AIAA AVIATION Forum
June 25-29, 2018, Atlanta, Georgia
2018 Aviation Technology, Integration, and Operations Conference

10.2514/6.2018-3361

Employing Model-Based Systems Engineering (MBSE) on a NASA Aeronautics Research Project: A Case Study

Kerry M. Gough[1] and Nipa Phojanamongkolkij [2]
NASA Langley Research Center, Hampton, Virginia 23681

Within NASA spaceflight projects, Model Based Systems Engineering (MBSE) is steadily gaining popularity as an alternative to the traditional, document-centric Systems Engineering process. However, MBSE has thus far been applied to relatively few NASA aeronautic research projects, perhaps due to their typically more flexible processes requiring significantly less formal documentation. The project manager for the Fostering Ultra-Efficient, Low-Emitting Aviation Power (FUELEAP) project at NASA Langley Research Center (LaRC) recognized at the start of the project life cycle that there were numerous potential benefits in using MBSE to document the project and improve and standardize communication between project stakeholders. Thus FUELEAP, a small aircraft technology demonstration project led by the Convergent Aeronautics Solutions (CAS) Project at LaRC, included Systems Engineering (SE) as a top-level project team from the beginning. The FUELEAP SE team modeled all major aspects of the project, including Functional and Physical Architecture, Flight Safety, and Requirements Traceability. This paper documents the implementation of MBSE concepts in support of FUELEAP, their benefits, and lessons learned that can be applied to the use of MBSE in support of future aeronautics projects.

Nomenclature

ARMD	=	Aeronautics Research Mission Directorate
CAS	=	Convergent Aeronautics Solutions
CRR	=	Concept Requirements Review
FHA	=	Functional Hazards Assessment
FMEA	=	Failure Modes and Effects Analysis
FTA	=	Fault Tree Analysis
FUELEAP	=	Fostering Ultra-Efficient Low-Emitting Aviation Power
FY	=	Fiscal Year
KPP	=	Key Performance Parameters
LaRC	=	Langley Research Center
MBSE	=	Model-Based Systems Engineering
NGO	=	Need, Goals, and Objectives
NPR	=	NASA Procedural Requirements
PI	=	Project Investigator
SE	=	Systems Engineering
SOFC	=	Solid Oxide Fuel Cell
SRR	=	Systems Requirements Review
SysML	=	Systems Modeling Language
TACP	=	Transformative Aeronautics Concepts Program

[1] Systems Engineer, Systems Engineering & Engineering Methods Branch, MS 290
[2] Operations Research Analyst, Systems Engineering & Engineering Methods Branch, MS 290

I. Introduction

NASA has a long history of creativity and innovation in a large number of areas of study, influencing numerous disciplines within the fields of science, mathematics, technology, and engineering. This includes SE, a relatively new discipline that has been the focus of a significant amount of research within the agency and has become a major component of NASA projects. In particular, NASA researchers have investigated numerous potential applications for MBSE, such as Reliability and Maintenance activities [1], Mission Assurance [2], and Interface Management [3]. MBSE has also been heavily utilized in the development of several major NASA projects, including the Space Communications Network [4], the NASA Europa Project [5], and Space Suit Development [6], to name just a few.

In addition to spaceflight applications, of course, NASA is also responsible for performing extensive research in aeronautics. However, there appears to be little if any research in the application of SE to these projects. There are numerous possible reasons for the lack of exploration into applying SE to aeronautics applications, but most likely it is a combination of several factors, including the fact that NASA aeronautics research has historically required a much smaller amount of formal documentation than spaceflight projects. But as SE, and particularly MBSE, continues to increase in acceptance and importance within the agency [7], MBSE is becoming a vital part of all NASA projects, whether they are spacecraft- or aircraft-focused.

Additionally, SE has often been added to projects only once they were well into the overall project life cycle, making it difficult for the systems engineer to effectively apply SE concepts to an already-established process. Fortunately, that trend seems to be changing. As SE has become a more integral part of the NASA project development process, systems engineers are increasingly being included in the project team at the earliest stages. In late 2016, the PI of the FUELEAP sub-project recognized the potential benefits of employing MBSE as early as possible, and therefore chose to include the Systems Engineering Team as a top-level project sub-team from the very beginning.

The FUELEAP sub-project, led at NASA LaRC, is a planned two-year effort within the CAS Project under the NASA Aeronautics TACP. TACP is a part of the agency ARMD, whose mission is to cultivate new concepts and capabilities that can lead to innovative design concepts and breakthrough technologies that will transform the aviation industry. FUELEAP is investigating the need for near-term, widespread use of new airborne propulsion technologies that can offer compelling improvements in emissions, efficiency, and performance without requiring major industry investment in infrastructure, certification, or energy storage. The project has chosen to specifically target a heavy-fuel SOFC as a potential solution to this need, due to its outstanding on-board efficiency and the fact that it leverages much of the existing industry infrastructure. The feasibility assessment for this work will be performed through three major activities: (1) safety-focused design and analysis of the integrated SOFC-powered aircraft; (2) development of a heavy-fuel hybrid-electric SOFC power system architecture; and (3) system and component testing for technology advancement including environmental and lifecycle economics impacts.

Potential benefits of early inclusion of MBSE identified for the FUELEAP project included clearer identification of the project NGOs, improved communication through the use of formal system models, better preparation for project life-cycle reviews, and easier identification of the interdependencies between project elements (i.e., the relationship of requirements to physical aircraft subsystems, the interfaces between subsystems, etc.).

This paper is organized in the following manner: Section 1 is the introduction and includes background information about the topic. Section 2 explains the recent history of the rise in MBSE research at NASA Langley Research Center. Section 3 describes the NGOs that were identified by the authors for the task of implementing MBSE concepts in support of project development. Section 4 discusses the various activities that were performed during the FUELEAP project in response to those Implementation NGOs for a generic project. Section 5 details the MBSE activities that specifically supported the FUELEAP project. Section 6 briefly describes the future work planned to be performed in support of this research, and Section 7 is a brief set of concluding observations.

II. NASA Langley's Investment in MBSE

During Fiscal year 2017, the Engineering Directorate at NASA LaRC kicked off a number of new initiatives aimed at various technologies and capabilities. One of these initiatives focused on the MBSE capability at the research center. MBSE is defined as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." [8]. It is not just a tool to be installed and run, but instead is a methodology that needs to be fully understood and rigorously developed in order that it can be successfully applied to the project development process.

The MBSE methodology offers several advantages over more traditional engineering approaches, including:

- Creating a common foundation for knowledge sharing, communication, and collaboration. By forming this foundation, MBSE helps to foster a corporate infrastructure wherein information can more easily be communicated within and between projects and organizations. This, in turn, can allow for less ambiguity in interactions between different groups and reduce the risk of misunderstandings and misinformation being generated – a familiar occurrence in organizations where individual sub-groups typically employ multiple methodologies.
- Enabling a robust, rigorous, end-to-end analysis capability. This ability helps organizations to generate modern processes that facilitate improvements in programmatic, technical, safety, and security applications, and to standardize those processes across multiple organizational teams.
- Streamlining management processes by facilitating real-time, system-wide situational awareness. By encouraging improvements in communication infrastructure and assisting in the development of a robust analysis capability, the common framework can increase the management team's understanding of current project status and familiarity with key project elements, allowing them to better project the future needs and potential impacts of management options.

