft horse power (SHP) instead of watts. Therefore, equation (1) becomes:

$$\text{SHP} = \frac{\text{F} \times \text{V}}{745.7} \qquad (2)$$

In addition, the engine torque and the speed of the power turbine in the raw data from the MDR are recorded in terms of pound-force-feet (lb-ft) and in revolution per minute (rpm), respectively. Therefore, equation (2) was further refined to account for unit conversion factors as follows:

$$\mathrm{SHP} = \frac{\left(\mathrm{T} \div \left(\frac{1\ \mathrm{pound}}{4.45\ \mathrm{newton}}\right) \times \left(\frac{3.28\ \mathrm{feet}}{1\ \mathrm{meter}}\right)\right) \times \left(\mathrm{NP} \div \left(\frac{60\ \mathrm{second}}{1\ \mathrm{minute}}\right) \times \left(\frac{1\ \mathrm{revolution}}{2\pi\ \mathrm{radians}}\right)\right)}{745.7}$$

$$SHP = \frac{T \times NP}{5252} \qquad (3)$$

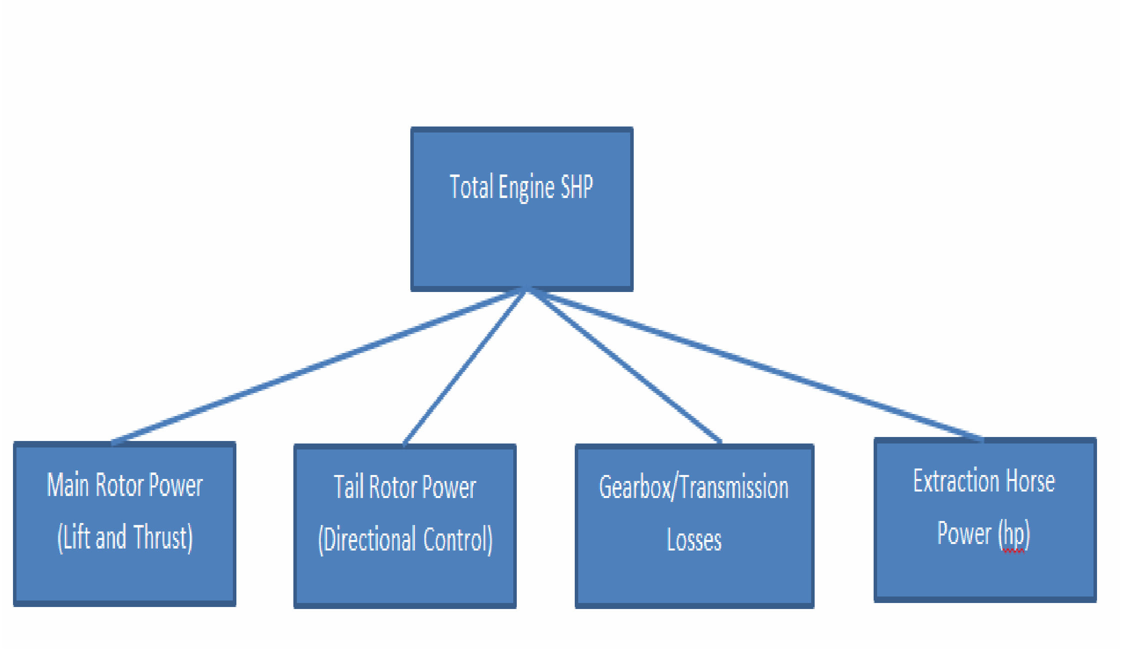
Where:

(T) is engine torque in pound-force-feet,

(NP) is power turbine speed in revolution per minute

The calculated values for SHP represented the total power that the main engine generated through its shaft. The majority of that power is used at the helicopter main rotor to produce thrust and lift forces. In addition, a percentage is used at the tail rotor to maintain stability and directional control (i.e. Anti-Torque). Also, the SHP is further reduced due to gearbox/transmission losses. The remainder is what is referred to as Extraction Horse Power (hp), which is mainly used to drive the electric generators and the hydraulic pumps on the aircraft. Figure 14 describes how the main engine shp is conventionally partitioned on a rotary wing aircraft.

Figure 14 Shaft Horse Power Partition on a Helicopter



The percentage of Engine SHP lost to the main rotor, tail rotor and the gearbox have been previously calculated for the aicraft. Using this information, values for (hp) were estimated for the entire mission.

As was the case with SHP calculations, raw mission data did not specify the (FF). Therefore, using SHP values that were previously calculated along with Specific Fuel Consumption (SFC) values at continuous SHP provided by the main engine OEM, (FF) rates were developed. Note that all the above calculations for SHP, FF and hp were performed only for the main engine of the aircraft. Gas turbine APU (SHP) and (FF) were assumed to be constant at 81 SHP and 175 lb/hr, respectively [2]. Also, APU (hp) estimations did not consider shp loses to the main Rotor and Tail rotor, since these are not used during APU ground operations.

The last of the five data inputs required to the model was an electric power profile for the aircraft. Raw mission data provided minimal information about the electric power load in terms of kilowatts. Therefore, engineering due diligence was done to establish the electric power profile for the aircraft mission, as explained further in the model assumptions and constraints section of this paper.

