JOURNAL OF AIRCRAFT
Vol. 48, No. 3, May–June 2011

What the United States Air Force is Doing Right About Systems Engineering

Paul C. Lambertson,* John H. Pletcher Jr.,† and Gary E. Yale‡
U.S. Air Force Academy, Colorado Springs, Colorado 80840

DOI: 10.2514/1.C031016

To address problems in the acquisitions program (e.g., cost overruns, delayed scheduling, engineering design errors, etc.), in 2003 then Secretary of the Air Force, the Honorable James G. Roche and Chief of Staff of the Air Force, General John P. Jumper, went to the U.S. Air Force Academy and asked for help developing a new breed of *systems thinkers*. The progenitors of the systems engineering major envisioned that a systems thinker would have a foundation in a classical engineering discipline (big E) such as aeronautical, computer, and mechanical engineering. The U.S. Air Force Academy Systems Engineering curriculum is heavily focused on classical engineering disciplines through seven concentration areas. Once the classical engineering foundation is laid, systems engineering (little s) is effectively layered on that basic engineering foundation. Application of systems engineering methods (and tools) culminates in the senior year when all sE cadets participate in a capstone design project. For example, SE-Aeronautical Systems (systems engineering students with an aeronautics foundation) cadets take the aircraft design capstone sequence. In this capstone design the cadet design team (sE and Aero engineering cadets) actually designs to customer requirements (e.g., the next generation bomber), builds a small prototype, flies the prototype, and evaluates its performance. In addition, the cadets perform cost modeling, risk tracking, and briefing of actual U.S. Air Force customers on their design. This systems engineering process better mimics the U.S. Air Force's actual acquisition process where systems engineers are integral to the design team. As the U.S. Air Force's next generation of systems thinkers, these graduates will take this education experience into future aircraft design and acquisition projects. For widest reader applicability, the SE-Aero concentration will be described. This paper focuses on the debate surrounding systems engineering education at the undergraduate level, application to aircraft design and development, and anticipated benefits of this educational investment.

I. Introduction

WHY can't the Department of Defense (DOD) develop and/or acquire technology without hemorrhaging significant time and money? This question echoes throughout the halls of Congress and has plagued the Pentagon for years [1]. One major reason is the DOD's loss of systems engineers and systems engineering expertise over the past several decades [2]. In 2003, then Secretary of the Air Force the Honorable James G. Roche and Chief of Staff of the U.S. Air Force (USAF) General John P. Jumper wanted to develop a new breed of systems thinkers who could mend the systems engineering breach. They went to the United States Air Force Academy (USAFA) and asked for help. At the USAFA, the progenitors of the Systems Engineering (sE) major envisioned that a systems thinker must have a firm foundation in a classical engineering discipline (big E) such as aeronautical, electrical, computer, mechanical, etc., (sE is used when discussing the USAFA Systems Engineering program and SE is used in course/concentration naming as well as for systems engineering beyond the USAFA). This foundation is critical to ensure and enable accurate understanding of engineering concepts to which systems thinking would be applied. Working knowledge of higher math, fundamental engineering principles, and engineering language are crucial to applying systems engineering thinking and tools, not to mention its lexicon. The foundation for a good systems engineer is his or her academic education in a technical area (e.g., aeronautical engineering, electrical engineering, or software engineering) [2]. To ensure this, the USAFA's Systems Engineering Major is divided into seven concentrations (Aeronautical, Computer, Electrical, Human, Information, Mechanical, and Space) each based heavily in that concentration's discipline with the Systems Engineering courses starting optimally in the junior year. For the purpose of this paper, the SE-Aeronautical Systems (SE-Aero) concentration will be the focus. Once the classical engineering foundation is laid, systems engineering (little s) can be effectively taught. Application of systems engineering methods (and tools) culminates in the senior year when all sE cadets participate with the classical engineering departments in a capstone design project. For example, SE-Aero cadets take the aircraft design capstone sequence alongside the Aeronautical Engineering students in the Aeronautical Engineering Department. In this capstone, the cadet team designs to actual customer requirements (e.g., the next generation bomber), builds a small prototype, flies the prototype, and evaluates its performance. In addition the cadets perform cost modeling, planning, risk tracking, etc., and then brief those real USAF customers on their design. This systems engineering process better captures the USAF's acquisition process where systems engineers are integral to the design team. As the USAF's next generation of systems thinkers, these graduates will take this education experience into future design and acquisition projects yielding overall savings in time and national treasure. This paper focuses on the debate surrounding systems engineering education at the undergraduate level, application to aircraft design and development, and anticipated benefits of this educational investment.