NASA LaRC is developing a MBSE capability throughout the center through the use of commercial SysML tools, training classes in SysML and associated software, and a center-wide SysML Users Group. SysML is a versatile modeling language used in SE applications to support the specification, analysis, and design of systems. The preferred tool for the creation and management of SysML diagrams at LaRC is No Magic, Inc.'s MagicDraw, a very powerful SysML modeling tool that has wide use throughout the SE industry. Several MagicDraw capabilities are being used in support of the FUELEAP project, as will be explained below.[3]

III. Need, Goals, and Objectives of Project MBSE Implementation

The Systems Engineering Team identified two distinct sets of NGOs: the project NGOs developed in collaboration with the FUELEAP PI, and an independent set of NGOs that were the focus of the effort to implement MBSE constructs in support of the project. Figure 1 shows the NGOs for the MBSE implementation effort. These MBSE effort NGOs were then further developed into a specific plan of action for the project SE Team to follow while supporting the FUELEAP project.

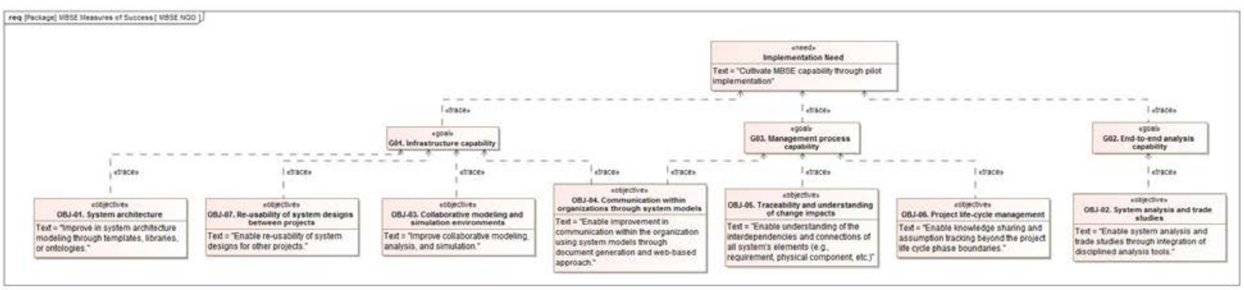


Figure 1: MBSE Implementation Process Need, Goals, and Objectives

The activities chosen for this plan are shown in Table 1 with their corresponding MBSE Implementation Process objectives. The FUELEAP SE Team used this table to keep track of the planned implementation efforts and their current progress. The color coding shown is an example of the ongoing use of the table as a team self-assessment tool at the time of this writing. Items highlighted in green are those where the SE Team feels it has made good progress, items in yellow are tasks where more effort is still required, and activities with no highlight represent opportunities to be pursued in future steps.

[3] MagicDraw is one of several commercial SE software packages that enable SysML modeling, and no NASA endorsement of a specific product is intended. The FUELEAP SE team chose to use this specific tool due to its existing licensing, familiarity, and support within the LaRC SE community.

MBSE Objectives	Traces to	Planned FUELEAP Activities
OBJ-01: System Architecture. Improve system architecture modeling through the use of templates, libraries, or taxonomy.	**G-01: Infrastructure Capability**	• Create templates, libraries, or taxonomy for system architecture
OBJ-02: System Analysis and Trade Studies. Enable system analysis and trade studies through integration of disciplined analysis tools.	**G-02: End-To-End Analysis Capability**	• Integration to disciplined analysis tools
OBJ-03: Collaborative Modeling and Simulation Environments. Improve collaborative modeling, analysis, and simulation capabilities by implementing tools for concurrent workflow.	**G-01: Infrastructure Capability**	• Use of concurrent modeling through MagicDraw Teamwork Server • Use of integration tools for collaborative analysis
OBJ-04: Communication Within Organizations Through System Models. Use system models to improve inter-organization communication through web-based tools and document generation techniques.	**G-01: Infrastructure Capability,** **G-03: Management Process Capability**	• Automated on-demand document generation capability • Web-based approach to facilitate communications
OBJ-05: Traceability and Understanding of Change Impacts. Enable understanding of the interdependencies and connections of all of a system's elements (e.g., requirements, physical components, etc.)	**G-03: Management Process Capability**	• Traceability between various model elements
OBJ-06: Project Life-Cycle Management. Enable knowledge sharing and assumption tracking beyond the project life cycle phase boundaries.	**G-03: Management Process Capability**	• Model usage from Concept Requirement Review and beyond. • Demonstrate use of models to satisfy entrance and success criteria for gate reviews
OBJ-07: Re-Usability of System Designs Between Projects. Increased reusability of system designs for other projects.	**G-01: Infrastructure Capability**	• Develop reusable templates, libraries, or taxonomy for use by other projects

Table 1: MBSE Activity Plan (color coding example)

IV. MBSE Implementation Activities for Project MBSE Implementation

As the project progressed, the MBSE Implementation team was able to implement many of the planned activities shown in Table 1. The following sections describe how these activities were put into action and explain how they affected the overall SE effort.

A. Concurrent SysML Modeling and Communication of Project Details

The NASA LaRC MBSE user community has an existing TeamWork server which allows multiple users to access and modify a single SysML model simultaneously. The project SE Team employed this server to enable team members to use MagicDraw to view the project SysML model without concern over accidentally making unintended modifications, and to permit modelers to "lock" only those section of the model which they were currently updating. Users could then focus on those areas where they needed to work and update the model, while also having the capability to examine the current state of other model diagrams that were being developed by other team members.

In addition, SysML diagrams serve as excellent visual representations of a system, which can be used to help communicate project concepts to both team members and outside shareholders. By including these diagrams in presentations and project documentation, modelers can better illustrate the relationships between system components, such as showing the planned physical interfaces between components, or enabling easier traceability from the high-levels NGOs to the individual requirements. When project SysML diagrams are organized in a hierarchical fashion, select diagrams can easily be used to demonstrate project information at either higher or lower levels of detail, depending on the intended audience for the data being explained.

In this way, a project's SysML models serve a dual purpose as both a definition of the system of interest and a drawing tool for project concepts. This can significantly reduce the need for separate figures to be developed in other software packages, saving time and money for the parent organization.

B. MBSE-Based Project Development

The project SE team focused on the use of MBSE concepts as a way to improve project management through the use of process automation and web-based communications. One critical process for NASA LaRC projects is planning and preparing for major project reviews, a complex, time-consuming effort that requires many elements to be completed properly.

One of the first tasks that needs to be done for any NASA project is identifying the project's Risk Classification. This is a key factor in defining which milestone reviews must be held for a project, and knowing the proper content of those reviews. The Risk Classification also drives the selection of artifacts required for reviews and the level of detail necessary for them. Figure 2 shows the SysML activity diagram that illustrates the process developed by the SE Team to streamline these tasks.

