Those with Imagination but Not Learning Have Wings but No Feet–

Challenges for Education in Aerospace & Engineering for the 21st Century

Human-powered plane.

by Drs. John H. McMasters and

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FOR MUCH OF THE 20th CENTURY, advances in aeronautics and then aerospace have served as a sort of poster child for modern technological progress. More recently, however, a spate of national studies and articles in both the popular and professional presses[1,2] has decried the seriously declining state of aerospace in general and aeronautics in particular in this country. Whatever the reasons for the putative decline in aerospace, two fundamental factors are cause for serious immediate concern. The first factor is that we as a technical community within aerospace and aeronautics have been unable to create a collective vision of our future as compelling and exciting as that which has driven our past. The technological dreams of Star Trek and the quest for the discovery of life on Mars or elsewhere in our universe are an exception. A second factor, reciprocal to the first, is the need for an aggressive means to replenish and sustain our pool of technical talent. This is required to maintain and advance an industry that continues to find a multi-billion-dollar-a-year market for its products and services, has almost singularly contributed a positive balance of trade to our economy, and is of fundamental importance to our national security. The pool of skilled practitioners is aging and retiring, and there is severe competition for both young and experienced talent in key technical areas (design, systems and computer engineering) from seemingly more dynamic sectors of our national and global economy. A central concern for our historically volatile and ever changing enterprise must be for the education and development of a future generation of practitioners as skilled and motivated as those who have created our history.

The authors have spent the great majority of our careers as aeronautical engineers and engineering educators and became acquainted under the auspices of the Boeing-Welliver faculty summer fellowship program[3] in 2000. Dismayed by the bad press attendant to the major changes in fortune of our industry during the past decade, we began collaborating on a series of writings[4-9] under the general rubric: "The Demise of Aerospace—We Doubt It." As our initial series of publications developed, so has our agenda that now includes making modest contributions to:

1. The national need *of our aerospace community* to revitalize itself by creating a more vividly positive vision of its future, as a means to …
2. Attract a next-generation technical workforce in aerospace that possesses a much broader *multi-disciplinary* and *systems engineering* perspective aided by …
3. Reform and enhancement of our technical education system (beginning at the elementary-school level) to …
4. Attract and *retain* a diverse student population (*especially women and minorities*) that reflects the shifting demographics of our society.

These topic areas cover a lot of territory, and describing how they relate one to another, *as a system*, is one purpose of this article. Aerospace experience also may serve as a lens for examining the future of other industries. Our future depends on our success in dealing with all of them.

AEROSPACE TODAY AND INTO THE FUTURE—SOME BASIC CHALLENGES

Our industry has traditionally been very effective in developing advanced technology of benefit to both our own business purposes and to many in our society. Indeed, if one examines the first century of powered flight from the initial success of the Wright brothers in 1903 to our success in placing humans on the moon and beyond, one sees truly dramatic progress, spurred by the simple mantra *farther, faster, higher*. Driven more recently by competitive and economic pressures and enabled to a massive degree by the advent of the computer and the broader scope of information technology, many companies also have made great strides in improving processes and increasing productivity—sometimes dramatically. In general, we know how to do these things, they are discussed exhaustively in our professional literature, and they are thus of peripheral (though significant) concern in discussions of some basic issues that are of current and future importance to the long-term health of our enterprise.

A principal motivation in our earlier writings has been the simple observation that the most important assets of most companies and institutions in our society are their people (their "intellectual capital") and the cash flow that results from their activities. In this people-centric view of our own industry, it may then be argued that: *The best technology and processes in the world are useless without the right skilled and motivated people to develop and apply them*. It is these social and "people" (technical workforce) aspects of our enterprise that underlie much of what we do and are of fundamental concern to our future. They are, however, too frequently ignored or treated as separate, disconnected topics in the aerospace engineering literature. In reality, technology, processes, and people form an inseparable triad in aerospace, and it has continued to be our purpose to treat them as a *unity* with emphasis merely shifting depending upon specific discussion topics.