II. Context

The following lists numerous elements forming the context surrounding the systems engineering undergraduate education debate and was foundational in determining the goal of the USAFA's sE program. Blanchard and Fabrycky's textbook *Systems Engineering and Analysis* provides a good baseline of what systems engineering entails. The fundamentals involve a top-down holistic approach and not solely an understanding of the constituent parts [3]. This holistic approach must be viewed from the overall system's life

Received 9 March 2010; revision received 10 July 2010; accepted for publication 4 August 2010.

*Director, Systems Engineering, Engineering Division.
†Distinguished Visiting Professor of Aeronautics and Systems Engineering. Associate Fellow AIAA.
‡Assistant Professor of Systems Engineering. Member AIAA.

cycle perspective, including "system design and development, production and/or construction, distribution operation, sustaining maintenance and support, retirement, and material phase out."

A better and more complete effort is required relative to the initial identification of system requirements, relating these requirements to specific design goals, the development of appropriate design criteria, and the follow-on analysis to ensure the effectiveness of early decision making in the design process [3].

Further, the USAF Science Advisory Board (SAB) formally defined systems engineering as an engineering discipline. The SAB is the USAF's senior scientific and engineering board of experts populated by scientific and engineering leaders throughout government, industry, and academia. The U.S. Congress decided that the DOD allowed the number of systems thinkers to greatly diminish over the last several decades [1]. The SAB further stated that "weak systems engineering" was not at fault for the major USAF acquisitions cost and schedule problems, it was the complete lack of systems and systems of systems engineering ("None exists") [4]. Two further direct examples of this systems thinking atrophy follow: 1) the depth of SE talent in the USAF has declined owing to policies within the DOD that shifted the oversight of SE functions increasingly to outside contractors, and 2) the result is that there are no longer enough experienced systems engineers to fill the positions in programs that need them, particularly within the government [2].

The FY 1999 Defense Authorization Act directed a two-thirds reduction of acquisition personnel (including systems engineers) [2]. So much has this weakening taken place that it is a cited primary cause of the top 95 acquisition programs running, in aggregate, $295B over budget and averaging 21 months in delay per program [2]. The Government Accountability Office cites the "lack of early and disciplined systems engineering analysis of a weapon system's requirements before beginning system development" as a prime reason for these cost and schedule overruns [5]. To address this, the Congress enacted and the President signed into law the Weapons Systems Acquisition Reform Act of 2009. This legislation requires the DOD to immediately "develop and implement plans to ensure adequate numbers of trained personnel" (ramp up production), grooming and recognizing systems engineers [6]. The loss of systems engineering expertise did not occur overnight, reinvigorating that expertise will take time. These are long term issues with long term solutions. But the USAF started down this path nearly seven years ago with the first graduates joining the officer ranks in 2006.

III. Debate

There is a contentious debate on the actual need for an undergraduate systems engineering program. As already stated, a firm grasp of a classical engineering discipline is required. Given that a firm foundation in engineering is required, the national debate centers around when systems engineering education should begin: at the graduate or the undergraduate level. The answer involves timing, growth, and investment. Waiting until the graduate level is often too late, especially for a military officer who has a short career relative to that of civilians and contractors.

A. Timing and the Goal of the USAFA's Systems Engineering Program

Officers in today's military rarely attend graduate school until about 3–5 years into their careers, if that early. However, they may require systems thinking shortly after graduation. The following real example demonstrates this. "Paul" earned his first masters at 9 years and a second at 15 years of service. But, at just over 2 1/2 years of service he was placed in charge of a 180 person aircraft maintenance unit responsible for $395M in aircraft, assets, and budget. Systems thinking, specifically life cycle cost, trade-off analysis, planning and risk identification/mitigation, was essential to successful operations. Paul had to quickly learn it on the job. This brings obvious risk; instead of doing his job, he had to spend valuable time and resources learning his job; an unnecessary handicap. The USAFA's Systems Engineering alumni can accomplish systems engineering tasks *immediately* upon graduation. Many recently graduated Second Lieutenants quickly find themselves in such leadership situations. However, as educated systems thinkers, their understanding of those systems' needs pays off quickly; they avoid the steep learning curve nonsystems thinkers face.