5.3 Model Assumptions and Constraints

A number of assumptions were considered to carry out the simulation. First, The FC power rating size of 50 kW used in the model was based on generic aircraft load requirements during APU Ground Operations. Also, the specific power density for the FC system, including the stack and BoP used in the simulation was 0.2kW/kg. Although higher power densities have been achieved with FC systems [22], a conservative figure was used to account for any unforeseen weight additions. Third, as was previously shown in the SysML descriptive model, the gas turbine APU is only utilized during ground operations and remains unused during flight, rendering it as a “dead weight” from an aircraft fuel consumption standpoint. The FC on the other hand is intended to be used during the entire mission, that is during ground and flight operations where it constantly shares the electric load with the main engine on the aircraft.

Previous research [20] [23] has shown that FCs operate more efficiently at part load conditions (i.e. below its rated power) and its efficiency gradually decreases as the FC reaches its maximum rated power. However, due to the higher electrical efficiency of a FC compared to the main engine, having the FC running constantly near its rated power lowers the load on the main engine and result in lower overall aircraft fuel consumption.

This constituted the basis for the fourth assumption in the model, where the FC is operated at maximum rated power with the engine-generator providing the remaining of the required power (i.e. load following).

One of the factors that influence FC performance is its operating pressure, which has a direct effect on the concentration and transfer rates of the main reactants (i.e. H_2/O_2) within the cell [24]. So while the aircraft is in flight and as it gains altitude, lower atmospheric pressure could result in lower FC power output. Nevertheless, given the low altitudes that a helicopter usually operates at, we are anticipating minimal atmospheric pressure effects on the FC performance [25]. Therefore, the Simulink model did not include provisions for additional pressurization.

Next, given that the gas turbine APU fuel consumption rate is approximately 175 lb/hr, and that it is normally used for approximately 30 minutes per mission, the simulation assumes that there is no change to the mass and volume of total fuel (Jet Fuel + Hydrogen] stored on the aircraft, when replacing the amount of jet fuel required for the gas turbine APU with the hydrogen required for the fuel cell. It is also assumed that the FC system is accommodated inside the aircraft without the need to modify the aircraft's fuselage and dimensions. Thus, the effects of drag on the resultant fuel consumption were not considered. Note that all of the above assumptions are subject to further investigation and will form the basis to develop a "what-if" analysis in future studies.

As previously mentioned, one of the inputs that were required for the simulation is an electric load profile for the aircraft. To do so, projected aircraft electric load requirements at various phases of the flight per MIL-E-7016F [26] were "mapped" to the actual mission data. For example, the electric load value in terms of (KW) during Load and Preparation (i.e. G2 condition), as obtained from the aircraft's electric load analysis, was correlated to the mission data during that time when the APU was being used on the ground. That is because MIL-E-7016F defines the "Loading and Preparation" phase of a mission as the period when "power is supplied by an auxiliary power unit, internal batteries or an external power source". The same approach was used to establish the power profile for the other phases of the mission including: Start and Warm-up (G3), Takeoff/ Hover/Landing (G4) and Cruise Combat (G5).

5.4 Model Output and Results

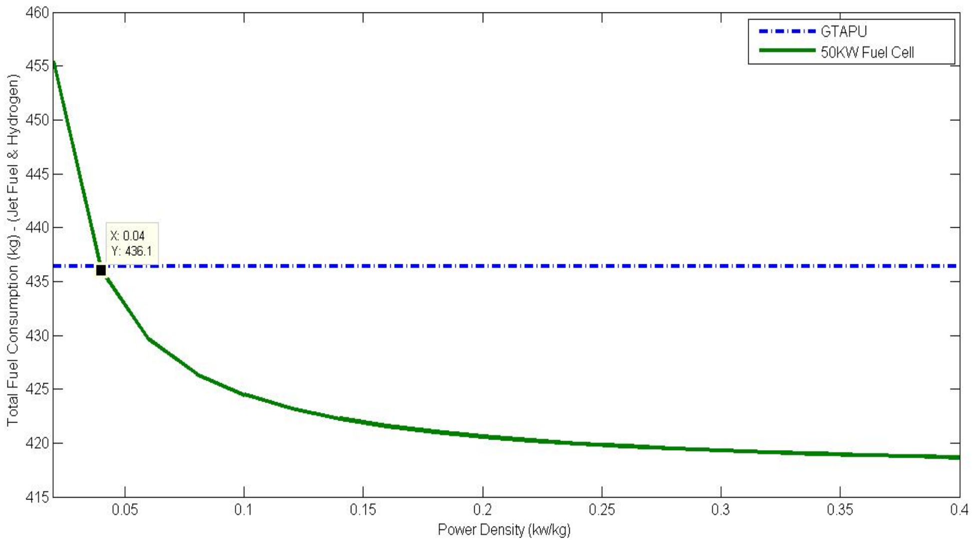
The primary focus of the simulation is to compare total fuel consumption (per engine) with a gas turbine APU installed, versus the scenario where a 50kW FC replaces the the APU on the aircraft. Model results indicate that using a FC could bring substantial improvements in aircraft fuel consumption over the span of the 3.8 hour mission, reaching up to 12% of fuel savings. As expected, the majority of the improvement (i.e. 40%) is realized during the 1.6 hour of ground operations since the weight of the FC is not considered a factor during that time. Nevertheless, during the 2.2 hour flight, the high electric efficiency of the FC surpassed its added weight penalty and resulted in additional fuel savings as well (i.e. 4%).

Table 3 Simulation Results

Fuel Consumption from Actual Mission Data With Honeywell 36-155 GT APU (Jet Fuel Only)	Fuel Consumption from Simulation Data With 50 kW, 0.2kW/kg Fuel Cell (H2+Jet Fuel)	Fuel Savings	% Improvement in fuel consumption
2.2 Hours Flight			
436 kg	421 kg	7 kg per flight hour	4%
1.6 Hours Ground Operations			
139 kg	84 kg	34 kg per hour of ground operation	40%
3.8 Hours Total Mission			
575 kg	505 kg	18 kg per mission hour	12%

Additional simulations were performed to study the effects of FC system weight variations on the aircraft's fuel economy. Keeping the rated output power and flight duration constant at 50kW and 2.2 hours, respectively, various power density values for the FC were used, as shown in the Figure 15.