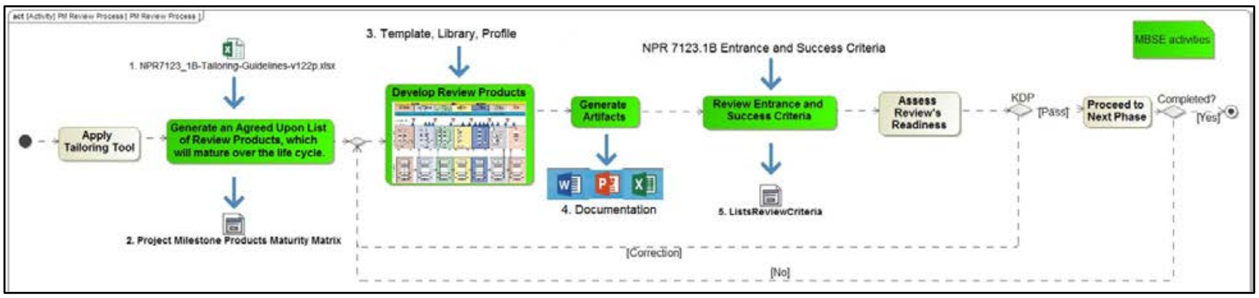


Figure 2: Risk Classification and Milestone Review Planning Process

As shown in Figure 2, the process begins by using a LaRC-developed tailoring tool [9] to determine the project's risk classification. The tailoring tool is an Excel-based application based on the standards set forth in NPR 7120.5 for Project Management [10] and NPR 7123.1 for Systems Engineering [11]. It prompts a project SE to identify a series of initial parameters that characterize the project's scope, budget, and other key features. Using these parameters, the tool identifies the project's recommended risk classification and provides a list of recommended and required project management products to be generated by the project team (i.e., Program/Project Plans, Cost Estimate, Schedule, System Requirements Document, etc.), as well as project reviews to be held. The SE can then use these recommendations to work with the project management team to reach consensus on the most appropriate plan for the project.

The figure shows the use of the tailoring tool (item #1) to generate the list of review products (item #2) which will continue to mature throughout the project life cycle. The template and library objects in item #3 are used to document the systems architecture and develop and link the system requirements. The templates are used to generate project documents (item #4) such as the project Requirements Document and the Compliance Matrix Checklist, as well as PowerPoint charts to be used for presentations. Item #5 is a list of entrance and success criteria for all planned project reviews, based on the outputs from the Tailoring Tool and the procedural requirements in NPR 7120.5 and NPR 7123.1. These criteria are used to assess a project's readiness to proceed with the upcoming reviews and to evaluate its level of preparedness for advancement to the next project phase.

The review criteria and products list established in the process shown above are used to construct a table showing the planned products required for each phase of the project, which can be updated as required to indicate the status of those products. Such a table, referred to as a Milestone Products Maturity Matrix, makes an excellent reference to track and update the project's progress toward preparation for each project phase and milestone review. Below, Figure 3 shows a partial example of a Milestone Products Maturity Matrix as it would be used by a project. (The full Milestone Products Maturity Matrix for a project would be much larger than shown here, with the length dependent on the Risk Classification level for the project and other factors determined in the early project planning phases.) Note the use of color coding, similar to that used in the MBSE Activity Plan shown in Table 1 above, which is updated as products for reviews are being developed and completed.

COMPLETED ONGOING [illegible]

Management Requirements (Taken from NPR 7120.5E Tables I-4 & I-5, NASA Space Flight Program and Project)		Type F	Milestone Products Maturity Matrix (Taken from NPR 7120.5E Tables I-4 and I-5, I-6)									
			Pre-Phase A	Phase A		Phase B	Phase C		Phase D		Phase E	Phase F
			KDP A	KDP B		KDP C	KDP D		KDP E		KDP F	
			MCR	SRR	SDR/MDR	PDR	CDR	SIR	ORR	MRR/FRR	DR	DRR
Table I-4 Headquarters and Program Products	1. FAD	Tailor	Baseline									
	2. Program Plan	Tailor	Baseline									
	2.a. Applicable Agency strategic goals	Tailor	Baseline	Update	Update							
	2.b. Documentation of program-level requirements and constraints on the project (from the Program Plan) and stakeholder expectations, including mission objectives/goals and mission success criteria	Tailor	Preliminary	Baseline	Update	Update						
	2.c. Documentation of driving mission, technical, and programmatic ground rules and assumptions	Tailor	Preliminary	Preliminary	Baseline	Update	Update	Update				
	3.Partnerships and inter-agency and international agreements	Fully Compliant	Preliminary	Update	Baseline U.S. partnerships and agreements	Baseline international agreements						
	5. NEPA compliance documentation	Fully Compliant				Final documentation per NPR 8580.1						
	6. Mishap Preparedness and Contingency Plan	Tailor				Preliminary		Update		Baseline (SMSR)	Update	Update
	1. Concept Documentation	Tailor	Approve	Update	Update	Update						

Figure 3: Sample Milestone Products Maturity Matrix (Partial)

The use of figures and matrices such as those shown in Figure 2 and Figure 3 serve as helpful tools and indicators for all project team members, not just the PI and SE teams. By using these tools in a project website, the information and status shown in them is easily accessible for all team members, and can be quickly updated as required with minimal effort. Key SysML diagrams can be posted to illustrate project status and upcoming tasks, and the outputs from the processes illustrated can be posted for download. By using this approach, team members can be notified when updated versions of project documents, drawings, and reports have been posted, alleviating the nuisance problem of having multiple copies of files emailed to multiple users.

C. Document Generation from a SysML Model

Documentation is, of course, a vital part of any project, but developing and maintaining project documents is often extremely tedious and time-consuming. In order to improve this process, the SE team created templates for the creation of Microsoft Word and PowerPoint files that could be used with MagicDraw to generate documents automatically using the content of the project SysML model. The text-based templates were created to be used by a report generation tool within MagicDraw called Report Wizard, which is the report engine using the Velocity Template Language to populate model's elements into a user-defined word template [12]. The SE must initially create the template in the desired Microsoft Office application, using both standard text formatting and the model's element variables as defined in Systems Modeling Language Standard [13], [14]. The completed templates can then be executed by Report Wizard engine, which will extract the most recent values and data from the specified model's elements and generate the desired output file.

Once generated, these templates can be revised in response to major changes in the model, or even to meet the needs of other projects. In particular, for documents that are routinely created for most or all projects, reusing an existing template allows the developers to focus on the primary content being explained, while allowing the template to insert much of the standard "boiler plate" information. Additionally, the Report Wizard can be easily re-run any time the model is modified, drastically reducing the amount of effort required to update documentation. Completed documents can then be added to a project website devoted to storing and sharing information and documentation among team members.

Figure 4 below is a graphic representation of the document generation process used by the project.