While systems engineering is an engineering discipline, it is not found solely in engineering fields, but is ubiquitous throughout *leadership*. The job of every USAF officer is to be prepared to lead. The role of the USAFA is to develop officers…leaders…of character. The goal, therefore, of the USAFA Systems Engineering program is to develop leaders of character who understand and employ systems engineering tools and thinking.

B. Growth

A second principal argument against undergraduate systems engineering is that systems engineers are "grown, not made." This view purports that systems engineers only emerge after surviving years in the "engineering growing pains" crucible. However, properly focused education of engineering depth with systems engineering breadth is proven to deliver a systems thinker. For example, a car manufacturer would maximize commonality where possible while remaining focused on the desired outcome. A truck and a sport utility vehicle (SUV) could have the same chassis and/or drive train. But the functions performed by a truck versus those of an SUV are significantly different. The manufacturer would use the appropriate components to produce the desired end result using common components (competencies) where appropriate. As previously stated, undergraduate systems engineering education requires a firm foundation in classical engineering with systems engineering as the finishing components to that engineering final product. At the USAFA, a systems engineering graduate is an SE-Aero, SE-Mech, SE-Space, etc. In the SE-Aero to Aero comparison (Fig. 1,[§] fully discussed in Sec. IV), *Advanced Aeronautics* is replaced by *Intro to Systems Engineering*. The main components are the same classical engineering competencies while the finishing touches (advanced aeronautics vs introduction to systems engineering) describe the differences between a USAFA Aero and SE-Aero graduate.

But this begs the next question: does USAFA graduate systems engineers? It is best to put this in the context of engineers in general and ask, "Does any undergraduate university produce engineers *in any discipline*?" By rule, these undergraduates are only eligible to take the Fundamentals of Engineering exam and become engineering apprentices. Only after four years of engineering experience are these apprentices able to apply for their Professional Engineer Licenses. The International Council on Systems Engineering (INCOSE) certification program follows similar rules. University undergraduates are eligible to take the Associate Systems Engineering Professional certification exam (Systems Engineering Apprentice) and can only attain the Certified Systems Engineering Professional level after five years of systems engineering experience.[¶] The import of teaching systems engineering at the undergraduate level is to inculcate these fundamentals early in a young engineering student's education, to assemble the proper finishing components on a common foundation. In fact, the positive effects of undergraduate systems engineering education become evident as early as the aircraft design Capstone Experience. The USAFA Capstone Experience allows students to "learn and do" in the same manner as the USAF accomplishes aircraft design. Introduction of systems engineering at this level is critical to continued engineering growth for these officer candidates. The Capstone Experience will be discussed later and it clearly exemplifies the import of apprentice engineers who think in systems terms.

C. Investment

USAFA's Systems Engineering program is only one part of a wider solution to the DOD's acquisition ailments. This early investment in

[§]Personal communication with Dr. Gary Yale (CSEP-ACQ), Assistant Professor of Systems Engineering, USAFA, Member AIAA (February 2010).

[¶]Data available online at http://www.incose.org/educationcareers/certification/ [accessed January 2010].

undergraduate systems engineering education is worth the loss of a more in-depth classical engineering education. Discussing two key points validates this statement; the goal of USAFA's undergraduate systems engineering program, as stated earlier, and understanding the *real* differences as compared with other USAFA engineering programs and other university engineering programs. A closer look at the USAFA's sE curriculum follows.