Figure 15 Aircraft Fuel Consumption versus FC Power Density



Note that the power density is related to the FC and not to the gas turbine APU curve, which is included for comparison purposes only. The plot shows that the “breakeven point” for installing a fuel cell is at a power density of 0.04kW/kg. At FC ratings smaller than that value, a gas turbine APU would make more sense from a fuel consumption standpoint. However, at larger power densities, a FC would result in greater fuel savings over the same flight time.

CHAPTER 6

PARAMTERIC COST EVALUATION

SysML parametric diagrams[36] were used to graphically depict the topological structure of the relations between key FC characteristics on one side, and a set of mathematical equations that define cost and design of the FC on the other side, in a similar fashion to Bipartite graphs used in the field of mathematical constraint theory [27]. Contrary to Bipartite graphs however, SysML parametric diagrams do not indicate causality, or the direction of the mathematical relationship. For this reason, dependent and independent variables were further identified and initialized, and then a computational equation solver, in this case, MATLAB's Symbolic Math toolbox was used to evaluate the equality relationships. The following sections show the derivation of the cost and design equations that were used in developing the parametric model.

Life Cycle Cost (LCC) of a single FC APU system is defined as:

$$FC\ APU_{LCC}(\$) = FC\ APU_{CC} + FC\ APU_{\mathrm{OMC}} \qquad (1)$$

Where,

-$FC\ APU_{CC}(\$)$: Capital cost of the system

-$FC\ APU_{\mathrm{OMC}}(\$)$: O&M cost of the system

6.1 Capital Cost

For consistency, the capital cost structure was developed in a manner that corresponds to the FC APU product tree description of Figure 11, such that:

$$FC\ APU_{CC} = FC_{CC} + \mathrm{H2Storage_{CC}} \quad (2)$$

$$FC_{CC} = Stack_{CC} + \mathrm{BoP_{CC}} \quad (3)$$

Where,

-FC_{CC}(\$): Capital cost of the FC

-$H2Storage_{CC}$(\$): Capital cost of the hydrogen storage

-$Stack_{CC}$(\$): Capital cost of the stack

-BoP_{CC}(\$): Capital Cost of the BoP

The dominant cost drive of a FC stack is platinum loading, or the amount of the platinum catalyst that is applied to both electrodes of a cell [28]. Early studies [29] [30] have indicated to an exponential relation between platinum loading and the stack cost. Since then, more recent studies have pointed to a linear trend that exists [28], such that:

$$Stack_{CC} = (3.7 \times 10^{-5} \times \left((0.87 \times active_{area} - 12.5)pt_{loading} \times pt_{price}\right) + (0.006 \times active_{area}) + 427.4) + 12200 \quad (4)$$

$$active_{area} = no_{cells} \times cell_{area} \quad (5)$$

Where,

-$pt_{loading}$ (mg/cm^2): Specific amount of Platinum catalyst used in the FC

-pt_{price} $(\$/ounce)$: Market price of Platinum

-$active_{area}$ (cm^2): Total area within the FC stack where the electrochemical reaction takes place

-no_{cells} : Number of cells inside the stack

-$cell_{area}$$(cm^2)$: Active area of a single cell

Equation (4) represents the overall cost of the stack including material and manufacturing cost. The equation was originally generated using regression analysis of a cost model developed for the automotive industry, and then calibrated for the purpose of this study to account for lower production rates (i.e. 1,000 stacks versus 500,000 as was in the original estimate)

Unlike the stack cost, the BoP capital cost is chiefly decided by material cost, with the humidification and the air management components (i.e. compressor, expander and motor) being responsible for the majority of the BoP cost [28]. However, considering the assumption that was made earlier in this study, specifically the one requiring no pressurization of the FC APU system on the helicopter, the air management components were excluded from the estimate. Using this assumption and accounting for all other BoP components, a constant figure of $120 per Kilowatt (120$/kW) was deemed appropriate to estimate the BoP capital cost.

$$\mathrm{BoP}_{\mathrm{CC}} = BoP_{per\_kw} \times \; FC_{power\_rating} \qquad (6)$$

Where,

-$BoP_{per\_kw}(\$/kW)$: BoP price per kW

-$FC_{power\_rating}(kW)$: FC power rating

Capital cost for hydrogen storage onboard the aircraft is dependent on the price of storing one kilowatt-hour worth of hydrogen energy ($/kWh), and the total amount of hydrogen energy (kWh) that is consumed by the FC APU during a single mission.

Regarding the price to store a single kWh, the study used a price target of $10/kWh as set forth by the DOE for the entire hydrogen storage assembly, including the cost of tank, valves, regulators, piping, mounting brackets and insulation [31].