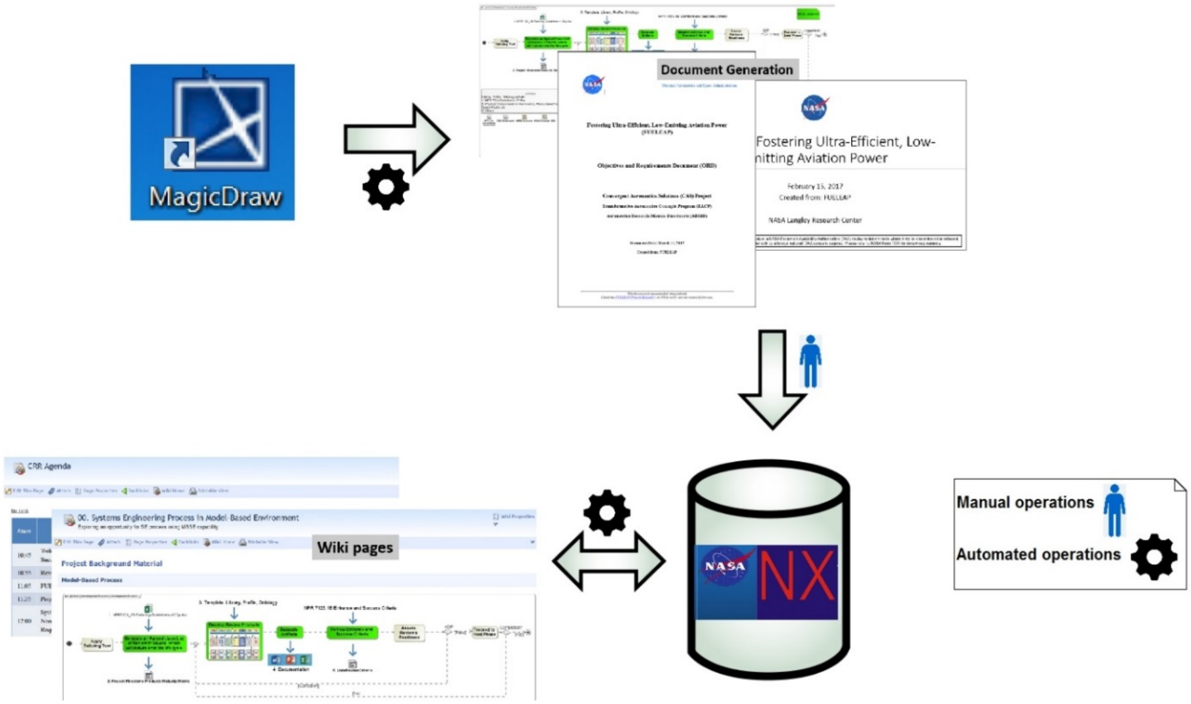


Figure 4: Automated Document Generation Process

As shown in the figure, project documents are generated from the SysML model content using previously-built templates and the Report Wizard capability within MagicDraw. These documents are then manually uploaded to NX, an online documentation repository at LaRC. Finally, the documents are made accessible through a wiki page built within NX that grants access to all project team members.

V. FUELEAP MBSE Development

As previously stated, the FUELEAP project included the SE Team from the very beginning, which was atypical for an aeronautic research project was atypical for NASA LaRC. Working with the PI, the project SE Team began creating a new FUELEAP SysML model on the LaRC TeamWork server using MagicDraw, allowing the PI and other project team members to access the model and assess its content. At the same time, the SE Team also began to define and develop the SE processes to be employed in support of the FUELEAP project.

A. FUELEAP Requirements Development and Modeling

The FUELEAP SE Team began by identifying and modeling the project NGOs and requirements, and developing the traceability to both their source and their child requirements. In order to fully understand the requirements of the FUELEAP project, the SE Team began by examining the NASA parent stakeholder organizations for the project and modeling the NGOs of each of them. This allowed the SE Team to trace the project's plans to the goals and objectives of the parent organizations (in the nomenclature of the ARMD and TACP programs, these are referred to as Thrusts). Figure 5 and Figure 6 show the SysML requirements diagrams created to model these organizations' main focus areas. These diagrams helped the SE Team better understand the overall purpose and focus behind the FUELEAP project, and were extremely useful when it came time to capture and model the project requirements.

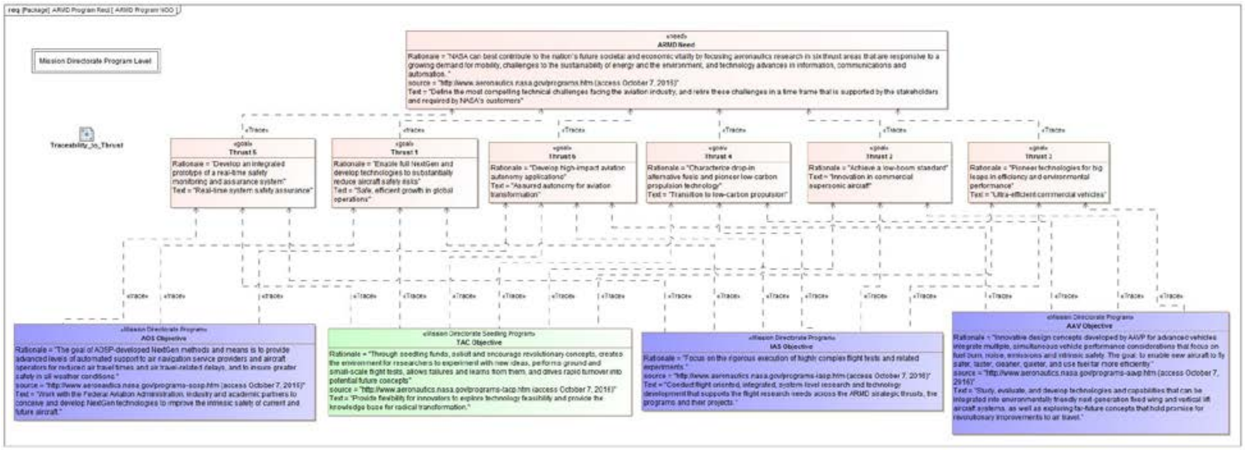


Figure 5: ARMD Organizational NGOs

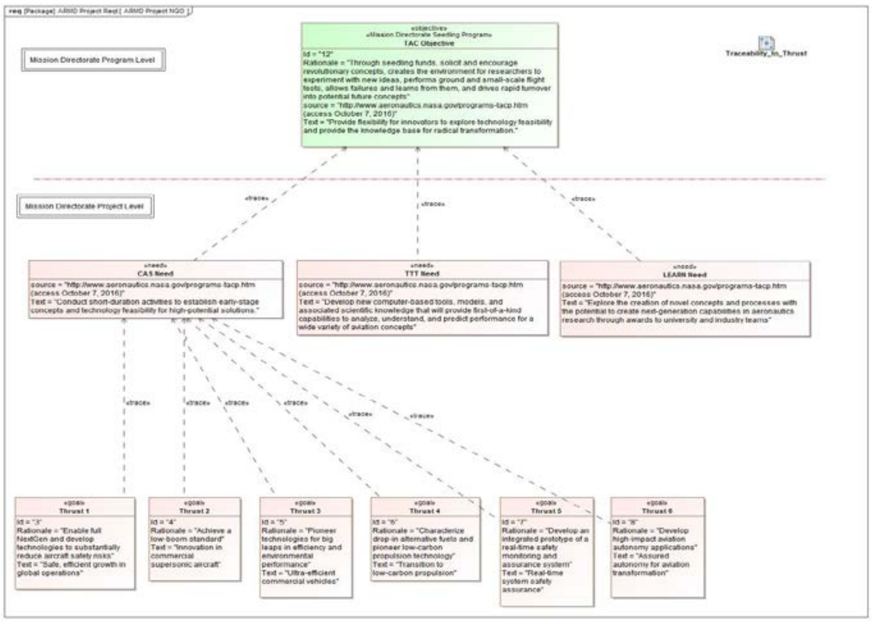


Figure 6: TACP Program NGOs

The team began the process of developing FUELEAP requirements by interviewing the project PI and sub-team leads to gain more insight into their individual project and team requirements. The PI worked with the SE Team to identify the project NGOs, and interviews with the PI and sub-team leads allowed the SE Team to decompose the objectives into high-level project requirements. These were initially captured in a MS Excel spreadsheet to allow for easier modification, while the requirements definition process was still being defined, and the requirements were then imported into the SysML model from the spreadsheet file. The project requirements were decomposed to the sub-team level, in order to better define the different tasks that would be required for the project and assign the ownership of each to the appropriate sub-team. The SysML model of the FUELEAP NGOs and requirements is shown in Figure 7.