IV. Curriculum, Credibility, and Benefits

USAFA's systems engineering curriculum covers a great deal of systems engineering fundamentals. Courses common to all systems engineering students, regardless of concentration area include: 1) Introduction to Systems Engineering, 2) Project Management, 3) Systems Analysis, 4) Probabilistic Models, 5) Probability and Statistics for Engineers and Scientists, 6) Introduction to Human Factors Engineering, 7) Calculus III and/or Differential Equations (most concentrations require both), 8) Introduction to Programming for Scientists and Engineers, and other courses dependent on concentration area (Aero, Mech, Space, etc.). Topics taught throughout the dedicated sE curriculum include: lifecycle interactions, planning, requirements generation, performance, cost, schedule, risk, commitment to knowledge of cost interactions, use of computer aided systems engineering (CASE) tools, reliability, maintainability, object oriented methodology, and many others. The sE curriculum finishes with the Capstone Experience. Research efforts are found in laboratory classes, and in special projects where cadets accomplish research over a myriad of systems engineering and classical engineering topics. Also the Cadet Summer Research Program engages cadets with USAF Laboratories, industry, and academia - this research often continues in the senior year under the special projects architecture.

This method of systems engineering education has been formally acknowledged by outside sources (Accreditation Board for Engineering and Technology (ABET), INCOSE, etc.) and is already taking effect in the USAF. USAFA's sE program just received a full six-year ABET accreditation with the maximum ABET allowed "back" accreditation, an "unprecedented" achievement for a brand new program according to the USAFA Dean of the Faculty. It was also described as a best practice, based on the ABET visitor's comparison to other systems engineering programs. Further, USAFA's sE graduates have already made a mark in design and improvement programs across the USAF. One example is Second Lieutenant Rachel Grant (SE-Aero) who found herself *leading* an improvement (lean engineering) process on the F100 jet engine at the Oklahoma City Air Logistics Center. As a Second Lieutenant, she reported directly to the Group Commander, a USAF Colonel. The task involved streamlining and simplifying engineering and supply efforts on the F100 jet engine. As an SE-Aero, Lt. Grant understood the propulsion engineering required to comprehend the involved system (the jet engine), but was the only officer in the meeting with deep knowledge of systems engineering methods and tools. She understood planning and life cycle fundamentals which allowed her to dissect the many challenges as a systems thinker. She was given the lead assignment, ahead of more senior officers, due to her systems engineering understanding. Her superiors were rewarded due to the excellent project results her selection yielded: 1) 3195 F100 engines in the fleet valued at \$11.2B, 2) high-pressure turbine module repair days from 45 to 13 days = 71% improvement, and 3) part annual distance traveled in aggregate; 982 miles reduced to 185 miles = 798 miles cut due to part redesign (removing unnecessary steps/locations) =80% improvement.**

Other graduates have reported similar benefits from their systems engineering education, especially in their understanding of performance, cost, schedule, risk, and their tradeoffs. Clearly, the Air Force is reaping the early fruits of its investment in undergraduate systems engineering education (first class of sE graduates was in 2006) with the promise of an even richer future harvest.

**Interview with with Lt. Rachel Grant (February 2010).

A. Aircraft Design Capstone

All sE students are required to take a yearlong design sequence, the model for USAFA sE is to integrate the sE cadets into the capstone design courses from the engineering departments. The capstone design sequence; integrates the principles, concepts, and models explored in previous core and engineering courses, applies the principles of systems design to real-world systems, and provides major design experiences with customer interfaces. The capstone courses are designed to provide actual experience interacting with a client and dealing with realistic engineering constraints. When possible, the design project is integrated with an external customer or design competition to add value to the experience. On occasion, the capstone course is aligned with a summer research project to provide a full 12 month design project. The Cadet Summer Research Program is comparable to a summer internship.

The capstone course sequence totals six semester hours and typically consists of 80 double-period classes, of which 40 h are devoted to instruction on engineering design topics with the remaining 120 h spent on team projects. sE students participate in capstone projects offered by five different academic departments during the current 2009–2010 academic year (current at the time of this writing). These projects work like any real USAF program, specifically with a contractor working under a USAF Program Manager. The cadet teams act as the contractors and the Academy faculty as their Air Force managers. The Aeronautical Engineering Capstone is an excellent example and is described below.