Among the most prominent hydrogen storage technologies that are currently under development, including Physical-Based (i.e. Compressed Gas, Cryo, Liquid) and Material-Based (i.e. Adsorbent, Hydride, Organic) [32], the study considered the compressed gas method with stored hydrogen purity at 99.97%, per SAE J2579 standard [33], an attribute of hydrogen captured in the SysML model diagram of Figure 4. From here, the theoretical amount of hydrogen consumed during a mission can be calculated using Faraday's law for the anode's Hydrogen Oxidation Reaction (HOR) with pure hydrogen:

$$H2Storage_{cc}(\$) = h2storageprice_{per\_kwh} \times h2kwh_{per\_mission} \tag{7}$$

$$\begin{aligned} h2kwh_{per\_mission} = stoich \times \frac{\left(active_{area} \times current_{density}\right)}{Faraday_{const} \times no_{electrons}} \times \\ mission_{time} \times 3600 \frac{second}{hour} \times \\ 2.0158 \frac{\text{gram H2}}{\text{mole}} \times 0.001 \frac{\text{kg}}{\text{gram}} \times \\ 120 \frac{\text{megajoule}}{\text{kg (H2)}} \times 0.278 \frac{kwH}{megajoule} \end{aligned} \tag{8}$$

$$stoich = \frac{1}{fuel_{utilization}} \tag{9}$$

$$current_{density} = \frac{stack_{current}}{active_{area}} \tag{10}$$

Where,

-$h2storageprice_{per\_kwh}$ ($\$/kWh$): Price target set by the DOE to store one kWh of hydrogen

-$h2kwh_{per\_mission}$ (kWh): Amount of hydrogen that is consumed by the FC APU during a single flight

-$Farday_{const}(Coulomb)$: Faraday's Constant

-$no_{electrons}$: Number of electrons that are liberated at the anode when the electrochemical reaction takes place

-$mission_{time}(Hours)$: Average aircraft operation time of combined ground and flight hours

-$stoich$: Stoichiometry factor for the chemical reaction

-$fuel_{utilization}$: Ratio of the amount of hydrogen that is utilized by the FC --relative to the total amount provided

-$current_{density}(A/cm\char`^2)$: Current density of the FC

-$stack_{current}(A)$: Total current provided by the Stack

6.2 O&M Cost

Next, the study used a set of mathematical relations to estimate the O&M cost of the FC APU system on the aircraft. To do so, LCC study over an amortization period (i.e. analysis period) of 10 years was done to calculate fuel and maintenance total cost. The study used empirical flight data, DOE target figures for both hydrogen price and FC durability, along with conventional Present Worth (PW) financial analysis methods used to estimate the cost of renewable energy systems [34].

From equation (1), the FC APU O&M cost can be defined as:

-$FC\ APU_{\mathrm{OMC}}(\$) = \mathrm{H2}_{\mathrm{LCC}} + Maintenance_{LCC}$ (11)

Where,

-$\mathrm{H2}_{\mathrm{LCC}}(\$)$: LCC of the hydrogen fuel that would be used by the FC APU

-$Maintenance_{LCC}(\$)$: LCC for the maintenance required by the FC APU

6.2.1 Hydrogen Fuel LIFE CYCLE COST

LCC of the hydrogen fuel can be defined as:

$$H2_{LCC} = \frac{h2kwh_{per\_year} \times dollar_{per\_gge} \times cpwf}{FC_{efficiency}} \times 0.992\,\frac{gge}{kg\ (H2)} \times 0.0083\,\frac{kg\ (H2)}{megajoule} \times 3.6\,\frac{megajoule}{kWh} \quad (12)$$

$$h2kwh_{per\_year} = \frac{h2kwh_{per\_mission} \times aputime_{per\_year}}{mission_{time}} \quad (13)$$

$$FC_{efficiency} = fuel_{utilization} \times \frac{cell_{voltage}}{1.25} \quad (14)$$

$$cpwf = \frac{1-\left(\frac{1+inflation_{rate}}{1+discount_{rate}}\right)^{no_{years}}}{1-\left(\frac{1+inflation_{rate}}{1+discount_{rate}}\right)} \quad (15)$$

Where,

-$h2kwh_{per\_year}(kWh)$: Average amount of hydrogen that is consumed by the FC APU per year

-$aputime_{per\_year}(Hours)$: Projected time that the FC APU will be used on the aircraft per year

-$dollar_{per\_gge}(\$/gge)$: Price target set by the U.S. DOE for the untaxed, delivered and dispensed hydrogen amount that is equal to the energy content of one gallon of gasoline, or Gallon Gasoline Equivalent (gge)

-$cpwf$: Cumulative PW factor for an annually recurring expense

-$FC_{efficiency}$: Efficiency of the FC using net calorific value of hydrogen

-$cell_{voltage}(V)$: Voltage potential across a single cell inside the Stack

-no_{years}: Number of years for the amortization period

-$inflation_{rate}$: Average inflation rate used for the purpose of the analysis

-$discount_{rate}$: Discount rate at which the initial investment needs to take place