Two interrelated technical workforce questions are of pressing concern to our industry: "How many engineers will we need in our future (nationally, world-wide)?" and "What will these engineers need to know and be able to do as changes continue in professional practice?" Before considering these issues, it is necessary to note that while the focus of this article is ostensibly on aerospace engineering, most companies in our industry employ many more electrical, mechanical, manufacturing, and computer-related engineering graduates than those with explicit *aerospace* engineering degrees. In this sense, the subsequent text relates to both our interests and those of other industrial sectors.

HOW MANY ENGINEERS DO WE REALLY NEED?

Historically, the aerospace industry has had a reputation for volatility, with a long series of well-publicized periods of either feast or famine in employment. It also has produced its share of notorious examples of supposedly "strategic" forecasts that have proved to be, on retrospective examination, extrapolations from either a bubble or a trough in the longer-term business cycle. We recognize that technical-talent development requires a considerably different (and much longer) time frame than that of product-development cycles, which are the basis for much industrial planning and general mindset. The challenge remaining is to make realistic forecasts to assure that an adequate supply of talent in the right skill areas is available at any given time. The strategic forecasting problem has been exacerbated in recent years by the fact that the industry overall (including a large number of suppliers and customers that spread far beyond the few remaining flagship companies upon which the press tends to focus its attention) has been subjected to a massive consolidation and extended downsizing in the wake of the Cold War. To what degree this now may have ended remains unclear. Events such as 9/11 are almost impossible to predict, and the degree to which their extended aftermath may cause reversals in trends is difficult to assess. While accurately predicting long-term workforce needs is probably impossible, reasonable estimates are needed to assure that proper steps are taken to attract and educate the talent we require to sustain the health of our industry.

Barring a complete collapse of the world economy or other massive catastrophe, one may examine the basic factors that could lead to either a significant increase or decrease in the number of engineers needed, relative to those we currently have, during the next couple of decades. Some of these factors are readily recognizable, and with regard to a need for more engineers and scientists, one must consider the anticipated growth in the world population with their attendant needs to levels never before experienced in the whole of human history. Added to this is the growth in global commerce, made possible by a combination of the IT/communications revolution and the existence of an effective global transportation system; the continuing traditional need to maintain our national security, exacerbated by the increased threat of terrorism that extends to our own shores; and perhaps most importantly, the need to deal with a range of increasingly pressing environmental issues.

Countering these growth factors are the parallel advances being made in the tools and knowledge available to do our work, the mechanization of an increasing number of routine, repetitious tasks and processes that have in the past provided employment for a significant percentage of our technical workforce, and the seemingly inexorable economic pressure to improve productivity (squeeze as much useful work as possible out of each individual still employed). Taken together with those factors that indicate a need for more engineers, a case could be made that, on a long-term average basis with fluctuations about the mean, the suites of factors might be roughly compensatory, and thus the number of engineers we have is roughly the number we will need for the foreseeable future. This modestly optimistic prognostication is based on the implicit assumption of evolutionary rather than revolutionary changes in the nature of the basic technical work or organizational context in which it is done.

OUTSOURCING AND GLOBALIZATION

Meanwhile, from a domestic perspective, globalization looks more like a revolution to some and carries with it the prospect of increasing outsourcing of work (including engineering) to those countries where labor is cheaper and workers compete with their U.S. counterparts because of their high-quality educational systems. These educational infrastructures have been constructed by increasing numbers of their citizens who were educated in universities in Europe, the Soviet Union, and, prominently, the U.S. and returned home—commencing from a trickle at the beginning of the post-Sputnik era in the early 1960s. In the grand scheme of things, U.S. citizens can take pride in what has been accomplished

Boeing's "Desired Attributes of an Engineer"

- A good understanding of engineering science fundamentals
  - Mathematics (including statistics)
  - Physical and life sciences
  - Information technology (far more than "computer literacy")
- A good understanding of design and manufacturing processes (i.e., understands engineering)
- A multi-disciplinary, systems perspective
- A basic understanding of the context in which engineering is practiced
  - Economics (including business practice)
  - History
  - The environment
  - Customer and societal needs
- Good communication skills
  - Written
  - Oral
  - Graphic
  - Listening
- High ethical standards
- An ability to think both critically and creatively —independently and cooperatively
- Flexibility—the ability and self-confidence to adapt to rapid or major change
- Curiosity and a desire to learn for life
- A profound understanding of the importance of teamwork
- DIVERSITY—wanted and needed!

www.boeing.com/companyoffices/pwu/attributes/attributes.html

Figure 1
The time-worn but still valid desired attributes of an engineer.

by those individuals who shared in our educational wealth and then worked to improve their countries' standards of living and competitiveness in the world market.

