JOURNAL OF AIRCRAFT
Vol. 39, No. 1, January–February 2002

Airplane Design—Past, Present, and Future

John H. McMasters*
The Boeing Company, Seattle, Washington 98124
and
Russell M. Cummings†
California Polytechnic State University, San Luis Obispo, California 93407

The state of the aerospace industry in general, and specifically the aeronautics and aircraft design portion of it, is examined in a long-term historical context. The current "crisis" in aeronautics is shown to be both a unique development and a continuation of our cyclical past, for reasons to be discussed in the text of the article. The evolution of the methods and techniques that have been available to synthesize and develop a new airplane configuration are also examined. Although much will change in terms of tools and techniques, much will remain remarkably invariant in basic overall design strategies and the attributes of those skilled in their execution. Finally, some positive steps are suggested that we individually (in our respective companies, agencies, and institutions), and collectively as an aeronautics community, can take to ensure the development of a future generation of airplane designers who are as skilled as those who have created our heritage.

Introduction

A RECENT spate of national studies and articles in both the popular and professional presses have decried the seriously declining state of aeronautics in this country (e.g., Refs. 1–3). This current situation has been brought about in part by major social/political/economic changes in the world in the wake of the Cold War, a supposed maturation of our traditional aerospace technologies, and the competition for resources (talent, research money, infrastructure maintenance, etc.) with the explosive growth in information, communications, and other newer technologies.

Whatever list of causes for the putative "decline" in aeronautics may be constructed, two more fundamental underlying factors are cause for serious immediate concern. The first is the fact that we (industry, government, and academe) as an aeronautics community have not yet been able to create a collective vision of our future as compelling and exciting as that which has driven our past. The second, which is reciprocal to the first, is the need for an aggressive means to replenish and sustain the pool of airplane design talent needed to maintain an industry that continues to find a multibillion dollar-a-year market for its products. The present pool is aging and being drained by retirement, and its replacement faces increasingly severe competition for both young and experienced talent from the emerging "dotcom" economy, which is rapidly surrounding us.

These and other issues must be addressed if the aerospace industry in general, and the aeronautics sector specifically, is to be able to continue to flourish and grow. The industry must have a compelling and realistic vision for the future, and that vision must be successfully imbued in students if the aerospace industry is going to prosper in the future.

Current Situation

Viewing the aerospace industry in a broader historical context is a complicated task because the industry is relatively young in years, but quite "mature" in knowledge and accomplishments. By any measure (including an apparent "equivalence" with Moore's Law in the current information technology world), progress during our first 100 years (1900 to the present) has been truly dramatic. Those of us who began our careers during the space race of the 1950s and 1960s realize how impressive our achievements have been. Others who started working in the early 1970s have lived in a constant state of boom or bust. Still younger engineers may wonder if they have entered an industry with little of interest left to do. The real target of this article, however, is the future generation of potential engineering talent that has yet to decide whether to join what has been (and we think will continue to be) a great profession.

From whatever vantage we view the current situation in our enterprise, it is worthwhile to stand back periodically and examine the nature of the industry as it has actually been for a majority of the past century. In this, one must assess both our technical progress and the equally important economic/social/political context within which it exists. This latter effort is of particular importance in understanding some of the "why" of where we are today and the influence of these factors on the development of the future human capital we will need to sustain the health of our endeavour.

One can easily argue that the development of aeronautics (and, more recently, astronautics) has always been a boom or bust enterprise, and the historical record of at least the past 50 years supports this contention. Wars, both "hot" and "cold," have been a major driving factor in a great deal of aerospace development, beginning prior to World War I and the beginning of the race for "faster, higher, farther" military aircraft. This course of development continued through World War II and the Cold War, with continuous improvements in aerodynamics, materials, structures, propulsion systems, and concomitant performance (speed, range, payload, etc.). In retrospect it is truly amazing to recall, for example, that it took less than a decade to progress from the first flights of liquid propellant rocket and jet-propelled aircraft in 1939 to the first supersonic manned airplane (the Bell X-I) in 1947. This then led very rapidly to a series of supersonic fighters and bombers, the first of which became operational in the early 1950s. This reflects an approximate doubling of operating speeds for fighter aircraft in a period of roughly a decade and a conquering of the whole transonic flight regime. World War II technology foundations and emerging Cold War imperatives then quickly led us into space with the launch of Sputnik in 1957 and the placing of the first man on the moon only 12 years later—a mere 25 years after the end of World War II.

A great deal of the research and subsequent advances in aerospace resulted from other than purely military motivations as well. The

Received 26 January 2001; revision received 10 August 2001; accepted for publication 20 August 2001.

*Technical Fellow. Associate Fellow AIAA.
†Professor, Aerospace Engineering Department. Associate Fellow AIAA.

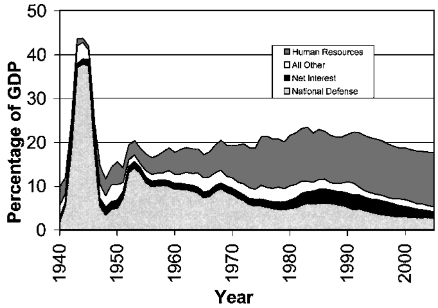

Fig. 1 Composition of federal outlays as a percentage of gross domestic product (Ref. 4).

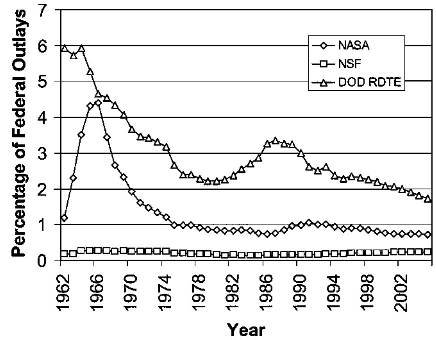

Fig. 2 Federal aeronautics-related expenditures as a percentage of federal outlays (Ref. 4).