The Aeronautical Engineering Capstone sequence consists of Introduction to Aircraft and Propulsion System Design and Aircraft Design or Aircraft Engine Design. They follow the system life cycle processes including; a systems requirements review, an analysis of alternatives, a failure modes and effects analysis, preliminary design review, and a flight readiness review. In these courses, cadets learn how to plan as an integrated team (airframe and engine), how to use the needed design tools, and how to proceed from requirements to first flight of a generic fighter aircraft prototype. Further, cadets apply everything they have learned to a real problem with requirements from an actual customer. They analyze requirements, perform a House of Quality study, synthesize an aircraft/engine conceptual design, conduct engineering analyses, perform tradeoffs, do cost estimates, build, and test fly a prototype to demonstrate the feasibility of the design. They manage all aspects of schedule, resources, risk, and performance, as well as executing system trades, recommending to the customer the relaxation/deletion of requirements that other key parameters (cost, range, etc.) might drive. Educational outcomes by the end of Aeronautics Capstone design sequence; each SE-Aero team should be able to [7] do the following:

1) Critically evaluate an aircraft design request for proposal (or other tasking document).

2) Satisfactorily synthesize and optimize an aircraft conceptual design to meet specified performance requirements and constraints.

3) Effectively employ advanced analysis methods to describe your design and predict its capabilities.

4) Effectively manage construction and flight test of a subscale model of your design.

5) Effectively employ various program management tools to manage program requirements, schedule, workload, logistics, risk and cost.

6) Produce accurate, timely, concise, and effective reports and briefings, and perform effectively as a member of an interdisciplinary design team.

1. Projects

Projects for the 2009–2010 academic year are:

CAMPUS: The cadet team designs, builds, and flight tests modifications for the Combat Aerodynamics Modular Prototype Unmanned Aerial System (CAMPUS) research aircraft. The design team focuses on accomplishing the engineering analysis, construction, integration, safety reviews, and flight approval necessary to fly the aircraft at Edwards Air Force Base later in 2010. CAMPUS is a small (200 lb takeoff gross weight) uninhabited aerial vehicle commissioned by the U.S. Air Force Research Laboratory to provide a modular and reconfigurable platform for flight testing new aerospace technologies. The vehicle is powered by a 100 lb thrust jet engine and, depending on its configuration, capable of speeds in excess of 200 mph. The CAMPUS design project challenges students to design, build, and fly modifications (typically new wings and control surfaces) to the core structure, allowing the vehicle to meet a new set of mission requirements. The resulting design experience exposes cadets to design, analysis, manufacturing, and operating methods representative of current light aircraft and a large portion of modern remotely piloted aircraft.

Fighter-Size Target (FST): The USAF is in the process of procuring a new FST and is currently evaluating four different aircraft configurations. Wind tunnel testing is now complete and some stability issues have been identified. The capstone design team conducts wind tunnel tests in the Academy's Aeronautics Laboratory's subsonic wind tunnel to identify ways to correct stability problems in the four candidate configurations. Also the team conducts an independent down-select and reports results of that decision to the customer. In this analysis of alternatives, the cadet team uses all available data on aircraft performance, stability, weight, center-of-gravity travel, controllability, cost, and risk to rank order the candidate designs and recommend a winner. Once a decision is made by the Office of the Secretary of Defense (midsemester) and a single configuration is selected for further development, the cadet team supports that process by designing, building, and flight-testing a subscale concept demonstrator of the final FST configuration. In this effort, the cadets place primary emphasis on accurately duplicating full-scale configuration geometry and weight distribution, then performing flying-qualities development testing to identify and correct any undesirable characteristics.

OA-X: The U.S. Air Force Air Combat Command needs a light attack/observation aircraft, referred to as OA-X, for close air support, armed reconnaissance, building partnership capacity with Allied Air Forces, and combat air forces training requirements. Last year a capstone design team produced a jet powered design that met all the user requirements, but was too expensive. This year the design team is working on a design that is significantly less expensive, to include looking at modifying an existing business jet or jet trainer.

TuffFalcon: The Academy Center for Unmanned Aerial Systems (UAS) Research requires a robust aircraft to safely carry research payloads under the current United States Air Force Academy UAS flight constraints. The cadet design team is designing, building, and flight testing TuffFalcon. This aircraft must be single-man portable and launch able, with a 9000 ft MSL maximum altitude, and 6 mile range (at maximum payload). Other design requirements include 6 lb (threshold), 10 lb (objective) maximum payload, and 60 min duration.