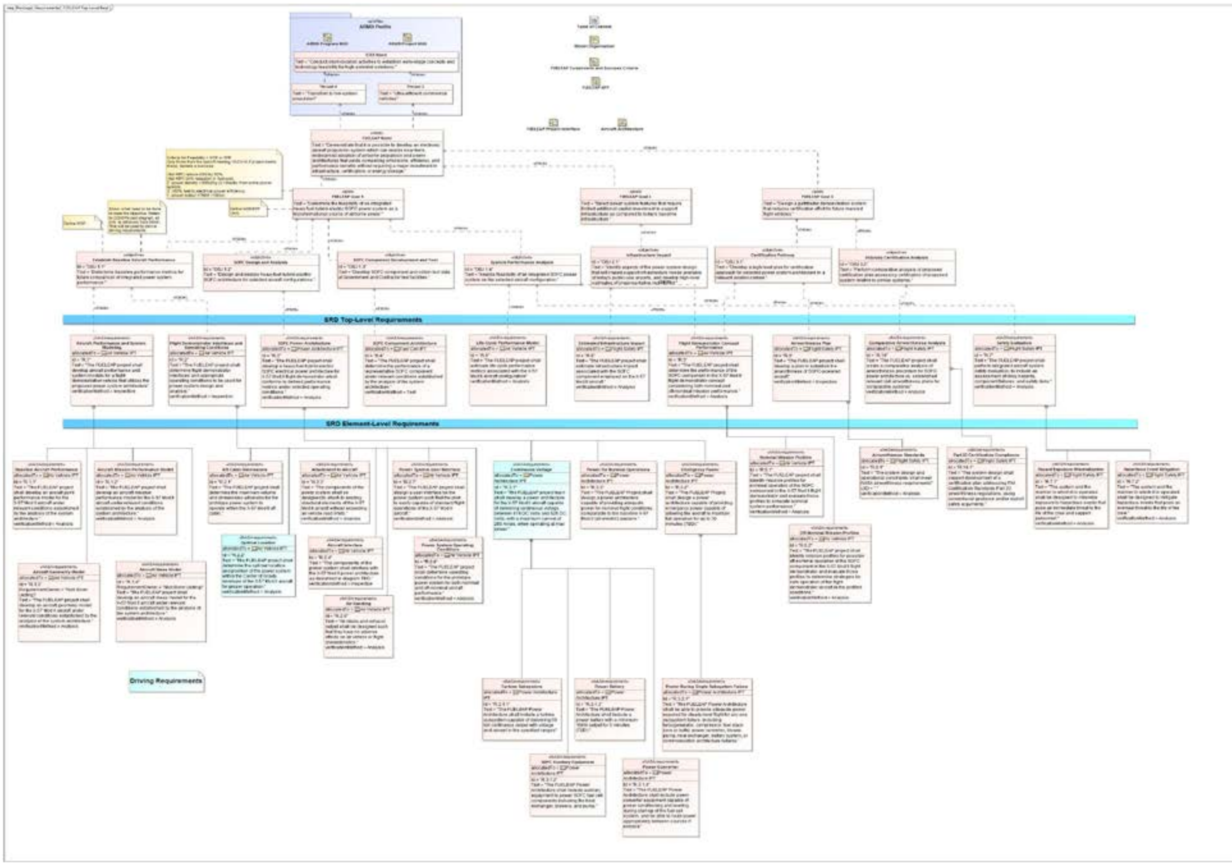


Figure 7: SysML Requirement Diagrams of FUELEAP NGOs and System Requirements

As the SE Team worked with the FUELEAP project to develop the list of project NGOs and requirements, a concurrent task was the identification of the project KPPs. The KPPs were derived from the initial conceptual constraints that helped drive the project from its inception, and were defined by the PI early in the project. They also helped the SE Team and the PI define the top-level project requirements. The SysML model for the KPPs is shown in Figure 8.

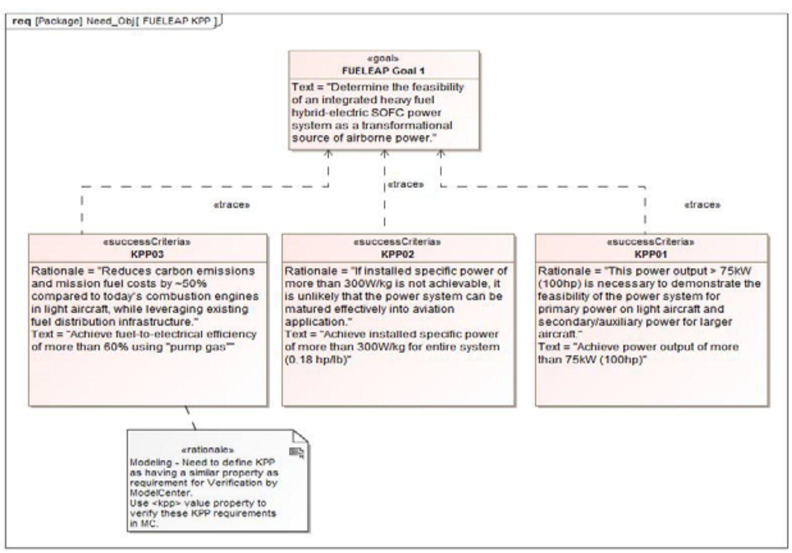


Figure 8: Requirements Diagram of FUELEAP KPPs

B. Modeling the FUELEAP Project in SysML

As the SE Team was beginning to gain a firm understanding of the FUELEAP requirements, they also chose to model many key elements of the physical target architecture and its operating environment. This served multiple purposes. First, of course, was the aforementioned development of conceptual illustrations of the system for use in communication of project concepts. In addition, by using SysML to define these elements and the interactions and relationships between them, any changes that needed to be made in any SysML diagrams or item definitions would automatically be reflected in other areas of the model that are directly affected. For instance, if the definition for a particular element type, such as a motor or switch, needed to be changed to include a new interface, then all of the model elements of that type anywhere in the model would immediately include that new interface.

The SE Team modeled numerous aspects of the project, including the major subsystems of the planned host aircraft to be used with the prototype fuel cell, as shown in Figure 9 below. The model also allowed the SE Team to focus on the interfaces between the planned power system and the host aircraft's avionics system. Figure 10 shows an internal block diagram of the interfaces between the FUELEAP power system and the host aircraft's cockpit interface and propulsor systems.