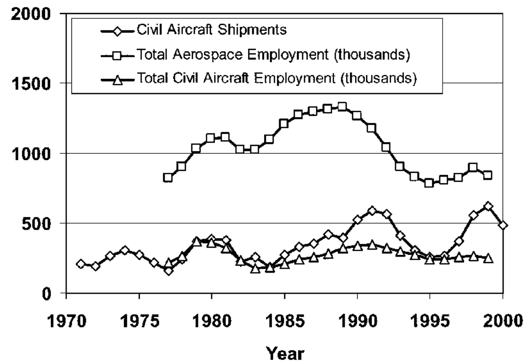

Fig. 3 Aerospace industry trends (data from Aerospace Industry Association of America).

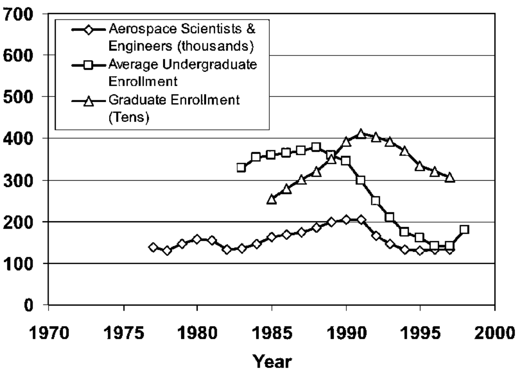

Fig. 4 Aerospace industry trends (data from Aerospace Industry Association of America).

development of the government N.A.C.A. in 1915 and the private funding to the "Guggenheim Universities" (e.g., Cal Tech, Massachusetts Institute of Technology, Washington, and New York University) in the late 1920s led to very significant advances in aeronautics. Major spurs to innovation were the various aviation prizes (first to fly the Atlantic, etc.) and air races such as the Schneider, Goodyear, Collier, and Thompson trophy events of the 1920–40s era. The value of these nonmilitary (though often nationalistic) endeavours should not be underestimated. It can be argued that air racing, like automobile racing, served to focus the attention of both companies and enthusiastic individuals on making great strides in high-performance internal combustion engines, drag reduction, improved structures and systems, etc., at a remarkable rate (and with only modest expenditure by their sponsors). The advent of commercial air transportation also motivated various aircraft manufacturers to develop improved aircraft for purely civil purposes, from the Ford Tri-Motor, to the Boeing 247 and Douglas DC-3, and finally to the jet-powered aircraft like the DC-8 and Boeing 707. These aircraft required improved navigation, communications, and other operating and safety systems, as well as the ability to fly faster, higher, and farther.

These developments took place, however, within a larger social and political context. Although few people would deny that military imperatives and funding had a large impact on the development of the airplane, the amount of funding available for research and development in this country from the U.S. government has not been as overwhelming and continuous as one tends to think. Since 1940, the overall federal budget has changed dramatically (see Fig. 1).[4] Certainly, the impact of World War II on the budget, as well as life in the U.S., was dramatic, with the national defense budget approaching 40% of the gross domestic product (GDP). But after the war the defense budget dipped dramatically (as was inevitable), with a significant increase seen in the 1950s caused initially by the Korean conflict and the increasing demands of the Cold War.

Overall, however, the defense budget, although large, has decreased significantly as a percentage of GDP, with the main exception being the latter 1960s that reflected the demands of our involvement in Vietnam and Southeast Asia. From that point until the present, the defense budget has continued to decrease drastically as a fraction of GDP, with a corresponding increase in social and other entitlement programs, interest on the national debt, etc., keeping the overall budget at a more nearly constant average level.

Examining the federal budget in more detail reveals a longer-term shift in the government's policy toward support for science and engineering research. Figure 2 shows NASA, National Science Foundation (NSF), and U.S. Department of Defense (DOD) research, development, test, and evaluation (RDTE) budgets since 1960 as a percentage of federal outlays. With the notable exceptions of the NASA budget increases during the 1960s for the Apollo program and the DOD increases in the 1980s, the research budgets for science and engineering generally have been decreasing for the past 40 years. These decreases can be viewed in two ways: 1) the need for government funding for research in science and engineering is decreasing because of the vibrant economy, which allows shifting of this burden toward the private sector; or 2) our country has lost the will (and perhaps the ability) to federally fund research and thus invest in the longer-term future. The reality of the situation is probably a combination of these two views, but the decline has caused a great deal of concern from a variety of people with very different perspectives (see Refs. 5–7). The decline has also taken place in spite of a great deal of evidence that aeronautics research investment pays this country dividends in the long run[8] and in the face of a European trend of increasing and improving aeronautics research.[9]

In spite of the decreasing support for research in general and aeronautics in particular in this country, the aerospace industry has not been in a continuous decline over the past 50 years. Instead, the industry has undergone a number of well-known (and highly publicized) peaks and valleys, as shown in Fig. 3. For example, civil aircraft shipments in the U.S. exhibit an oscillatory behavior that generally reflects the state of the world (rather than our national) economy. As would be expected, total aerospace employment exhibits the same cyclical behavior (actually preceding the increases and decreases in shipments). In turn, the publicity accompanying these cyclical variations has been a primary driver in student enrollment in university aerospace engineering programs (Fig. 4), with enrollment lagging behind the industry by about four or five years.