ESTI: The Extended Supercruise Test Initiative (ESTI) is to perform a feasibility study of a modified B-1B aircraft at the request of engineers supporting the Defense Advanced Research Projects Agency. The ESTI aircraft serves two purposes: first, a long endurance, high speed, large payload testbed; and second, a demonstrator of supercruise capability for a long range strike aircraft. Several modifications to be B-1B are being studied. First, the engines, inlets, nozzles, and nacelles are changed to accommodate the F-119 engine as well as an advanced engine designed by the cadet propulsion design team. The airframe design team analyses modifications to the wings and the placement of the engines. In addition they consider the trade-offs between variable sweep and fixed wings. The results of the feasibility study will include a comparison of the baseline B-1B, the B-1B with F-119 engines, and the B-1B with a modified wing (fixed and variable sweep) with the cadet designed engines. A small prototype of this final design is built and flight tested.

2. *Role*

To better understand the role of the system engineering student in the capstone design, the specific duties of the sE in the ESTI design project are herein described. The team program manager is not an sE, but the chief systems engineer may be either an sE or aeronautical engineering student as chosen by a team vote. The sEs participate in the actual design and test activities side-by-side with the aeronautical engineering students. They also are responsible for the following:

1) Early on, doing a system requirements review (SRR) to assure that both the team and the customer agree on what needs to be done.

2) Developing the analysis of alternatives (AOA) for various wing designs and engine placements.

3) Giving biweekly update briefings to the government program manager and the final briefing to the customer.

4) Completing the failure modes effects and criticality analysis (FMECA).

5) Performing a risk analysis for both technical and cost risks to include recommended risk mitigation efforts.

6) Assisting the aeronautical engineering students in the critical design review (CDR), the structural design certification and the flight readiness review (FRR).

7) Using existing models and working with the systems engineering managers, completing a cost analysis of the new design (airframe and engine) to include a Monte Carlo analysis for confidence in the determined costs.

8) Performing a constraint analysis and using the results to perform tradeoff analyses so as to provide viable options to the customer.

9) Preparing reports for each deliverable such as the SRR, AOA, CDR, and FRR.

10) Participating in an ethics exercise showing how the integrity of a program can be compromised and how to avoid ethically compromising situations.

As evidenced above, the aircraft design Capstone Experience is extremely engaging and relevant. Further, the systems engineering cadets are critical to the process and its success due to their systems thinking attributes and leadership, points often described by their peers during end of course reviews.

B. Curricular Comparisons

One point of curricular confusion often arises in discussing the Systems Engineering Management (SEM) major. SEM is taught from the Department of Management. While SEM is an excellent and necessary major, it not an engineering major and not part of the technical discussion addressed by this paper. This issue is important for this audience because it is often raised in the national debate as a reason against undergraduate systems engineering education. While students in both majors take similar systems engineering courses, they are separate and distinct majors with sE ABET accredited while SEM has no plans to seek ABET accreditation.

The following describes the similarities between the USAFA's sE program and other USAFA engineering programs. Figure 1 illustrates the similarities between Systems Engineering–Aeronautical Systems and Aeronautical Engineering. Comparisons to all of the sE concentrations (except SE-Human Systems because there is no classical engineering discipline at the USAFA for comparison) are similar in nature. Details are available upon request. Again, the SE-Aero/Aero comparison is used due to the aircraft capstone design relevance to this audience. The white courses are identical in each program. Dark gray represents differences, whereas the gray represents the possibility for increased commonality. For example, the systems engineering option on the left is fulfilled by one of the five gray courses on the right. The pie charts demonstrate the commonalities across the full 147 semester hour curriculum as well as a closer comparison of the 93 semester hour Science, Technology, Engineering, and Math (STEM) curriculum. This figure clearly illustrates the heavy emphasis on classical engineering with the first sE courses programmed for the junior year - Introduction to Systems Engineering and Program Management.

The pie charts in Fig. 1 were developed to allow comparison to other first rate universities. A current study is further exploring comparisons to other university systems engineering and classical engineering curricula. Of those universities who have responded thus far the general consensus of those engineering programs requires approximately 120–130 semester hours each for graduation.