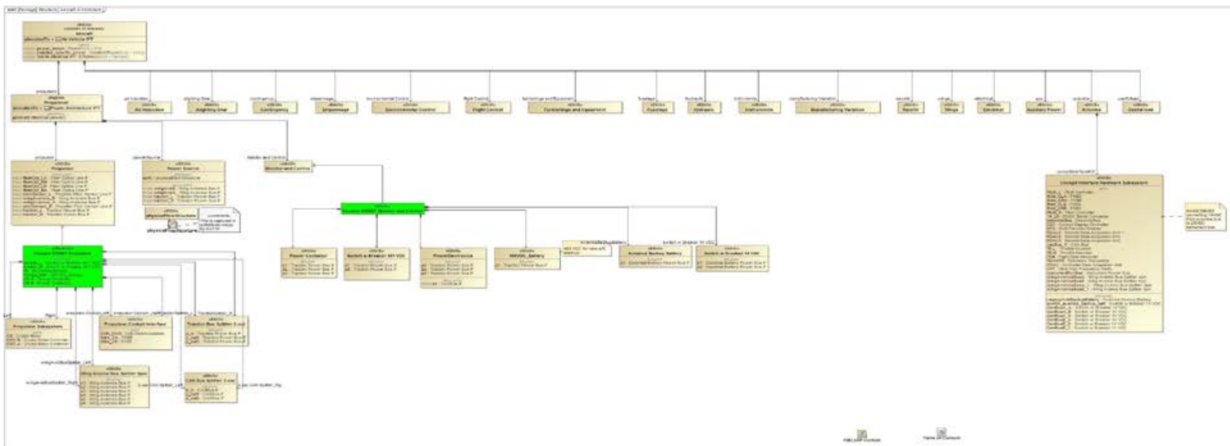


Figure 9: Host Aircraft Architecture

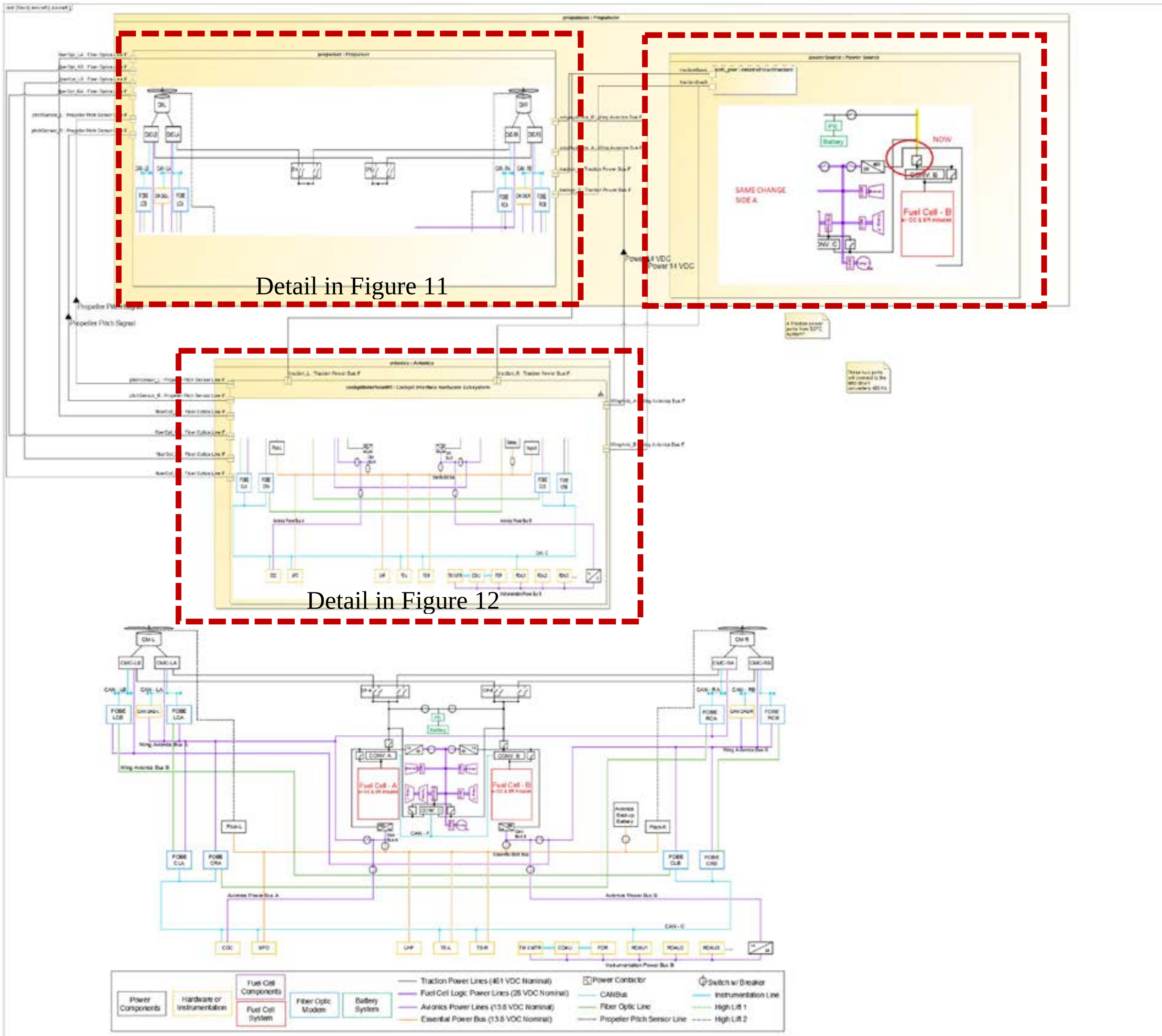


Figure 10: FUELEAP Interfaces to Host Aircraft Propulsion and Avionics

The SE Team created models of electrical flows (power, communication command, optical signal, and propeller pitch sensor) for the propulsor system (top-left dashlined box in Figure 10) as seen in Figure 11, and similarly for the cockpit interface system (bottom dashlined box), shown in Figure 12. The top-right box represents an interface (electrical flow) to the Solid Oxide Fuel Cell system, which is presented in another companion paper of this session [15].