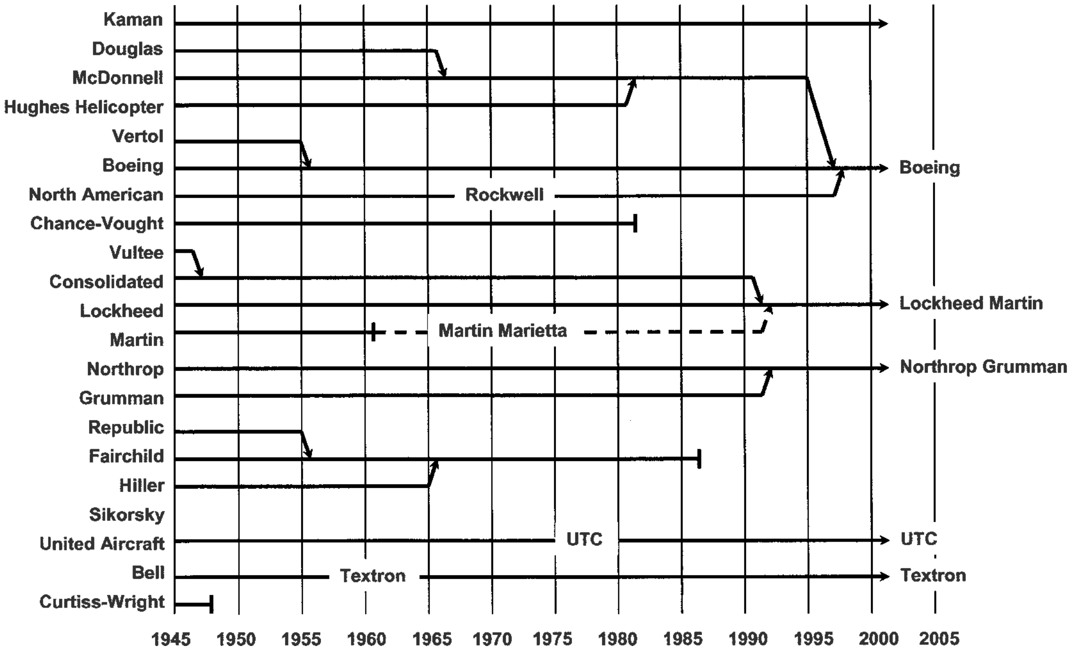

Fig. 5 Consolidation of U.S. military aircraft manufacturers.

However, and most importantly, the actual number of engineers and scientists in the industry has not changed a great deal, even as shipments of aircraft—and the perceived health of the industry—change dramatically. One of the important messages here is that students have been (and continue) basing their decisions about pursuing careers in aerospace on readily available, but inaccurate or incomplete information. The press reports every layoff and every program cut at major aerospace firms, but rarely do they delineate between layoffs of factory workers and engineers, even though the industry has done fairly well at maintaining a steady engineering workforce. Of course, there are examples of large changes in employment numbers at individual firms, but the overall industry has been able to maintain healthy employment levels even in lean times. To some degree, the future of our enterprise is held hostage by this phenomenon, and a message of this article is that this situation should not be allowed to continue. It is far from time to write the history of the aerospace industry as an obituary.

Another factor leading students and aerospace industry workers to worry about the future has been the consolidation of the industry. Since World War II, the number of companies manufacturing military aircraft, for example, has continued to dwindle as a result of a number of factors. These include an inability of some companies to change with changing times and markets, the rapidly escalating cost of bringing new products to market, and government defense policy, which has encouraged mergers to maintain supplier strength while cutting excess capacity in a post-Cold War world. Figure 5 shows the amazing consolidation of the industry, and there is no reason to believe that even further "belt tightening" may not happen in the future. This vast consolidation tends to give the impression that the industry is shrinking, whereas Fig. 3 shows that only small changes in employment of scientists and engineers has taken place. Further, there are no signs that the total worldwide market for aerospace products and services is significantly declining, despite significant changes in individual sectors.

Technical Progress

Having examined the trends in the economic and business context of our enterprise over the past several decades, we turn to the question: Can the history of aviation technological advancement tell us something about the future of aeronautics? Have we been in similar situations before, or is it obvious that we have reached a final state in our "evolution" to a "mature" (i.e., moribund) technology in aeronautics? Looking at actual advances in airplane performance

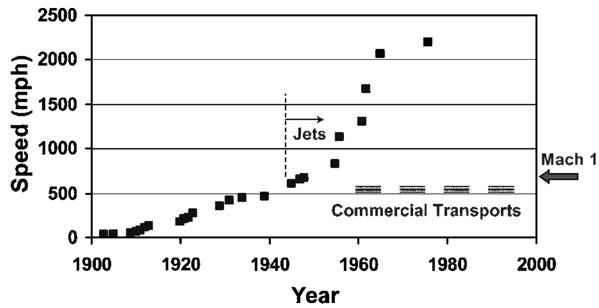

Fig. 6 Absolute airplane speed record (Refs. 10 and 11).

parameters such as speed and range over time can be informative. Figure 6 shows the absolute airplane speed record (IAF Class C) for the past 100 years.[10,11] The most dramatic increases in speed took place between 1955 and 1965, when the jet engine matured and enabled various military aircraft (e.g., the SR-71 and MIG 25) to obtain very high speeds relative to those of only a decade earlier. The records have come few and far between since that time, however—a supposed symptom of a mature technology with few frontiers left to conquer.