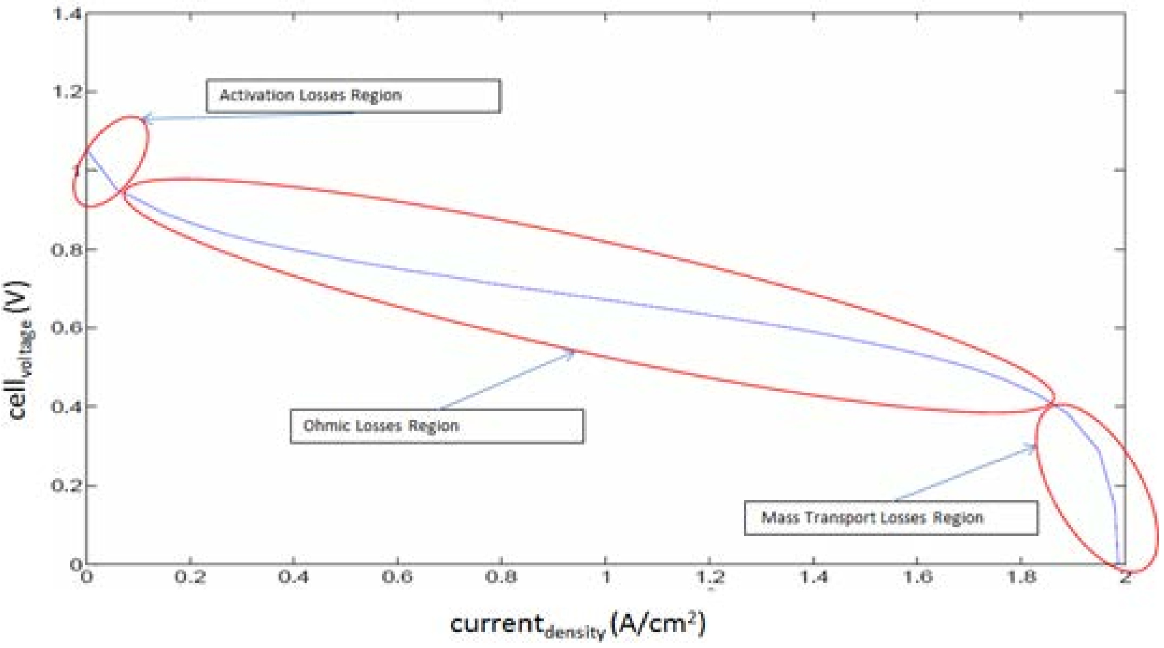
To determine average time per year that the FC APU will be used (i.e. $aputime_{per\_year}$), operational data from previous flights was used. Since the assumption is that the FC APU will be turned on during the entire mission time, including flight and ground operations, the total number of flight hours and APU ground hours over the course of one year were used to find FC APU time.

Furthermore, PW analysis was used to determine the amount of dollars that needs to be invested at the present time, with a specific rate of return, in order to purchase an item at a future time, assuming a particular inflation rate. In this study, hydrogen fuel cost was considered an equally recurring expense, which is incurred annually over the span of the 10 year amortization period. Therefore, we used cumulative PW factor (i.e.cpwf) [34] to calculate the PW of all fuel-related expenses. Also, to select a reasonable discount rate for the financial analysis, a 12.8% Capital Recovery Factor (CRF) as obtained from the U.S. Army Financial Management Office [35] was used. The corresponding discount rate was then obtained from the CRF using the following relation:

$$crf = \frac{discount_{rate} \times (1+discount_{rate})^{no_{years}}}{((1+discount_{rate})^{no_{years}}) -1} \qquad (16)$$

Next, the cell voltage (i.e. $cell_{voltage}$) was obtained from the FC polarization curve which characterizes the Voltage to Current relationship of a FC, as shown in Figure 16.

Figure 16 PEMFC Polarization Curve

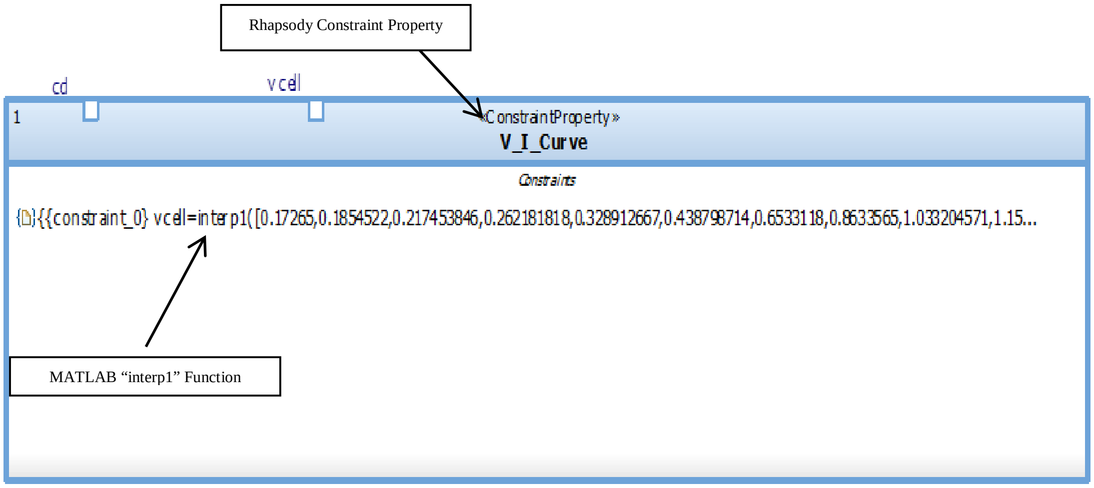


The curve was developed from the FC Simulink model of section V. As noted on the figure, the curve is defined by three distinct regions categorized according to the type of the irreversibility (i.e. voltage loss) that takes place as the current demand (A/cm2) on the cell varies. First are the activation losses which occur mainly due to slow reaction kinetics on the surface of both electrodes, but more severely on the cathode side. Second is the Ohmic losses region, or the linear region, which the FC experiences due to the combined electrical resistance of the electrodes and electrolyte inside the FC. The third region is the mass transport region where the hydrogen and oxygen supply cannot keep up with the electric demand on the FC, resulting in deprivation of the main reactants and a rapid drop in the cell voltage output. For performance stability, FCs are normally operated in the linear region of the curve [24]. Thus, for a selected current density point, cell voltage value can be obtained by interpolating across that linear region, such that,

$$\text{cellvoltage=Table Lookup ([currentdensity Table Points] ,[cellvoltage Table Values], currentdensity Query Point} \qquad (17)$$

To use the interpolated values in conjunction with the rest of the parametric model, we leveraged the capability of Rhapsody to accept specific MATLAB expressions [36], such that MATLAB’s function “interp1” [37] was embedded as a constraint in one of the constraint property blocks in Rhapsody, as demonstrated in Figure 17.