<table>
<tr><th>SE - AERONAUTICAL SYSTEMS</th><th>AERONAUTICAL ENGINEERING</th></tr>
<tr><td colspan="2">Bio 315 Introductory Biology with Laboratory</td></tr>
<tr><td colspan="2">Chem 100 Applications of Chemistry I</td></tr>
<tr><td colspan="2">Chem 200 Applications of Chemistry II</td></tr>
<tr><td colspan="2">Comp Sci 110 Introduction to Computing</td></tr>
<tr><td colspan="2">Physics 110 General Physics I</td></tr>
<tr><td colspan="2">Physics 215 General Physics II</td></tr>
<tr><td colspan="2">Aero Engr 315 Fundamentals of Aeronautics</td></tr>
<tr><td colspan="2">Astro Engr 410 Introduction to Astronautics</td></tr>
<tr><td colspan="2">Engr 101 Introduction to Air Force Engineering</td></tr>
<tr><td colspan="2">Engr Mech 220 Fundamentals of Mechanics</td></tr>
<tr><td colspan="2">ECE 231 Electrical Circuits and Systems I</td></tr>
<tr><td colspan="2">Math 141 Calculus I</td></tr>
<tr><td colspan="2">Math 142 Calculus I
or Math 152 Advanced Placed Calculus I</td></tr>
<tr><td colspan="2">Math 243 Calculus III</td></tr>
<tr><td colspan="2">Math 245 Differential Equations</td></tr>
<tr><td colspan="2">Math 356 Probability & Statistics for Engineers and Scientists</td></tr>
<tr><td colspan="2">Aero Engr 241 Aero-Thermodynamics</td></tr>
<tr><td colspan="2">Engr Mech 320 Dynamics</td></tr>
<tr><td colspan="2">Aero Engr 341 Aero Fluid Mechanics</td></tr>
<tr><td colspan="2">Aero Engr 351 Aircraft Performance & Static Stability</td></tr>
<tr><td colspan="2">Aero Engr 352 Aircraft Stability and Control</td></tr>
<tr><td colspan="2">Aero Engr 361 Propulsion I</td></tr>
<tr><td colspan="2">Aero Engr 481 Intro to Aircraft & Propulsion System Design (Capstone I)</td></tr>
<tr><td colspan="2">Aero Engr 482 Aircraft Design (Capstone II)
or Aero Engr 483 Aircraft Engine Design (Capstone II)</td></tr>
<tr><td>Sys Engr 310 Introduction to Sys Engineering</td><td>Aero Engr 442 Advanced Aerodynamics</td></tr>
<tr><td>Sys Engr 301 Project Management</td><td>Aero Engr 342 Computational Aerodynamics</td></tr>
<tr><td>Comp Sci 211 Programming for Engs & Sci (MATLAB)</td><td>Math 346 Engineering Math</td></tr>
<tr><td>Ops Rsch 310 Systems Analysis</td><td>Aero Engr 471 Aeronautics Laboratory</td></tr>
<tr><td>Ops Rsch 321 Probabilistic Models</td><td>Engr Mech 330 Mechanics of Deformable Bodies</td></tr>
<tr><td>Beh Sci 373 Intro to Human Factors</td><td>Aero Elective</td></tr>
<tr><td>Sys Engr Option</td><td>Structures and Materials Elective</td></tr>
<tr><td>Sys Engr 405 SE Seminar I</td><td></td></tr>
<tr><td>Sys Engr 406 SE Seminar II</td><td></td></tr>
</table>

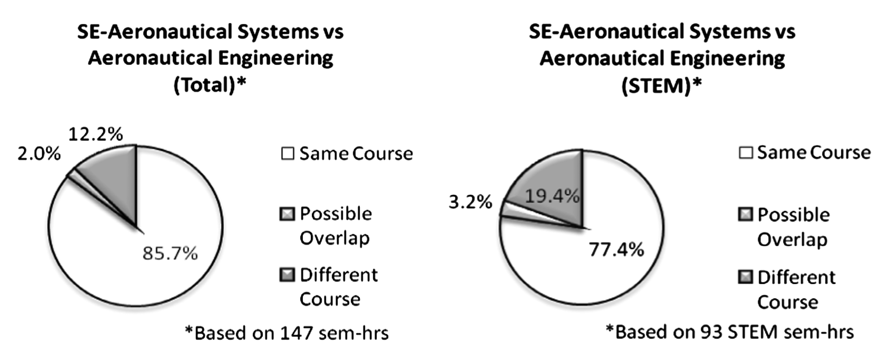

Fig. 1 USAFA systems engineering aeronautical systems comparison to USAFA aeronautical engineering.