Closer examination of Fig. 6 shows some interesting details, however. In terms of radical increases in speed, there have been several discrete eras of amazing improvement over the past century. The advances in performance, configurations, and construction techniques between the beginning and the end of WW I mark one such era. A second period of notable development was spurred by the advent of the now famous air races, especially the Schneider Trophy competition, circa 1921–1931, that led to incredible increases of speed for seaplanes thanks to great improvements in aerodynamics, structures, materials—and most importantly, in engines and fuels. It was this technology base that formed most nations' aeronautical capabilities as they entered World War II a decade later. The revolutionary advent of the jet engine, as already mentioned, eventually allowed huge increases in speed. How do we know that there are not future advances waiting to be made as a result of hybrid engine technology, new mission requirements, or other configuration and systems concepts that have not yet been imagined or developed (at least outside the "black world" that remains invisible to us)?

Military developments aside, Fig. 7 illustrates the evolution in productivity [operating speed times useful load (fuel plus payload)

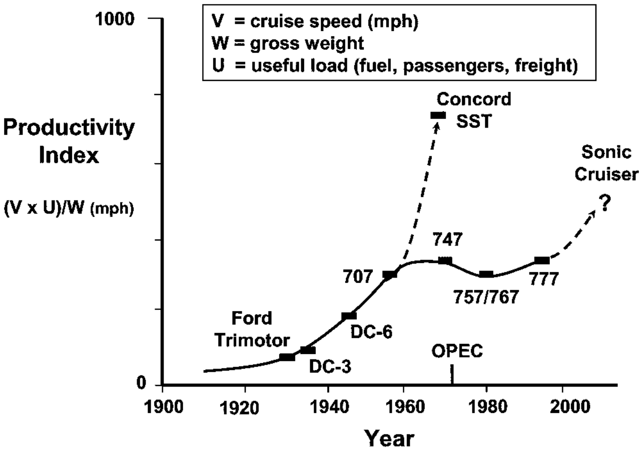

Fig. 7 Evolution in the productivity of commercial aircraft (Ref. 12).

divided by gross weight at takeoff] for commercial transport aircraft since circa 1930 as a major economic measure of progress in civil aviation.[12] The initial portion of the curve tracks rather well the overall trend in speed capability shown in Fig. 6, which in turn suggested that the "next big thing" in commercial air transportation circa 1960 should be the development of a supersonic transport. This line of exuberant optimism (vintage Cold War technical hubris) of course produced the Anglo-French Concord, Soviet Tu 144, and the stillborn Boeing SSTs. The history and epilogue of this initial effort to conquer yet another frontier in aviation are well known. Although we thus remain able, in principle, to produce commercial aircraft that are capable of operating at faster than transonic speeds, we have continued to be limited to this flight regime by economic and environmental considerations. These issues with regard to supersonic commercial operations have yet to be resolved, despite renewed major attempts to do so during the last decade. Thus, at least one clearly identifiable challenge still remains for a future generation of designers.

Figure 7 further serves to illustrate the sensitivity of commercial airplane development to economic and political factors. The rise of OPEC in the early 1970s, for example, had two consequences, only one of which is shown in the trend illustrated. The expected continuing major rise in fuel prices following the oil crisis of 1973 led the designers of transports like the Boeing 757 and 767 to include equipment and make design trades (e.g., selection of modest reductions in optimum cruise Mach number) that significantly enhanced fuel economy. This was consciously done at the expense of raw productivity increase as had been the trend in the preceding time period, and this is demonstrated by the modest retrograde trend shown in Fig. 7. Not shown in the figure is the concomitant increase in the cost of newer-generation, quieter, and more fuel efficient machines. As we now know, the cost of fuel did not increase at the rate anticipated in the 1970s, and the high relative cost of these aircraft has haunted us ever since. It has been this factor, among others, that has served to spur the development of "lean manufacturing" concepts and techniques that have become dominant design considerations in more recent product development efforts.

"Higher, faster, farther" has given way to "better, cheaper, faster" (i.e., reduced cycle time) as the mantra of the commercial airplane segment of our industry. To many of those individuals who grew up in the (third or fourth) "golden age of aviation" of the 1950s and 60s, the quest for cheaper seems to have taken much of the fun and excitement out of what designers can and must do in our current (and near future) environment. Have we thus reached the stage of technological maturity in which mere derivatives and retrofits of our past triumphs are to be our future? Or is this yet another stage—a long but possibly temporary (finite) plateau—in a continuing longer-term upward progression? How do we know that there are not revolutionary concepts remaining to be found that will enable us to take commercial aircraft in new directions? Are the challenges in "better, cheaper, faster" somehow inferior (intellectually and motivationally) to those of "faster, higher, farther"? To this last question, at least, a definite answer is possible: No! The challenges are just different, and the differences are boring only to those of an older school who have not tried to deal with them in all of their new complexities and nuances. Assuming that the future is (or should be) merely an extrapolation of the past would be dangerous (e.g., the OPEC example just discussed) for the long-term viability of the industry. We must continue to search for new technologies and new methods while being very careful not to extrapolate from the peak or trough of too short a bubble in time.

Where Are We Going?

Whatever our future may hold, many people believe that the current state of the airplane business is proof that we have transitioned (i.e., declined) from an industry that has won the "faster, higher, farther" revolution to an enterprise that must resign itself to a "better, cheaper, faster" evolution. Many of the trends that have been shown in this paper certainly could be interpreted that way. But could not the same thing have been said at various other moments in our history? Engineers during the 1930s might have believed that the internal combustion engine was about to reach its zenith (which was true), and therefore airplanes could not go faster than 500 mph (which was not true). But the advent of the jet engine, and its subsequent improvements, led to dramatic increases in aircraft speed. Anyone taking a purely evolutionary viewpoint of airplanes in 1940 might have seen limits to performance capabilities. A revolution in engine technology changed that perspective. We now believe that we have reached the zenith of subsonic commercial aircraft, but are we not really admitting that we have simply evolved the current norms to their logical ends? Are there no new revolutionary concepts or processes that could dramatically change the design, manufacturing, and use of aircraft?