To an increasing number of U.S. workers, however, there is cold comfort in our past generosity and emerging opportunities for transferring work previously performed here to other countries. To many, it can only raise the specter of continuing job loss among engineers, as well as factory workers who must compete with increasing numbers of highly qualified non-U.S. citizens. While outsourcing may make good business sense (at least theoretically), it becomes something of a shell game for major manufacturers in dealing with related people issues. For a given work statement, the specified tasks have to be performed by someone, somewhere—whether inside our fence or by an outside supplier. Continued process improvements can reduce the number of people required, but some bottom line number of highly qualified and knowledgeable individuals are required (to write specifications for work to be done, monitor supplier performance) at any given state of this evolutionary improvement process. A prudent balance in "sourcing" work is needed to manage risk and assure the integrity of the final products delivered.

Concerns about outsourcing also have masked a more ominous prospect—that of simple *job disappearance* which, over the longer haul, may be much more significant and disruptive at a societal level. Thanks to advances in IT and robotics, we are increasingly capable (in principle) of automating tasks that have become sufficiently routine and well understood unless there is some compelling reason a human must remain in the loop. The issue of job elimination, rather than mere job loss via outsourcing of work, is becoming of increasing concern to some of us. To our knowledge, the whole suite of longer-term implications surrounding it has not yet become a necessary subject of national discussion. If this seems to some readers a mere jeremiad, a reading (or re-reading) of Kurt Vonnegut's possibly prescient 1952 satire, *Player Piano*, provides one dark thought-provoking scenario for our possible future. As we have observed in earlier publications[4-8], it is highly premature to write the history of our industry as an obituary, and attention may focus on the question of defining the capabilities of its future practitioners.

UP THE VALUE CHAIN IN ENGINEERING PRACTICE

Much thought has been devoted in both industry and academe to the future of our enterprise and the technical workforce needed to support it. Although largely unstated, we have employed a "futurist's" rather than Jules Verne approach in our earlier writings[4-12] to project further progress in airplane design, related technology and process developments, and educational needs. In this approach, one examines a sufficiently long historical time period to attempt to discern basic trends and *durable* characteristics (it is dangerous to focus on a too short-term time frame in any evolutionary process and thus miss the real targets of importance or inadequately consider long-term consequences). With this knowledge in hand, one then may examine what new developments such as possible "disruptive technologies" or changes in the geopolitical environment may occur and thus produce fundamental changes in the previous ways of doing business. Thus, the futurist's role is not to predict the future with any certainty, but rather to attempt to estimate "what could happen, if wanted events occur (and no unknowable events intervene)."

One successful example of this approach was its use in developing the 1993-94 Boeing list of "Desired Attributes of an Engineer" *(Figure 1)*. The original purpose in creating this list was to establish a basis for an ongoing, constructive dialogue with academe. The list was created at a time when much legitimate criticism was leveled at various companies for a seeming propensity to "change their minds all the time" and to send conflicting messages to schools regarding "what industry needs." What seemed needed, instead, was a simple list of *durable* skills and knowledge—one that contained no "flavor of the month" and that could be used as a solid basis for making systemic changes in engineering education programs to better align them with *strategic* employer needs. This list has stood us well for a decade and has been used as one of three basic source documents in framing the "student learning outcomes" section in ABET Engineering Criteria 2000 approved in 1996. The list is considered a success because it has not been necessary to change anything in it since publication, and much constructive dialogue has been generated by it. The list remains our basic message to academe regarding what industry requires of its graduates.