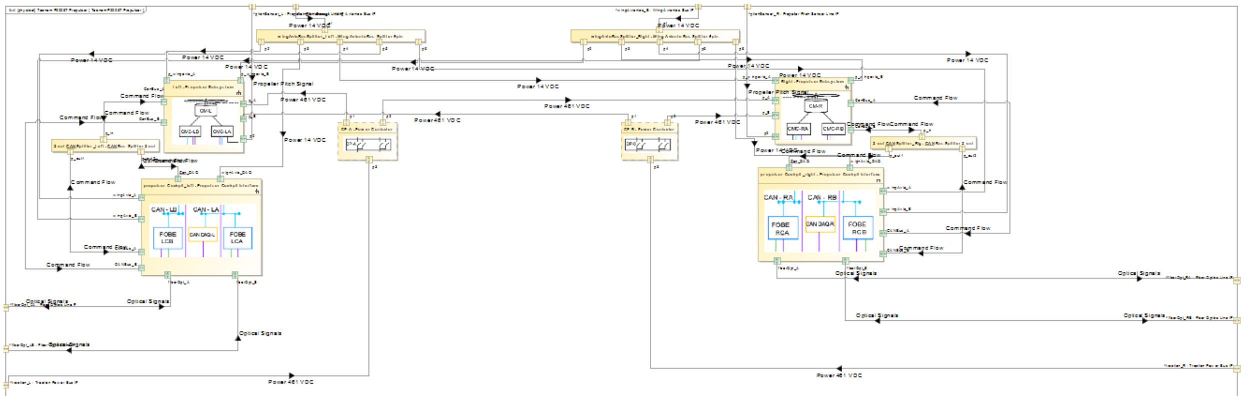


Figure 11: FUELEAP Electrical Flows for Propulsor System

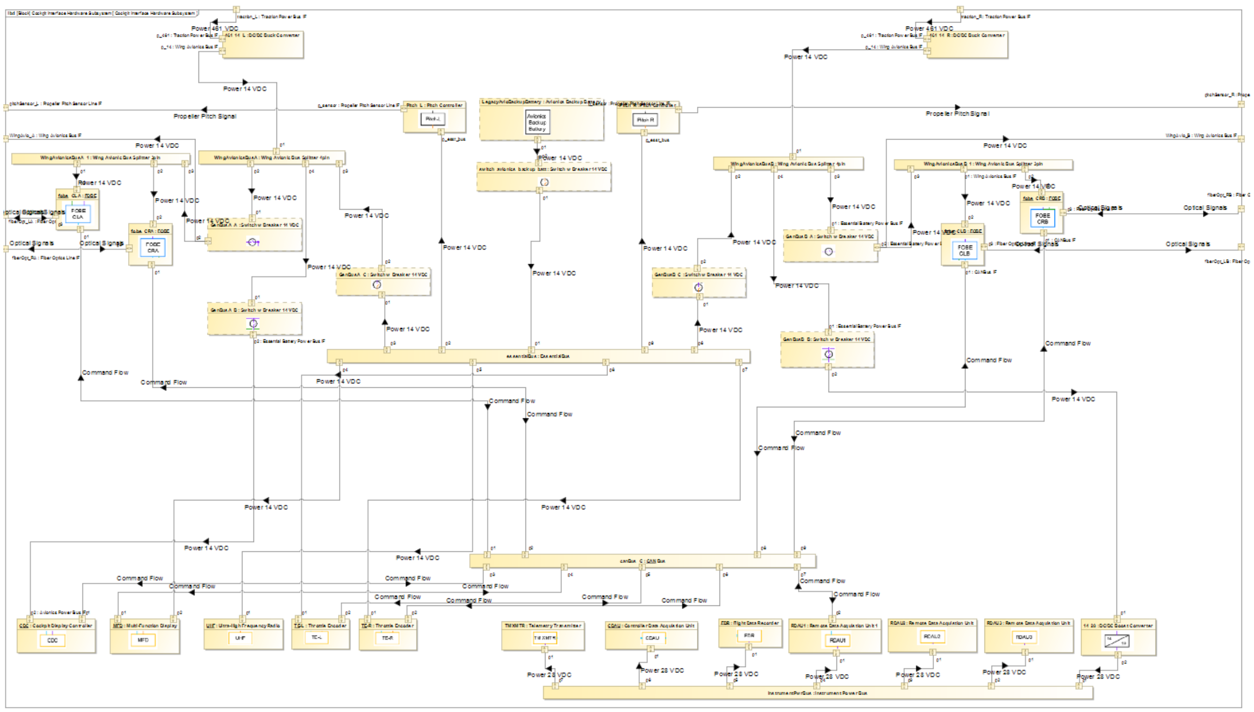


Figure 12: FUELEAP Electrical Flows for Cockpit Interface System

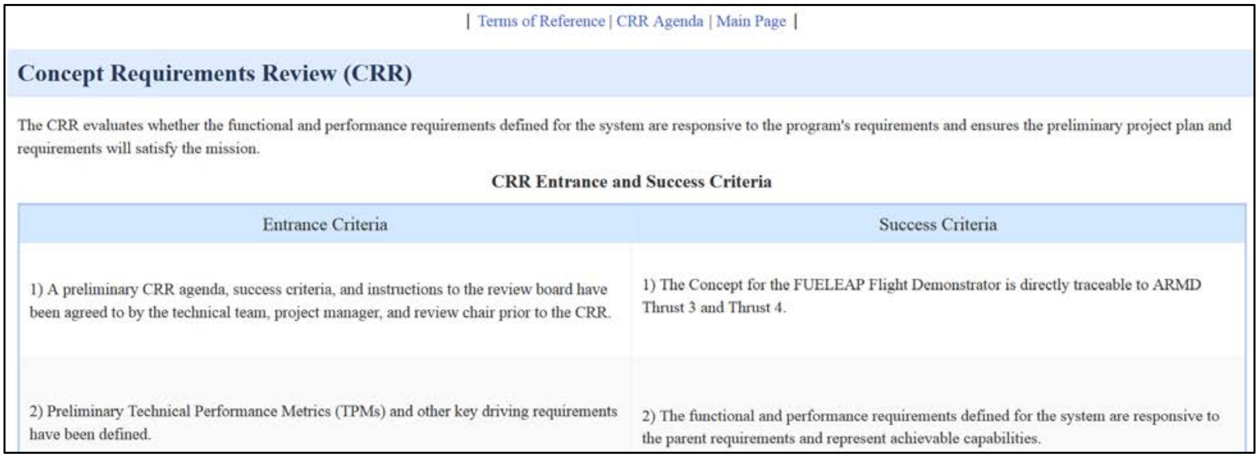
By creating models of key elements of the aircraft and the power system, the SE Team was able to capture many of their most important characteristics in a graphic format that is not only useful for communication to both team members and outside stakeholders, but also contains logic and information to describe the interactions between systems. Through the use of SysML and MagicDraw, the SE Team has been able to model numerous logical and physical characteristics of the FUELEAP project and to use the common system modeling language throughout and across multi-disciplinary teams. The examples listed here are a small subset of the total number of project elements included in the full model.

C. FUELEAP Concept Requirements Review Planning

As the FUELEAP requirements and KPPs were being captured and modeled, the SE Team also worked to develop MBSE-based processes that would benefit the project. They chose to focus specifically on the development of the processes for identifying the project's Risk Classification and planning the required tasks to prepare for a milestone review, which resulted in the procedure shown above in Figure 2.

During the third quarter of FY17, the FUELEAP project discussed plans to hold a SRR. In the traditional NASA project life cycle for spaceflight projects, the SRR serves as a milestone to verify that a project's system requirements are sufficiently well defined to meet the project's needs, and that the project is therefore ready to proceed to the system design phase. In the case of FUELEAP, the project requirements were more conceptual, and defined at a project level rather than a system level. Therefore, the decision was made to instead hold a project CRR, which would be similar in many ways to the SRR. The purpose of the CRR would be to verify that the overall project concept was complete and ready to proceed toward defining system requirements and a system design.

As described in Section IV.B above, the FUELEAP SE team tailored the SRR entrance and exit criteria to meet the project's need for a CRR, and worked with the PI to plan and convene the review. A sample of the CRR entrance criteria and success criteria that were developed through this process is shown in Figure 13.



| Terms of Reference | CRR Agenda | Main Page |

Concept Requirements Review (CRR)

The CRR evaluates whether the functional and performance requirements defined for the system are responsive to the program's requirements and ensures the preliminary project plan and requirements will satisfy the mission.

CRR Entrance and Success Criteria

Entrance Criteria	Success Criteria
1) A preliminary CRR agenda, success criteria, and instructions to the review board have been agreed to by the technical team, project manager, and review chair prior to the CRR.	1) The Concept for the FUELEAP Flight Demonstrator is directly traceable to ARMD Thrust 3 and Thrust 4.
2) Preliminary Technical Performance Metrics (TPMs) and other key driving requirements have been defined.	2) The functional and performance requirements defined for the system are responsive to the parent requirements and represent achievable capabilities.