Comparing total number of semester hours provides some insight, but is not necessarily a true comparison. Comparing STEM courses (or even engineering topics) is better focused. For example, the USAFA has 147 semester hours vis-à-vis the 120–130 semester hour consensus indicated earlier. But the USAFA core is very robust and includes areas of study like foreign language and management that a more traditional engineering undergraduate degree may not require. These potential "core" differences could mean that, even with 17–27 more semester hours than other university programs, the USAFA's curriculum may have fewer engineering discipline hours. Continued research into these comparisons is ongoing.

V. Conclusions

The USAFA graduates systems thinkers as requested by the U.S. Air Force's Secretary and Chief of Staff, whose vision saw undergraduate systems engineering education as part of their holistic solution to the critical systems engineering expertise problem. Systems engineering practitioners are those systems thinkers who can accomplish systems engineering tasks and overall leadership. USAFA systems engineering apprentices capably perform systems engineering tasks even before graduation and can very successfully grow into systems engineering practitioners and leaders. USAFA educated systems engineering graduates are well prepared to bring the systems thinking approach to the engineering team, complimenting the classical engineering depth.

This paper discussed the debate surrounding systems engineering education at the undergraduate level, application to aircraft design and development, and anticipated benefits of this educational investment. The USAFA sE program fulfills a number of important USAF requirements. It was borne of the critical need to reinvigorate the service's systems engineering workforce.

"The USAFA program for SE. . .[has] important value. . .their Air Force Academy training will have instilled in them an appreciation for what systems engineering means and for its importance [2]."

While teaching systems engineering at the undergraduate level is not the only way to systems engineering success, it is a very clear path to that success. USAFA sE graduates like Lieutenant Grant are already demonstrating excellent return on investment, earlier than originally speculated by the program's progenitors. It is telling to witness such a young officer successfully acting in a more senior role. While certainly not the only occurrence experienced across the USAF enterprise, it directly relates to this discussion. The USAFA's heavy focus on a selected classical engineering discipline is crucial to meeting the USAF's overall need for systems thinkers: those who can do systems work within the context of engineering. One must well understand engineering concepts and laws to truly be successful within the systems engineering discipline. The USAFA's sE curriculum culminates in the Capstone Experiences, many of which are aircraft design projects focused on warfighter needs. Cadet engagement is greatly increased as they realize who their customers are, how they are transforming those customer needs into real requirements, and ultimately designing their system to those requirements. Systems engineering methods and tools, those items that further systems thinking, are also keenly felt throughout leadership. The goal of the USAFA Systems Engineering program is to *develop leaders of character who understand and employ systems engineering tools and thinking*. USAFA sE well accomplishes that goal: our USAF, DOD, and nation are better for it.

Acknowledgments

The authors gratefully acknowledge the sponsorship of the U.S. Air Force Academy's research directorate in publishing this article, and the contributions of Thomas McLaughlin in editing and reviewing the manuscript.

References

[1] Testimony to Congress during deliberations on the Weapon Systems Acquisitions Reform Act of 2009.
[2] Committee on Pre-Milestone A Systems Engineering: A Retrospective Review and Benefits for Future Air Force Systems Acquisition, Air Force Studies Board, National Research Council, "Pre-Milestone A and Early-Phase Systems Engineering: A Retrospective Review and Benefits for Future Air Force Acquisition," ISBN: 0-309-11476-4, 2008.
[3] Blanchard, B. and Fabrycky, W., *Systems Engineering and Analysis*, 4th ed., Prentice Hall, Englewood Cliffs, N.J., 2005.
[4] USAF Scientific Advisory Board, "Report on System-of-Systems Engineering for Air Force Capability Development," SAB TR-05-04, July 2005.
[5] Sullivan, Michael J., "Defense Acquisitions: DOD Must Prioritize its Weapon System Acquisition and Balance Them with Available Resources," Testimony Before the Committee on the Budget, U.S. House of Representatives. Government Accountability Office 09-501T, March 2009.
[6] Weapon System Acquisition Reform Act of 2009, PL 111-23.
[7] USAF Academy Department of Aeronautics, Aero Engr 482/SE 492A/ SE 492HA Aircraft Design, Course Policy Letter, Spring 2010.