Continuing in this vein, the issues of what will stay constant versus what will change in our enterprise during the coming decades in terms of both professional practice and educational system responses may be examined in the historical context shown in *Figure 2*. It may also be

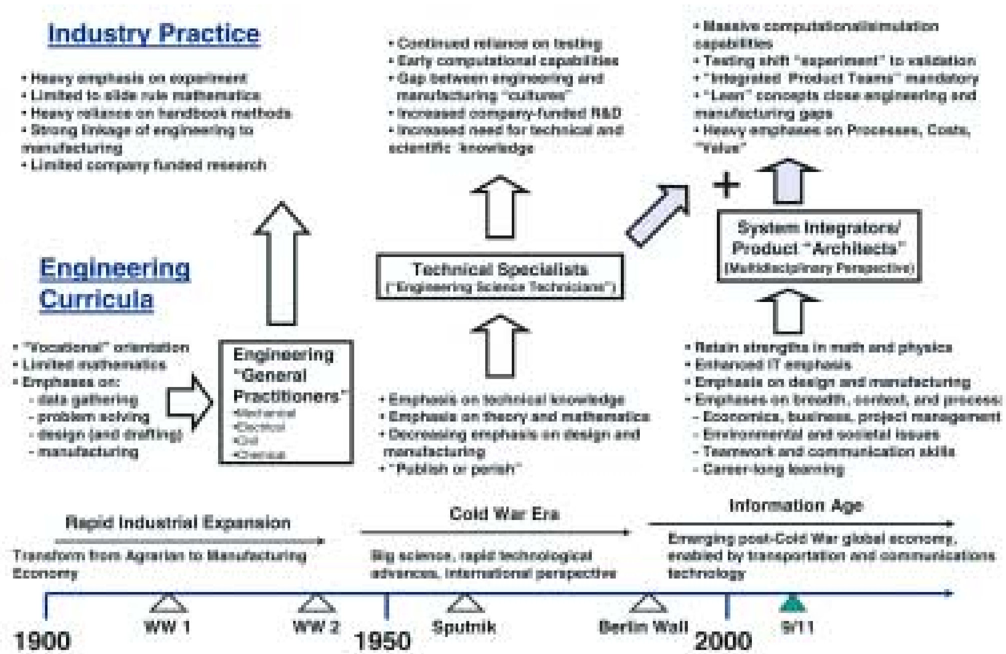

Figure 2
Long-term trends in engineering practice and education.

noted that some of the factors that underlie the discontent about our future in aerospace are suggested in this figure. Many of our colleagues who grew up and matured professionally in the long-running Cold War era continue to lament the supposed end of *farther, faster, higher* as the driving force for progress, with maintaining national security under the threat of potential nuclear holocaust providing substantial license. Our older friends may be partially correct (from their perspective), as the far less dramatic quest for *quicker, better, cheaper* has become the more recent mantra for aerospace. The newer imperative of "cost *uber alles*" has been forced on us by a new economic and geopolitical reality, however, as competition in all phases of the market has grown increasingly fierce. Such imperatives will not soon disappear, but more likely simply increase in their complexity because of a formidable list of issues (environmental concerns, our finite global fossil fuel supply) and constraints (resources available, an aging infrastructure) in our current state of affairs. As suggested in the title of one of our recent papers[6], a new mantra for airplane development might properly be *leaner, meaner, greener* as a somewhat more optimistic prospect for our future—at least technologically. It certainly presents a suite of opportunities no less creatively challenging than any others that our industry has faced in its first century of existence.

Meanwhile, the ways in which we design and develop our products to meet these new challenges will continue to change. This will be made possible, in part, by the continually increasing power of the computer and the tools (direct analysis and inverse-design methods and simulations, CAD/CAM systems, multi-disciplinary optimization) available to exploit their capabilities. Further globalization of our economy and changes in societal priorities, combined with technological advances available or envisioned (robotics, nano-technology) will likely cause further transformations in the airplane-design process and the products that result. At the same time, terms like "customer focus," "lean manufacturing (and engineering),"[13] "up the value chain," and "integrated product teams" have become major elements of the new vocabulary of the aerospace industry, with all the baggage and implications they carry with them.