It can be argued that our situation in aerospace has become bimodal, with space being our "last frontier" where most of the real challenges and opportunities remain, whereas aeronautics has become a pretty much "been there, done that already" affair. It can also be argued that in manned flight we have largely "conquered" the region of the atmosphere from sea level to 50–80,000 ft in altitude at most practical flight speeds—at least on a clear day in good weather. This still leaves a pretty large gap between traditional atmospheric flight and low Earth orbit, however, and represents one interesting frontier yet to be fully explored. And nothing has yet "flown" in the atmosphere beyond that of Earth (at least to the best of our current knowledge). Thus, to write aeronautics off as a finished topic would be absurdly short sighted in the authors' opinion.

The assertion that we are not yet done in the airplane business is based on two central premises. The first is that our world is far from stationary and what worked well enough last year may be far from a satisfactory solution to next year's problem. The second is the entire several million-year-long historical, archaeological, and paleontological record of the restlessness and curiosity of the genus homo. An urge to travel and explore seems to be an intrinsic part of being human, and, as any successful salesman knows, we are far from being able to establish trust or conduct essential aspects of business and commerce by purely virtual interactions.

One new frontier that is clearly before us is the creation of a truly global economy and the transportation and communication system required to support it. We of course have major elements of such a system, but it can be argued that we have only begun to deal with all of its new challenges and opportunities in a post-Cold War environment. The development of an effective and efficient 21st century global transportation system, of which airplanes must continue to be a key element, remains one of our great challenges in the coming decades.

A second, and in some aspects related, frontier to be conquered might be categorized as flight in hostile environments. This covers the vast range of possibilities from robot air vehicles intended for missions in places or situations that are either impossible or too dangerous for manned vehicles to operate, to commercial air transports able to operate anytime, anywhere, in any weather. Recent reports in the press of passengers on scheduled airline flights being "trapped"

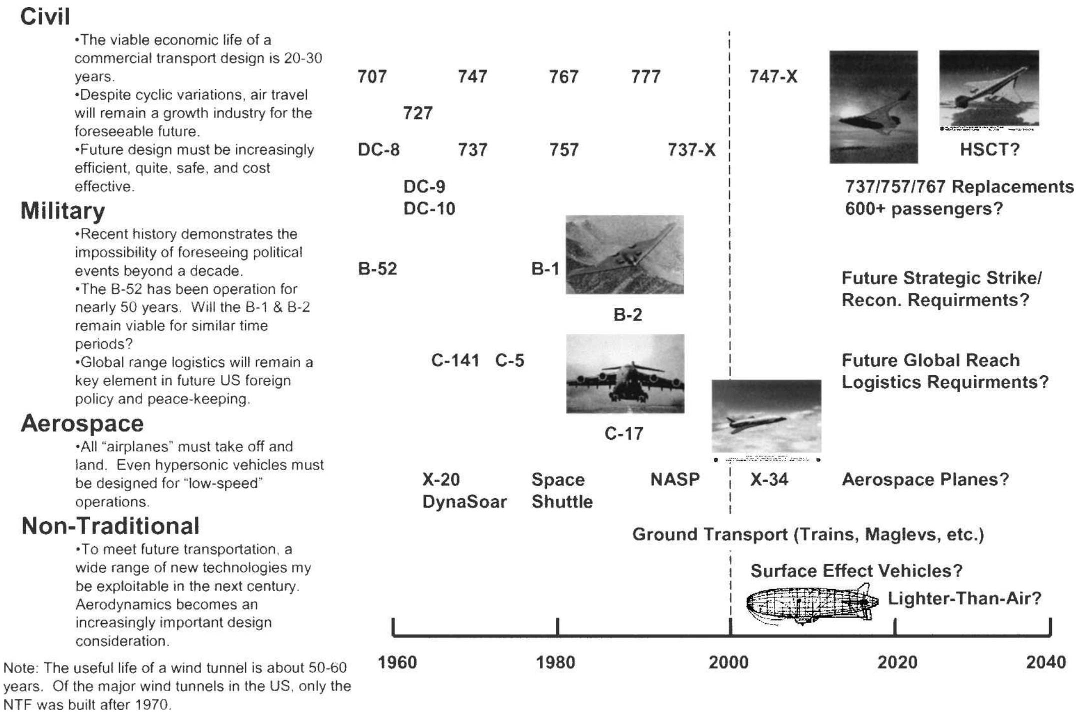

Fig. 8 Future of large airplane development and testing.

for over nine hours on a series of airplanes because of a ludicrous sequence of minor mechanical failures and weather-related delays suggests that we have yet to fully conquer the demands of routine commercial air transportation.

As but one example of what remains to be accomplished over the next 40–50 years in aeronautics, consider the range of opportunities in the development of large aircraft, as shown in Fig. 8. Much will change over the next 30–50-year time period, and much still remains to be done—even in this single niche of aeronautical development.

New Tools and New Prospects

To anticipate the future of aeronautics, we also need to make an assessment of what is going to be new in terms of tools and processes compared with what is going to stay pretty much the same in aircraft design (e.g., creative thinking, artistic ability, understanding whole systems, etc.). The following subsections give a partial list of areas where changes and improvements can and will be made.