Figure 17 Rhapsody Constraint Property



```
{🗋}{{constraint_0} vcell=interp1([0.17265,0.1854522,0.217453846,0.262181818,0.328912667,0.438798714,0.6533118,0.8633565,1.033204571,1.15...
```

6.2.2 FC APU Maintenance Cost

The APU on the aircraft does not require any scheduled maintenance, and is only repaired (or replaced) on as needed basis. Building on this fact and making a similar assumption for the FC APU, the maintenance LCC was estimated by considering the frequency at which the main components of the FC APU system are Removed and Replaced (R&R) by their End Of Life (EOL), over the 10 year analysis period. Due to the harsh environment that the aircraft might operate in, we used conservative FC and Hydrogen storage durability figures that are based on DOE targets for these components [22] [31].

The durability figure used for the FC, which includes stack and BoP, was 2000 hours of operation. This consists of the projected time to 10% voltage degradation from the rated voltage of the FC. On the other hand, the durability of the H2 storage was assumed to be 1000 fill-up Cycles with each cycle defined as 1/4 tank to full. Using this information along with aircraft historical data specifying average hours of aircraft operations and number of missions per year, it was possible to estimate at which year each component is replaced. PW analysis was then used to calculate the life cycle cost associated with maintenance of the FC APU:

$$Maintenance_{LCC}(\$) = \sum_{n=4,7,10} FC_{CC} \times pwf_n + \sum_{m=5,9} H2Storage_{CC} \times pwf_m \quad (18)$$

$$pwf_{n(m)} = \left(\frac{1+inflation_{rate}}{1+discount_{rate}}\right)^{n(m)} \quad (19)$$

Where,

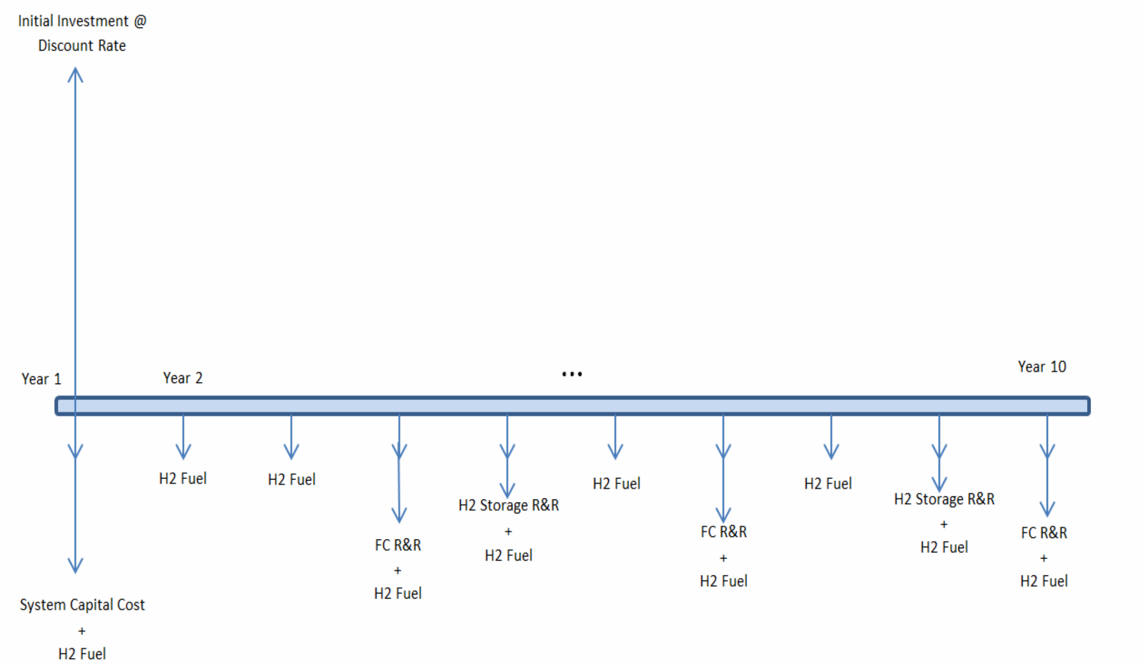
-$n(m)$: The year the component is be R&R’ d.

For example, if a FC is to be removed and replaced after 3 years, then “n” is 3.

-$pwf_{n(m)}$: Present Worth factor for a one-time expense of replacing the component at year n (m).

A cash flow diagram describing all the expenses that are incurred when installing a FC APU, including capital, fuel and maintenance costs is shown in Figure 18.

Figure 18 LCC Cash Flow Diagram



Note the all the cash flows above are incurred at the beginning of the indicated year, with all the downward pointing arrows describing expenses, and a single upward arrow at the onset of the first year representing the initial investment that needs to take place, at a specified discount rate, to pay for all the anticipated expenses.