It is within the context above that one may examine the skill needs anticipated in our future, particularly with regard to those buffered against outsourcing or mechanization out of existence. Referring to *Figure 2*, we see that as engineering practice and industrial needs continue to evolve, we continue to need "subject-matter" experts (engineering science specialists) who were the central focus of most engineering education programs for the past 40 years. They should increasingly be complemented by the need for more "systems-oriented talent" such as systems-oriented architects, integrators and analysts. Much of our earlier writing has focused on this topic.[8-10, 12] The creation and cultivation of this talent pool remains of fundamental importance to the future of our enterprise and a major challenge for our system of engineering education. Overarching this issue is the need for academe to educate the sorts of well-rounded engineers *(Figure 3)* who can assume the roles that will be the core of our technical workforce of the future.

ENHANCING EDUCATION— FROM CONCEPTION TO LEGACY

During the past two decades our *undergraduate* engineering education system has been subjected to substantial criticism and calls for reform from industry, some governmental sources (NSF, NAE, NRC), and from within academe itself. Some of the more pointed concerns that have been widely expressed include:

Our future supply of engineering talent is threatened.

- Current engineering education programs are failing to attract and retain an adequate number of students, especially women and minorities.
- Undergraduate programs look more like "preparation for a Ph.D. program" than "preparation for professional practice" in too many colleges and universities.

A (too large) majority of faculty have little or no significant industrial experience and have a very limited understanding of rapidly evolving employer needs. *[It may be noted that the Boeing-Welliver program[3] was created in 1995 to address this issue.]*

Engineering education costs a lot for what we get.

- Engineering education programs are expensive to offer, and costs are rising alarmingly, while undergraduate students are not getting full value for their money and too many are turned off by what is offered—especially women and minorities.

Employers continue to pay the full (often hidden) bill for teaching graduates what they need to know, but are not taught in school. There also is a potential major net savings for industry in investing early in the educational process, rather than paying the bill later. A better sharing of costs and other resources between industry and academe is necessary.

- Major opportunities for reform exist but remain unexploited.
- Significant advances have been made in our knowledge of how people learn and develop, while new teaching methods and curricular organization have been demonstrated[14], but have not been widely accepted. Too little has changed in undergraduate engineering education delivery in the past 50 years.
- New ABET EC 2000 accreditation rules encourage—rather than block—educational experimentation[15], although many schools have failed to respond fully to these new opportunities.

A Well-Rounded Engineer

Knowledge of many skills with career choices based on talent and ability

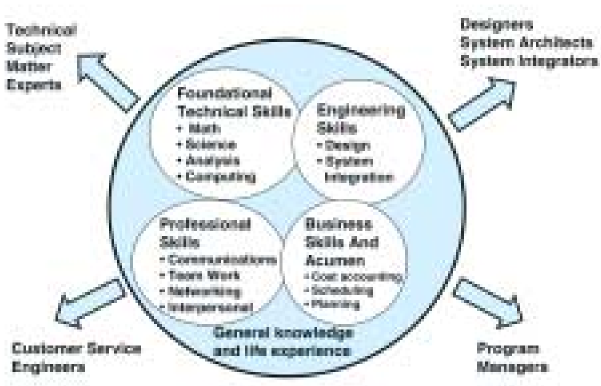

Figure 3
Engineering education objective—the well-rounded engineer.

Learning Structure for (Systems) Engineering

A conception to legacy (cradle to grave) hierarchy for engineering education

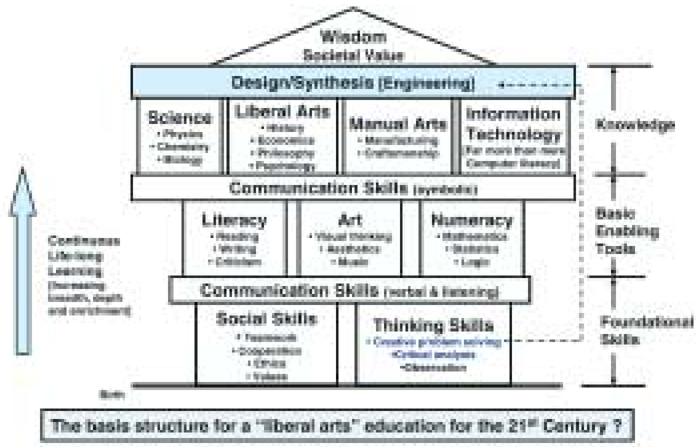

Figure 4
Thinking about future engineering curricula from first principles.