Computational Simulation Tools

We currently use computers to perform many tasks virtually that engineers routinely performed in the past by physical techniques (e.g., drafting and the use of mock-ups, wind-tunnel testing and experimentation). Computer simulations are available for modelling a wide variety of physical systems, including aerodynamics, structures, flight mechanics, control systems, etc.—and more recently and significantly, manufacturing processes. These simulations have given designers the ability to learn far more about the various processes and physics involved than they might have been able to learn from physical experiments. For example, a computer simulation of a supercritical wing offers a great deal more (some would argue too much) information than a wind-tunnel test of the same configuration. But many current design simulations might be considered rather crude, merely mimicking the processes that humans use to accomplish the same task by more traditional methods. Because of this, many believe that the full potential in productivity gains from use of computers has yet to be realized.

A great deal of effort is being spent on the creation of efficient multidisciplinary design methodology, but a great deal more work may be required to see the full benefits of computer-based synthesis and optimization. In the past a design engineer had to go from dreaming, to back-of-the-envelope sketching, to the drafting table (with "handbook data" in hand), to the wind tunnel, to flight test. Many of those steps have now been (or can be, in principle) mechanized so that one can go pretty much from daydream to simulation to some sort of flight-test validation of predictions with the computer and its massive databases as the core element of the process. But has that made the design process better? Have we not actually started merely to codify our biases and assumptions and thus essentially stifle creativity and new configuration explorations by relying on the computer to perform most of the routine mechanical work? There should be new ways to use computers to revolutionize the design process, as a complement to, rather than just a copy or extension of, the thought processes of human designers. As only one example, use of inverse methods in which ones specifies the desired physics and then uses computers to extract the shape which produces them can be considered a proper approach to design that complements rather than mimics human capability.

Multidisciplinary Optimization

The advent of practical and powerful nonlinear multidisciplinary optimization (MDO) tools have two interesting advantages: 1) they let us look at the proper changes in a whole system rather than having to do some sort of linear superposition-based suboptimization, and 2) they are great teaching tools. New strategies need to be developed that may be unique to the aircraft industry, which take advantage of the assumptions and techniques that airplane designers use, rather than letting a computer churn away and come up with theoretically possible, but practically impossible, configurations. The linkage of computer graphic and visualization techniques with the mathematical power of MDO methodology has real promise and potential in this regard.[13]

Robotic Aircraft

We now have the capability of building a whole continuum of X-plane-type vehicles starting with miniature robot airplanes (using components of which an amazing array are now readily available from local hobby shops) to full-scale proof-of-concept demonstrators. This offers the capability of simulating a very wide range of aircraft concepts very quickly and affordably. This also gives us the opportunity to do flight testing at a rate that has not really been possible since near the beginning of the last century! The opportunities here are truly marvelous and almost unlimited. These "little airplanes" also give us the opportunity to address a major auxiliary issue: With the timescale between major new projects increasing at an alarming rate, how do our people gain the necessary project/program experience with real hardware? How do we get the hands-on experience required to design the next new thing from a base of real knowledge rather than purely theoretical possibility? Even minidesign/build/test X-plane projects have the necessary ingredients to give this necessary experience—and at an affordable price.

Redefining Aircraft Design

Finally, and perhaps most importantly (fully enabled by the advances just mentioned and with 100 years of experience behind us), we can rethink the way we think about airplanes. What would an airplane designed entirely on the basis of "lean" principles look like? What airplane configuration(s) provide an optimum transportation-system solution(s) for a given route structure? What would a truly passenger-centered commercial transport airplane look like? How would we make such a machine appealing to an airline customer as well? What prospects do we have for creating a class of "green" transport aircraft that, among other features, are no longer dependent on fossil fuels, the future supply of which is unknown, but finite? All of these questions can help to redefine the "playing field" (renew the vision) for aeronautics in the new century (Ref. 14).

Some Actions for the Aeronautics Community

So, how do we get there from here? Should we, individually and as a community, continue to do what we have been doing in what we know to be a cyclic and ever-changing enterprise? Unfortunately, without a more sweeping and exciting vision of our future, for many of us that would be a case of "been there, done that." Looking at the same problems in the same way, we will indeed see that there is little new left under the sun and thus see little prospect for attracting the talent needed to follow those of the current generation of designers as they gradually retire and fade into the sunset. The future of aerospace is not to be defaulted to our colleagues in the astronautics side of our house to have all of the fun in their myriad new worlds to conquer. But clearly there is a lot left to do in aeronautics, and a lot of new horizons if we let our imaginations run loose a little. This past decade has been amazing in many ways, but we think it a mistake to say that the current environment is any more "permanent" than the nine decades that preceded it. How do we know what will take place between 2010 and 2020? Why cannot that decade be just as interesting as the decade from 1950 to 1960, even though everything we as engineers think about our business will be *very* different? And that returns the discussion to the question of how to attract and develop a future generation of airplane design talent.

Again, from a longer-term historical perspective, we can see that major changes have occurred in tools available to us, in utilization of talent, and the ways in which engineering has been organized and practiced in our companies over the last century. As shown in Fig. 9, academe has responded to these needs in various ways. It is strongly argued that it is time for another change in academic programs to prepare the next generation of our students for our industry as it continues to change. In this new era industry must be a strong and active participant in the education of our future generation from well before their graduation. What is wanted is a future generation of designers with many of the attributes that have characterized their breed since the beginning, however. Many things change with time, but some remain remarkably invariant as our list of desired attributes of a configurator [an aeronautical Frank Lloyd Wright or Eero Saarinen (i.e., "an airplane architect)] shows: 1) an "airplane nut," fascinated with the art and science of our products (airplanes); 2) possesses a breadth of skill and knowledge (including business/cost practices) anchored in significant depth of expertise in one or more basic core disciplines (aerodynamics, structures, systems, manufacturing, computing/information technology, etc.); 3) a multidisciplinary large-scale system thinker—naturally grasps the essential elements of the entire airplane system before delving into specific details in requirements, design, manufacturing, maintenance, operation, cost, etc; 4) possessed of an "artist's eye," a developed and informed aesthetic sense of what an airplane can and should look like; 5) curiosity and the desire and ability to learn for life—6) the ability and self confidence to think and act "ambidextrously" as a given situation requires, a) think both creatively and critically, b) act independently and cooperatively as a member of a team, and c) behave with open-minded flexibility and stubborn tenacity; 7) strong communication skills (written, oral, graphic, and listening); 8) possess high standards of ethics and intellectual integrity; 9) eagerness to take judicious risks and willingness to make