6.3 Cost of Energy

When performing conceptual studies involving analysis of a new system, it is imperative to exploit the LCC in relation to the main function(s) that the system provides, or what is often referred to as cost effectiveness of the system. For this study, since we are considering a new FC-based APU system where its main function is to provide energy, we chose the metric ($/kWh) to assess the Cost Of Energy (COE), such that,

$$coe\ (\$/kWh) = annual_{LCC}/kwh_{per\_year} \tag{20}$$

$$annual_{LCC}(\$) = \ FC\ APU_{LCC}/cpwf \tag{21}$$

$$kwh_{per\_year}(kWh) = FC_{power\_rating} \times \ aputime_{per\_year} \ \times dc2ac_{efficiency} \tag{22}$$

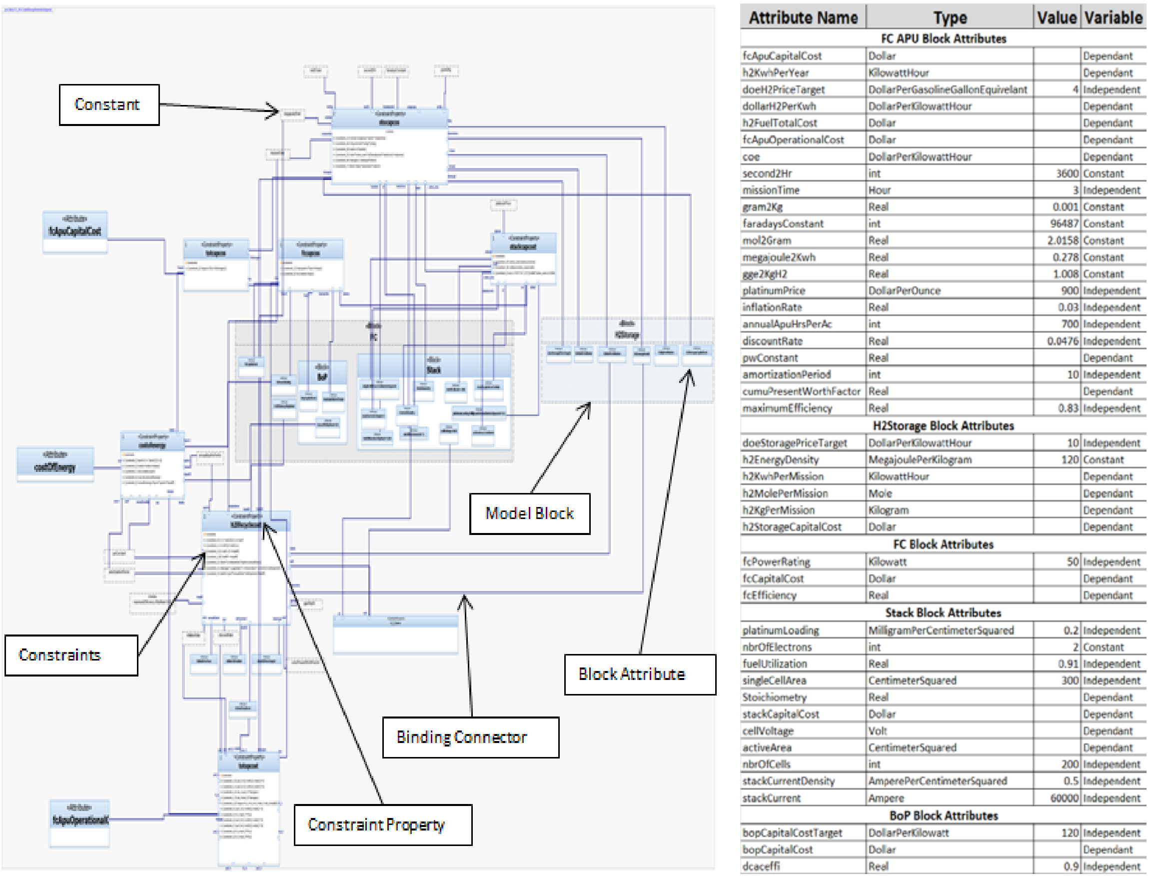
Where,

-$annual_{LCC}$: annualized LCC of the FC APU

-kwh_{per_year}: Projected amount of energy that would be produced by the FC APU per year