For many years, undergraduate engineering education has been based on the implicit (and foolish) assumption that we somehow need to teach students "everything they might need to know" before they enter professional practice—while trying hard not to lose too many of them in the process. If a new technological area became important in an engineering discipline, faculty would add a course on that subject to the curriculum. This "throw a course at the problem" mentality forces engineering programs to struggle continually with the question of what to remove from the curricula to make way for the next big item on the often-conflicting agendas of faculty. The faculty is involved in graduate-research programs and in the needs of the employers of their graduates. With too much to know, and too little time available to teach it, (as long as *industry* clings to an increasingly archaic engineering degree structure via its hiring practices), academe too often continues to use a balkanized approach in curriculum development. Undergraduate students (especially women and under-represented minorities) are too often casualties of what is offered to them.

One possible solution to our overall dilemma is to expand the box and finally face the facts that the traditional B.S. degree is no longer adequate as the entry-level requirement for professional practice and that some sort of five- or six-year program is needed. In whatever creative ways a new engineering degree structure might be contrived, we believe that this would be at best only a partial solution to the problem.

At the undergraduate level, we need to adopt a modern systems engineering perspective and do a much better job of determining what really needs to be presented (and how to present it) in our efforts to *educate* students to operate in a modern engineering environment, rather than merely thinking about what specific skills they may

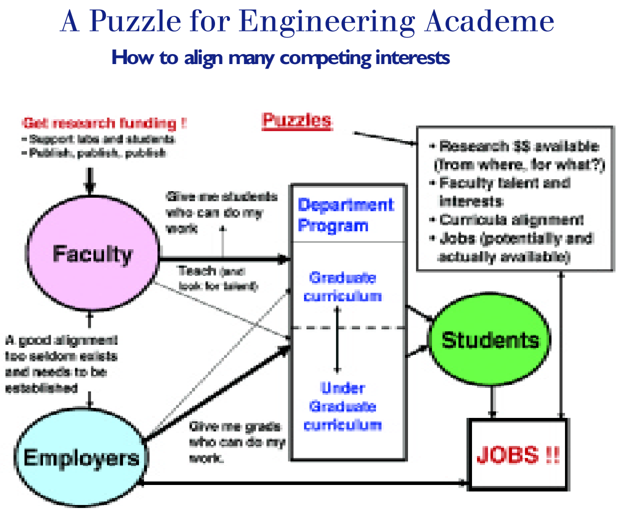

Figure 5
A basic system-of-systems design problem for academe and industry.

need in order to gain initial job assignments or to begin graduate programs in research. Instead of creating courses to meet specific (and too often parochial) needs, we must develop in our students a basic *understanding* of the fundamental tools and concepts needed for engineering practice, rather than providing them a vast bag of tricks for solving selected problems.

A way to think about future curriculum development might be to proceed from a "first principles base" as shown in *Figure 4*, keeping in mind the quote attributed to the late Theodor von Kármán *[California Beta 1902]*: "The *scientist* discovers that which exists. The *engineer* creates what has never been." The authors have long believed that the fundamental purpose of our college and university system is to prepare graduates to become informed, contributing members of society and that engineering is really about design (in the more general sense of open-ended problem solving). While science and mathematics provide the engineer much of the basic tool and knowledge suite needed for practice, it is design—and more recently its abstraction into *systems engineering*—that is the essence of our profession. In educating engineers for our future, we need to think in terms of a truly student-centered approach with quality rather than quantity being an objective at the undergraduate level and with much of the specialization in current programs deferred to the graduate level and career-long learning opportunities.