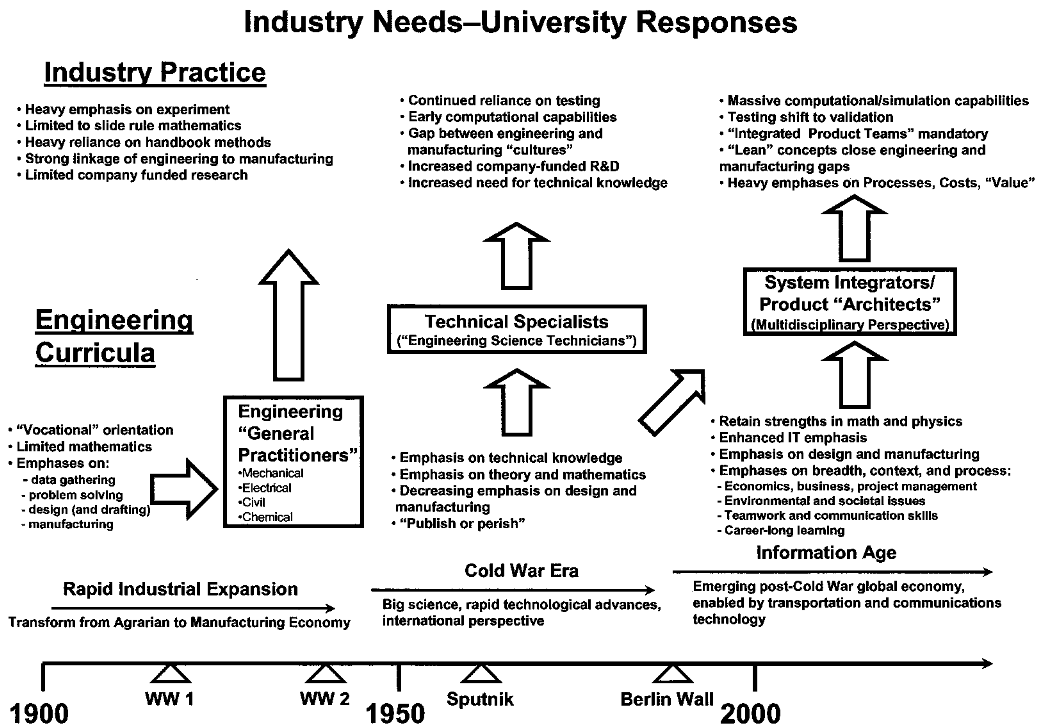

Fig. 9 Evolving trends in engineering education and practice.

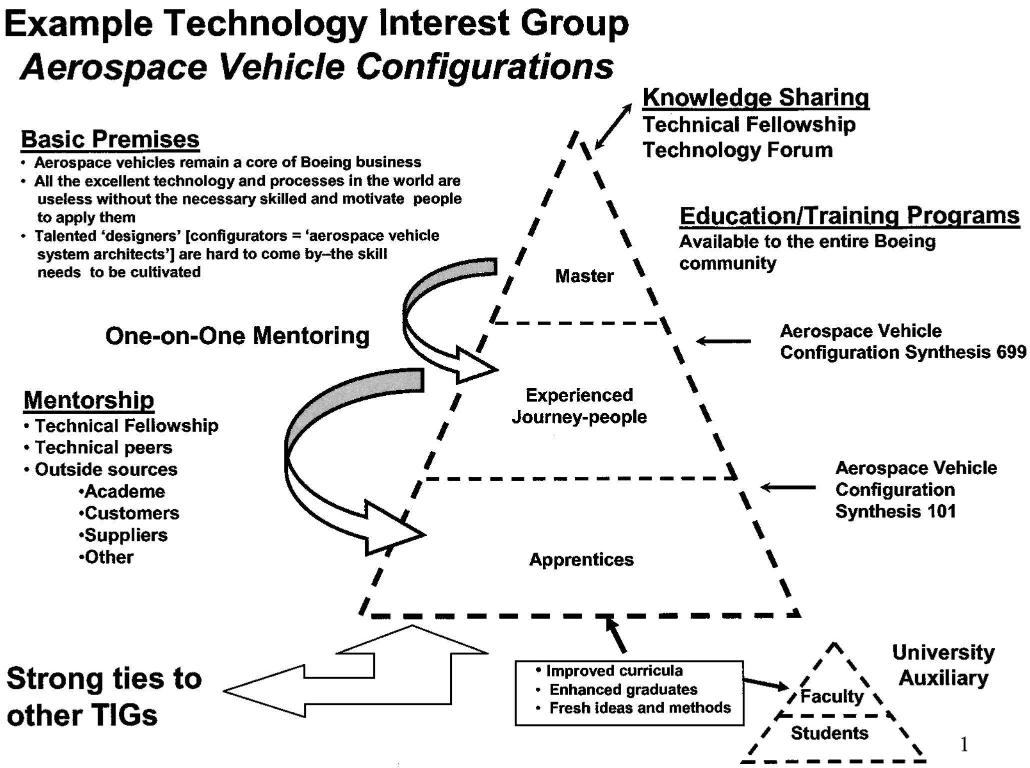

Fig. 10 Example technology interest group.

mistakes; 10) leadership ability including vision and entrepreneurial skills. [It is unrealistic to expect to find any individual within our present or future workforce who has all of the attributes listed in a fully developed or complete form. On the other hand, experience demonstrates that most of the really great designers (configurators in the sense of being airplane or other technology architects) in the history of our industry possessed an unusual measure of the great majority of the attributes on this list. Thus, although the breed is rare, the importance of these "key few" to the ongoing success of our enterprise makes it necessary to make special efforts to cultivate a future generation of such individuals.]