Figure 13: Sample of CRR Entrance and Success Criteria for the project

The FUELEAP PI relied heavily upon the outputs of the MBSE process during the planning and execution of the review. The project also presented its progress status to the CAS management team and it was well received. In particular, the CAS management team applauded the FUELEAP project for taking the initiative to pilot the use of a model-based methodology to an aeronautics project. The FUELEAP team has been asked to document best practices and lessons learned on this piloting activity. This effort is ongoing. Observed benefits for the project currently include enhanced communications related to NPR compliance to both the project's team members and stakeholders; automated systems requirement document generation; and reusable processes and templates that can be employed both in the next FUELEAP lifecycle phases and potentially in other NASA projects.

Follow-on efforts after the completion of the CRR have included refinement of project requirements to a greater level of fidelity, further development of the FUELEAP SysML model to include the updated requirements and re-generation of the project requirements document, and initial investigation into the creation of interfaces to other FUELEAP sub-team SysML models, as shown in Section V.B .

VI. Plan for next steps to meet objectives

Although much work has been done in support of FUELEAP to meet both the project's objectives and the more general objectives for MBSE implementation, there are still several planned activities that need to be completed. Currently, there are two fully integrated SysML models for the FUELEAP project. The first is the main model, capturing the NGOs, requirement flow-down, programmatic concept of operations and its traceability to the requirements, and the aircraft architecture along with its internal and external interfaces. The second model is that of the SOFC system, capturing the component architecture of the fuel cell and its mechanical and electrical interfaces. These two models can be developed concurrently and independently, provided that they comply with the predefined electrical interfaces. As the SE and System Safety Teams continue to develop both models, several tasks are planned to further develop the project's use of SysML modeling.

A. Next Steps

With the collaboration with all FUELEAP disciplined teams, a number of follow-on analysis activities are projected to be added to the existing models, including:

- System safety analysis, including FMEA and FTA, for the integrated SOFC power system
- Complete aircraft FHA

- Feasibility analysis of the integrated heavy fuel hybrid-electric SOFC power system as a transformational source of airborne power, using research-defined objective performance criteria as threshold values for feasibility

These analyses will require the integration of multi-disciplined analysis tools into the existing process, which will be used in a collaborative analysis environment, and whose parameters and results will be incorporated into the project SysML models. In turn, these efforts are intended to satisfy the planned activities for activities OBJ-02 and OBJ-03 as described in Table 1.

B. Lessons Learned

As earlier noted, the FUELEAP SE Team has been asked to document any lessons learned while applying MBSE techniques to the FUELEAP project, and the impact – both positive and negative – that they had on the overall project outcome. One important lesson that should be noted here is that of the effort required to model project requirements, and the importance of looking ahead to the expected scope of the task from the beginning.

Modelling requirements in SysML can easily become an unwieldy process, especially for projects with large numbers of requirements to model and track. Since spaceflight projects frequently have hundreds (or even thousands) of requirements, modeling every individual requirement in SysML for them can be not only very time-consuming, it can also result in a model which is so large that it ends up being of very little use to the project. However, in the case of aeronautics research projects like FUELEAP, if project requirements are formally captured and tracked, they are usually defined at a much higher level. This results in a much smaller overall number of documented requirements, which make them good candidates for requirement modelling using SysML. It is imperative that the SE Team define very early in the life cycle the level to which requirements will be modeled for any such project.

VII. Conclusion

While the use of Model-Based Systems Engineering concepts at NASA is becoming more and more commonplace, it has thus far been applied almost exclusively to spaceflight-oriented projects. Relatively few NASA aeronautics projects are implementing MBSE by comparison. However, this is beginning to change. The use of MBSE for the FUELEAP project demonstrates that aeronautics projects can also benefit greatly from this technology. Through the use of MBSE and SysML, communication of many key project concepts were clarified for FUELEAP, planning for project reviews was simplified, and templates were created which can easily be updated and reused for future NASA LaRC aeronautics projects. Key project documentation was generated using these templates directly from the project SysML model, and FUELEAP has shown that those documents, and project presentations as well, can be quickly re-generated at any point as the model evolves, allowing for vast improvement in flexibility and responsiveness to change.

As NASA LaRC aeronautics researchers become more familiar with SE, and in particular MBSE, the advantages of employing these techniques and technologies will hopefully encourage future projects to incorporate model-based concepts into their process more routinely. This will allow for more consistency among projects, better communication both within projects and between projects and stakeholders, and greater acceptance of more current development processes.

[1] Izygon, M., Wagner, H., Okon, S., Wang, L., Sargusingh, M., and Evans, J., "Facilitating R&M in Spaceflight Systems with MBSE," *2016 Annual Reliability and Maintainability Symposium (RAMS)*, 2016, pp. 1-6.

[2] Evans, J., Cornford, S., and Feather, M., "Model Based Mission Assurance: NASA's Assurance Future," *2016 Annual Reliability and Maintainability Symposium (RAMS)*, 2016, pp. 1-7.

[3] Vipavetz, K., Shull, T, Infeld, S., and Price, J., "Interface Management for a NASA Flight Project using Model-Based Systems Engineering (MBSE)," *INCOSE International Symposium*, 2016, vol. 26, no. 1, pp. 1129–1144.

[4] Bhasin, K., Barnes, P., and Reinert. J., "Applying Model Based Systems Engineering to NASA's Space Communications Networks," in *Systems Conference (SysCon), 2013 IEEE International*, April 15-18 2013.

[5] Jackson, M., Wilkerson, M., and Castet, J., "Exposing Hidden Parts of the SE Process: MBSE Patterns and Tools for Tracking and Traceability," in *IEEE Aerospace Conference Proceedings, 2016*, Big Sky, Montana, March 5–12 2016.

[6] Cordova, L., Kovich, C., and Sargusingh, M., "An MBSE Approach to Space Suit Development", NASA PM Challenge, 2012.

[7] Weiland, K. and Holladay, J., "NASA Model-Based Systems Engineering Pathfinder 2016 Summary and Path Forward." 2017 Annual INCOSE International Workshop, Los Angeles, CA, January 28-31, 2017.
[8] INCOSE Technical Operations. 2007. *Systems Engineering Vision 2020*, version 2.03. Seattle, WA: International Council on Systems Engineering, Seattle, WA, INCOSE-TP-2004-004-02.
[9] Price, J., Vipavetz, K, Rogers, J, Boadway, K., "NPR 7123.1 Overview and Associated Tool for Tailoring NPR 7120.5E and 7123.1B Products", NASA LaRC Presentation, January 2016.
[10] NASA Procedural Requirements 7120.5, *NASA Space Flight Program and Project Management Requirements*, Revision E, 2012.
[11] NASA Procedural Requirements 7123.1, *NASA Systems Engineering Processes and Requirements*, Revision B, April 2013.
[12] No Magic, Inc., *MagicDraw Report Wizard User Guide 18.1*, 2015.
[13] Object Management Group, Inc., http://www.omg.org/spec/SysML/1.5/.
[14] No Magic, Inc., MagicDraw UML Meta-Model User Guide 18.1, 2015.
[15] Woodham, K., Graydon, P., Borer, N., Papathasis, K., Stoia, T., and Balan, C., "FUELEAP Model-Based System Safety Analysis," *2018 AIAA Aviation Forum*, June 25-29, 2018, Atlanta, GA (to be published).