What this means to the faculty in our universities is possibly even more work, with little prospect for near-term reward. Changing the goals and rewards for faculty may be more difficult than changing the curricula they teach, but an effort must be made to attract diverse, well-qualified educators who have strong practice-oriented teaching ability and the desire to perform meaningful research and publish in the right journals. Perhaps most difficult of all is to create a culture and climate where faculty are willing and able to function as a *team*. In doing so, they serve as powerful role models for their students—as a group of *engineers* who are true exemplars of life-long learning and team-based problem solving.

CONNECTING SOME DOTS

The preceding discussion suggests that engineering academe faces as many challenges today as does our industry as a whole. At root, however, it must be recognized that despite all criticism, we still retain arguably the finest graduate education system in the world. Any attempts to reform *undergraduate* programs must be done in a way that does not damage the quality of what we now have at the graduate level. It must be also recognized that research remains the life-blood of much of the current system. The basic problem thus posed to all of us is shown in *Figure 5*. How all this is to be resolved is left as an exercise for the "student" and may be seen by engineering faculty as just a major "system of systems design problem."

Two specific opportunities should identified. After a long period of neglect in the 1970s and '80s, *design-build-test* project experience has been increasingly reintroduced in many curricula as an effective means to bridge the gap between engineering theory and practice and to enhance significantly student learning, motivation, and retention. Even more project experience is needed, however, and it should become more pervasive from the beginning of the freshman year through graduation as a fundamental complement to the math and science that must remain core elements in any curriculum. The second opportunity related to the first is to adopt a much more multidisciplinary perspective than is customary and greatly increase the intellectual playing field of engineering inquiry. With respect to aerospace interests, the authors have found the biomechanics of flight and, by large-scale extension, paleoecology to be fruitful areas in which to expand student (and their own) thinking and to introduce the concept of "system of systems" and a myriad of new student and faculty research and project ideas. Further thoughts on these topics may be found in our companion publications.[6-12]

AND THEN WHAT?

Aerospace indeed may be considered a mature industry even as it continues to change dramatically. That is far from identifying it as a dying industry, however, as can be seen from an examination of future prospects in large-airplane development *(Figure 6)*. Among the significant things our industry has to do in the coming decades include:

- Continue to maintain and develop an effective global transportation system that is increasingly safe, secure, and responsive to the needs of our environment.
- Continue to contribute to our national security when threats and effective responses continue to change in significant ways.
- Contribute a necessary aeronautics component to the issue of providing affordable access to space and enabling the further exploration of our universe.

While aerospace can be expected to remain volatile and dynamic through its foreseeable future, design and systems thinking likely will remain a core capability in any imaginable version of our industry. As shown in *Figure 7*,