-$dc2ac_{efficiency}$: DC to AC inversion efficiency

Figure 19 SysML parametric model

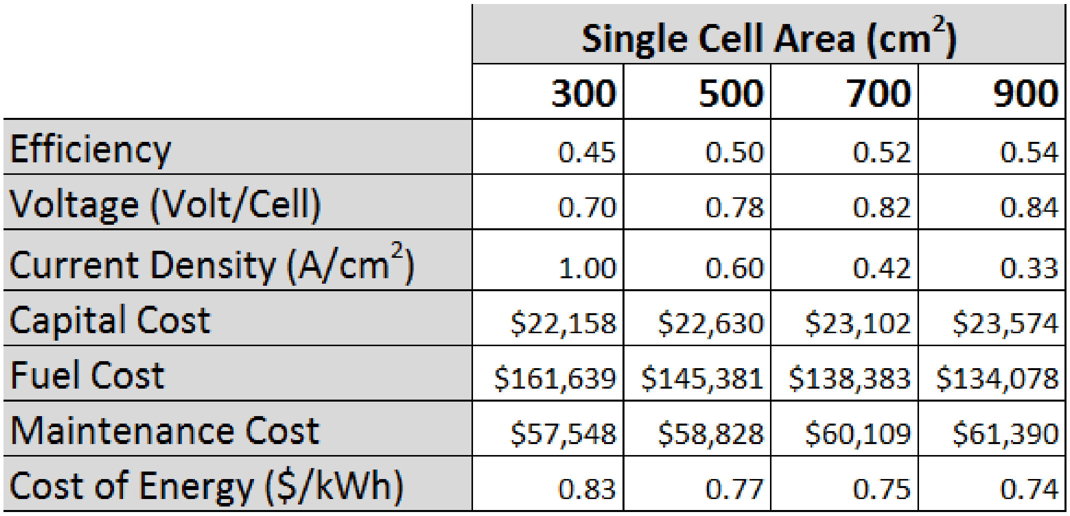


Attribute Name	Type	Value	Variable
FC APU Block Attributes			
fcApuCapitalCost	Dollar		Dependant
h2KwhPerYear	KilowattHour		Dependant
doeH2PriceTarget	DollarPerGasolineGallonEquivelant	4	Independent
dollarH2PerKwh	DollarPerKilowattHour		Dependant
h2FuelTotalCost	Dollar		Dependant
fcApuOperationalCost	Dollar		Dependant
coe	DollarPerKilowattHour		Dependant
second2Hr	int	3600	Constant
missionTime	Hour	3	Independent
gram2Kg	Real	0.001	Constant
faradaysConstant	int	96487	Constant
mol2Gram	Real	2.0158	Constant
megajoule2Kwh	Real	0.278	Constant
gge2KgH2	Real	1.008	Constant
platinumPrice	DollarPerOunce	900	Independent
inflationRate	Real	0.03	Independent
annualApuHrsPerAc	int	700	Independent
discountRate	Real	0.0476	Independent
pwConstant	Real		Dependant
amortizationPeriod	int	10	Independent
cumuPresentWorthFactor	Real		Dependant
maximumEfficiency	Real	0.83	Independent
H2Storage Block Attributes			
doeStoragePriceTarget	DollarPerKilowattHour	10	Independent
h2EnergyDensity	MegajoulePerKilogram	120	Constant
h2KwhPerMission	KilowattHour		Dependant
h2MolePerMission	Mole		Dependant
h2KgPerMission	Kilogram		Dependant
h2StorageCapitalCost	Dollar		Dependant
FC Block Attributes			
fcPowerRating	Kilowatt	50	Independent
fcCapitalCost	Dollar		Dependant
fcEfficiency	Real		Dependant
Stack Block Attributes			
platinumLoading	MilligramPerCentimeterSquared	0.2	Independent
nbrOfElectrons	int	2	Constant
fuelUtilization	Real	0.91	Independent
singleCellArea	CentimeterSquared	300	Independent
Stoichiometry	Real		Dependant
stackCapitalCost	Dollar		Dependant
cellVoltage	Volt		Dependant
activeArea	CentimeterSquared		Dependant
nbrOfCells	int	200	Independent
stackCurrentDensity	AmperePerCentimeterSquared	0.5	Independent
stackCurrent	Ampere	60000	Independent
BoP Block Attributes			
bopCapitalCostTarget	DollarPerKilowatt	120	Independent
bopCapitalCost	Dollar		Dependant
dcaceffi	Real	0.9	Independent

A snapshot of the entire parametric model along with a summary of all the variables that were used is captured in Figure 19. The diagram is only shown here to illustrate to the reader the main elements that make up the parametric model. As mentioned earlier, the purpose of a SysML parametric diagram is to graphically depict the binding of block attributes with constraint properties to facilitate analysis of system performance, cost and physical properties. The diagram shows various model blocks including Stack, BoP and H2Storage. It also graphically depicts model attributes nested within their respective owning blocks, and then bounded using SysML "Binding Connecter" to constraint properties, having a number of mathematical constraints.

The parametric model was used to conduct sensitivity analysis to demonstrate the effect of the area of a single cell inside the stack on the FC APU cost, as shown in Table 4.

Table 4 Parametric Model Results



	Single Cell Area (cm^2)			
	300	**500**	**700**	**900**
Efficiency	0.45	0.50	0.52	0.54
Voltage (Volt/Cell)	0.70	0.78	0.82	0.84
Current Density (A/cm^2)	1.00	0.60	0.42	0.33
Capital Cost	$22,158	$22,630	$23,102	$23,574
Fuel Cost	$161,639	$145,381	$138,383	$134,078
Maintenance Cost	$57,548	$58,828	$60,109	$61,390
Cost of Energy ($/kWh)	0.83	0.77	0.75	0.74

The analysis revealed that variations in the area of a single cell inside the stack do have propagating effects on various aspects of the FC APU system including efficiency, output voltage, capital and operational costs. Note that the fuel and maintenance costs reflect the dollar amount that needs to be invested at a discount rate of 4.76% as specified in the model, at the beginning of the first year, to pay for all the operational expenses that we projected for the next 10 years.

Furthermore, the table shows that the area of a single cell is directly proportional to the capital and maintenance cost of the system; whereas, it is inversely related to the total fuel cost. Therefore, when considering FCs as energy sources, one of the central points that future trade studies should address is to select a suitable operating point for the FC, in terms of current density and cell voltage, that yields a compromise between low fuel consumption cost (high cell efficiency that occurs at high voltage/low current density) and low capital cost (less cell area that occurs at low voltage/high current density).

CHAPTER 7

CONCLUSION

The paper demonstrated a MBSE methodology to conduct a first analysis, architectural study of a PEMFC when used as an auxiliary electrical power source on a helicopter, to replace traditional gas turbine APUs. The study used the graphical modeling language SysML to build a descriptive model of the legacy APU architecture, including its operational context, functional architecture and its interfaces. Based on the gas turbine APU graphical model, a new FC APU model was also created, highlighting the main differences from a functional standpoint between the FC and the gas turbine. Next, a Simulink analytical model was adapted and modified from previous studies that were done on commercial fixed-wing jets, to assess the combined effect of PEMFC weight and fuel efficiency on overall helicopter fuel consumption. Lastly, a cost parametric evaluation was done to demonstrate the sensitivity of the LCC of a PEMFC to variations in its design and performance parameters.

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