In this, we are going to be a lot better off working as a technical community as contrasted with adopting the "us vs them" attitude so prevalent during the Cold War. Certainly, the merger of former rival aircraft manufacturers will lead to a certain amount of shared ideas and creativity, but the large scope of these new merged companies also makes it quite difficult to communicate, even within a single site or organization. In discussing our technical community, it is important to our future to ensure that our universities are considered an intrinsic part.

One method to deal with a whole suite of related problems in aeronautics is to embrace a concept from current knowledge management theory by forming what are known generically as "communities of practice." Boeing is currently adapting this idea and developing technology interest groups (TIGs) in an attempt to enhance corporate knowledge sharing and skill retention in major technology areas of interest to the company. Figure 10 shows an example of the Boeing TIG concept, including how it can be extended further to include universities. Technical committees and other common topic interest affiliations within the AIAA can be viewed as an already existing framework for a more broadly based expansion of the communities of practice concept beyond single company or organization boundaries.

Within the Boeing model mentoring is an intrinsic part of TIG activities. People with high levels of experience within various technical disciplines will set up mentoring programs with next level technical employees, and these employees will in turn mentor down the line. These mentoring chains would mimic the positive aspects of medieval guilds, where skills were passed from generation to generation via a master/apprentice relationship. As people work their way up in one or more TIG, they will have retained the durable experiences, methods, and philosophies of those that have gone before them. This would not necessarily occur in a formal "written in a book or document" sense, but as shared corporate knowledge passed down by personal interaction (often by virtual means now available to us). The TIGs would be organized around specific disciplines (such as aerospace vehicle configurations, as shown in Fig. 10), but members would be encouraged to participate in other TIGs with overlapping interests (aerodynamics, structures, or flight control TIGs, for example). The TIGs could also share their knowledge and experience with TIG auxiliaries at universities, where a similar mentoring program could be established. Faculty and graduate students could mentor upper-classmen, who in turn could mentor lower-classmen. Students would be learning "how to" knowledge that is often sorely missing in our theory and analysis-based engineering curricula. Students would also be able to have direct contact with engineers in industry to establish important ties for their future careers. Students spending time in these auxiliaries would certainly make desirable employees for the aerospace industry, and they would have gained additional experience from their education by understanding the importance of integrating their knowledge and skills into design applications. They would also develop a strong sense of the heritage of our enterprise and a strong sense of a positive vision of our future, which they themselves would be helping to create.

Conclusions

Recent reports of the decline or possible eminent demise of the airplane business are ludicrously premature. However, to remain in good health the aeronautics community needs to develop a collective vision of our future that is as vivid as that which reflects our past. The central purpose of this article is to make a modest contribution to what that vision might contain. Much more needs to be said on this fundamentally important topic, however.

References

[1] "The Demise of Aerospace," *Flight Journal*, Dec. 1999, pp. 122–121.

[2] Scott, W. B., "'People' Issues Are Cracks in Aero Industry Foundation," *Aviation Week and Space Technology*, Vol. 150, No. 25, 1999, pp. 63–66.

[3]Murman, E. M., Walton, M., and Rebentisch, E., "Challenges in the Better, Faster, Cheaper Era of Aeronautical Design, Engineering and Manufacturing," *The Aeronautical Journal*, Vol. 104, No. 1040, 2000, pp. 481–489.

[4]*Historical Tables*, Budget of the U.S. Government, Washington, DC, Fiscal Year 2001.

[5]North, D. M., "Aeronautics Has Become NASA's Neglected Stepchild," *Aviation Week and Space Technology*, Vol. 152, No. 10, 2000, p. 66.

[6]Kandebo, S. W., "ASME, NASA at Odds over Aeronautics," *Aviation Week and Space Technology*, Vol. 152, No. 17, 2000, pp. 27, 28.

[7]Harris, R., Jr., "The First A in NASA," *Aerospace America*, March 2000, p. 3.

[8]Pestak, C. J., "Aeronautics R&D Yields Greener Economy and Environment," *Machine Design*, March 2000, p. 384.

[9]Sparaco, P., "Europeans to Unite Aeronautics Efforts," *Aviation Week and Space Technology*, Vol. 141, No. 19, 1994, pp. 24, 25.

[10]*World and United States Aviation and Space Records*, National Aeronautics Association of the USA, Arlington, VA, 1992.

[11]Baker, D., *Flight and Flying: A Chronology*, Facts on File, New York, 1994.

[12]McMasters, J. H., "Reflections of a Paleoaerodynamicist," *Perspectives in Biology and Medicine*, Vol. 29, No. 3, Pt. 1, 1986, pp. 331–384.

[13]Braun, R. D., Moore, A. A., and Kroo, I. M., "Collaborative Approach to Launch Vehicle Design," *Journal of Spacecraft and Rockets*, Vol. 34, No. 4, 1997, pp. 478–486.

[14]McMasters, J. H., and Kroo, I. M., "Advanced Configurations for Very Large Subsonic Transport Airplanes," NASA CR 198351, Oct. 1996; also *Aircraft Design*, Vol. 1, No. 4, 1998, pp. 217–242.