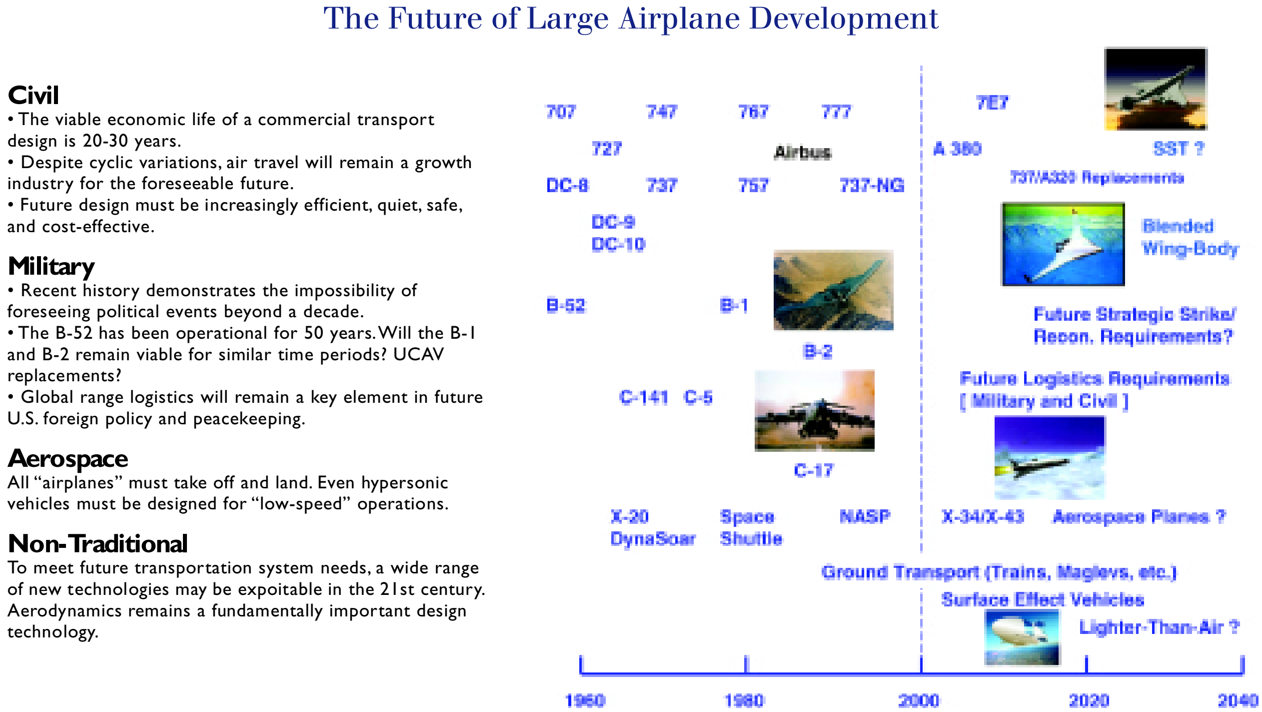

Figure 6
One element in the future of aerospace in the new century.

aerospace engineering remains the single *institutionalized* multi-disciplinary, large-scale systems-oriented program in our engineering education system. As the need increases for "systems-of-systems thinkers" across a broad range of professions, the nation can expect to need more, not fewer aerospace engineering graduates. Colleges that offer such programs should learn to market their graduates effectively as an aid to assuring a continued supply for the aerospace industry and many others as well.

Acknowledgments and Disclaimer

The authors owe a substantial debt to many individuals who have contributed thoughts or inspirations used in this article. Several must be acknowledged for their singular importance including: Robert E. Spitzer, Boeing; Dr. John W. Prados, University of Tennessee; Dr. William A. Wulf, NAE; Dr. Bruce Kramer, NSF; and our old friend, "Dr. Sliderule[1]" (whoever, he may be). We, however, remain solely responsible for all opinions expressed, which in no way reflect the views or positions of our respective employers, the Boeing Company, the University of Washington, and the USAF.

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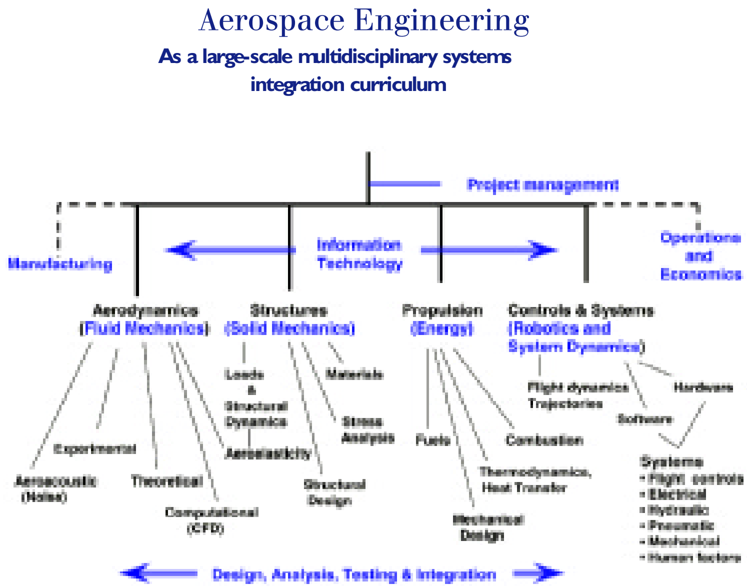
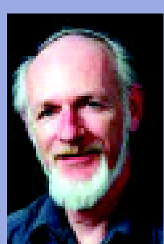


Figure 7
A generalized view of the aerospace engineering curricula.



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